Carbon Free Boston

Transportation Technical Report 2019

BOSTON Green Ribbon COMMISSION

BOSTON UNIVERSITY

CAMBRIDGE SYSTEMATICS

Project Team

Cambridge Systematics

Christopher Porter
Martin Milkovits
Xiao Yun (Jane) Chang
Scott Boone

Institute for Sustainable Energy (ISE), Boston University

Cutler J. Cleveland
Principal Investigator
Professor, Department of Earth and Environment, ISE

Peter Fox-Penner
Co-Principal Investigator
Director, ISE
Professor of Practice, Questrom School of Business

Michael J. Walsh
Technical Lead, ISE
Research Assistant Professor, Department of Earth and Environment

Margaret Cherne-Hendrick
Senior Policy Associate, ISE

Sucharita Gopal
Professor, Department of Earth and Environment, ISE

Joshua R. Castigliego
Research Fellow, ISE

Taylor Perez
Graduate Research Assistant, ISE

Adam Pollack
PhD Student, Department of Earth and Environment, ISE

Kevin Zheng
Research Fellow, ISE

Robert Perry
Administrative Coordinator, ISE

Laura Hurley
Communications Manager, ISE

Olivia Simpson
Web Site Developer, ISE

Carbon Free Boston Steering Committee

Janet Atkins
Ridgeway Philanthropy

Vineet Gupta
City of Boston

Richard McGuinness
Boston Planning & Development Agency

Bud Ris
Boston Green Ribbon Commission

Carl Spector
City of Boston

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Commonwealth of Massachusetts

Green Ribbon Commission Staff

John Cleveland
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Green Ribbon Commission Carbon Free Boston Working Group

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Ceres (Chair)

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Boston University

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City of Boston

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Bank of America

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Eversource

Marcy Reed
National Grid

Israel Ruiz
MIT

Al Scaramelli
Beacon Capital Partners

City of Boston Staff

Alison Brizius
Kat Eshel
Lexi Smith
Vineet Gupta

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Carbon Free Boston: Transportation Technical Report

Christopher Porter,[1] Martin Milkovits,[1] Xiao Yun (Jane) Chang,[1] Scott Boone,[1] Michael J. Walsh,[2,3] Joshua R. Castigliego,[2,3] and Cutler J. Cleveland[2,3]

[1]Cambridge Systematics Inc., Medford, MA, USA
[2]Institute for Sustainable Energy, Boston University, Boston, MA, USA
[3]Department of Earth and Environment, Boston University, Boston, MA, USA

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Carbon Free Boston: Summary Report
Carbon Free Boston: Social Equity Report
Carbon Free Boston: Technical Summary
Carbon Free Boston: Buildings Technical Report
Carbon Free Boston: Waste Technical Report
Carbon Free Boston: Energy Technical Report
Carbon Free Boston: Offsets Technical Report

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CONTENTS

1 OVERVIEW

Transportation connects Boston's workers, residents and tourists to their livelihoods, health care, education, recreation, culture, and other aspects of life quality. In cities, transit access is a critical factor determining upward mobility. Yet many urban transportation systems, including Boston's, underserve some populations along one or more of those dimensions. Boston has the opportunity and means to expand mobility access to all residents, and at the same time reduce GHG emissions from transportation. This requires the transformation of the automobile-centric system that is fueled predominantly by gasoline and diesel fuel. The near elimination of fossil fuels—combined with more transit, walking, and biking—will curtail air pollution and crashes, and dramatically reduce the public health impact of transportation. The City embarks on this transition from a position of strength. Boston is consistently ranked as one of the most walkable and bikeable cities in the nation, and one in three commuters already take public transportation.

There are three general strategies to reaching a carbon-neutral transportation system:

- Shift trips out of automobiles to transit, biking, and walking;[1]
- Reduce automobile trips via land use planning that encourages denser development and affordable housing in transit-rich neighborhoods;
- Shift most automobiles, trucks, buses, and trains to zero-GHG electricity.

Even with Boston's strong transit foundation, a carbon-neutral transportation system requires a wholesale change in Boston's transportation culture. Success depends on the intelligent adoption of new technologies, influencing behavior with strong, equitable, and clearly articulated planning and investment, and effective collaboration with state and regional partners.

2 SUMMARY OF KEY FINDINGS

- About 2 million metric tons of greenhouse gases are currently emitted each year as a result of travel in and out of Boston. Three-quarters of the city's GHG emissions come from passenger vehicles, with 15 percent from trucks and 10 percent from transit. GHG emissions are driven by the total vehicle activity, fuel efficiency of vehicles, and carbon intensity of fuels used. Without further policy action, Boston's transportation GHG emissions are expected to fall 28 percent by 2030 and 40 percent by 2050, mostly as a result of currently adopted Federal and State fuel economy standards. This is a marked improvement, but not nearly enough to attain the City's goal of carbon neutrality in 2050.
- Clean vehicles that rely on low or zero-carbon fuels are the cornerstone to achieving carbon neutrality without compromising mobility. The most viable path forward appears to be electrification of vehicles, in conjunction with the development of a clean energy grid. Achieving widespread electrification will require local policy support and incentives such as investment in home, worksite, and public charging infrastructure, to complement further advancements and cost reductions in electric vehicle technology. However, full electrification by 2050 could increase electricity demand by up to 25 percent compared to 2016 City of Boston consumption.

[1] A trip is a one-way movement of an individual by any mode of transport. A person that who bikes from home to a commuter rail stop (1 trip), rides the train to a rail station near work (1 trip), and then walks from the station to her place of work (1 trip) will have made 3 trips. For the purposes of this study, a trip is defined as one that starts or ends in Boston.

- Without further action, vehicle-miles of travel (VMT) are expected to hold steady, despite increasing population, as growth occurs mainly in centrally-located, transit-rich neighborhoods. Clean transportation investments and policies, including travel pricing, transit investment, bike and walk improvements, and other measures to reduce vehicle travel, could reduce VMT by nearly 30 percent at the most aggressive levels of implementation, with corresponding GHG emission reductions. Clean transportation investments will support mobility, livable neighborhoods, equitable access, and the continued economic growth of the City. Capacity, efficiency, and reliability improvements will be critical to accommodating further population and job growth in the City, which will reduce regional VMT and GHG emissions as people cluster in centrally-located, more transportation-efficient locations. Reducing VMT will also lessen the need for new clean energy sources to power electric vehicles.
- Smart mobility options, such as ride-hailing services and self-driving vehicles, have the potential to transform transportation in ways that are not yet fully understood. In today's policy environment, ride-hailing and self-driving vehicles are likely to primarily serve single-passenger trips and therefore increase VMT and GHG emissions. City policies are needed to shape these new mobility options so that they are used mainly by multiple occupants and they rely on clean vehicle technology.
- Three-quarters of Boston's transportation GHG inventory is generated by trips that start or end outside of the City's boundaries. Cooperation with neighboring municipalities, as well as state and regional policies, will be needed to fully realize the benefits of clean transportation policies and incentives.
- Policy actions for the City and its local, regional, and state partners include:
  - Actions implemented through annual capital plans and budgets to turn over the vehicle fleet (e.g., EV purchases, public charging stations, outreach programs) and accelerate development of clean infrastructure (e.g., separated bike lanes, fast and reliable transit).
  - Short-term implementation of land use policies to affect the built environment to set the stage for future clean travel (e.g., EV charging readiness, expanded TDM requirements for new development).
  - Development and testing of policies to steer emerging mobility options (e.g., occupancy-based trip pricing, curb space management) – to evolve over time as these technologies are more broadly introduced and policy impacts can be evaluated.
  - Development, analysis, and piloting of longer-term options to shape travel, e.g., congestion pricing, parking pricing, or restrictions on internal combustion engine operation, to test options and develop support.

3 INTRODUCTION

The scope of this study focused on two general approaches for curtailing emissions: reducing low occupancy automobile use by shifting trips to other modes, and shifting vehicles to be powered by zero-GHG electricity. Conceivably, the electrification strategy by itself could achieve carbon neutrality without any mode shift. An optimistic scenario would enable such a transition to happen readily in which charging an EV is just as easy as filling up a gas tank. Alternatively, options for EV charging in the urban environment could be constrained, and the continued reliance on automobiles continues to place the region at the top of the country's most congested cites [1]. While electrification could still enable carbon neutrality under such a scenario, the urban environment would be less attractive, leading to more residents and business locating outside of the urban core, where the carbon intensity of lifestyles and economic activity is higher. Lower-income people continue to be burdened by long and expensive trips.

We thus focused our analysis on broader-systems solutions that could promote a more efficient, economic, and equitable transportation system that could be more readily electrified. Achieving this requires strategies to reduce vehicle demand in the urban region which rest upon the foundation of a modern transit system that provides rapid and reliable service. When electric automobiles are used to fill the gaps in service, they transport multiple people. Declining demand for vehicles allows for the reallocation of roadway and curb space to dedicated bus and bike lanes. Fewer vehicles on the roads leads to faster travel times for buses and cars, and safer streets for bikers and pedestrians.

Such complete-systems solutions can also promote emissions reductions and deliver significant broader benefits. Our analysis below begins by assessing the impacts of single strategies, but then evaluates how these strategies can be integrated together to achieve ambitious GHG reduction goals while improving mobility and accessibility in Boston.

3.1 BOSTON'S TRANSPORTATION SYSTEM

Boston's urban structure and transportation system already support lower per-capita GHG emissions than most American communities. The city is served by six rapid transit lines, multiple high-frequency bus routes, and ferries; most of its neighborhoods are walkable and it is regularly considered one of the nation's top walking cities. Fewer than half of resident Bostonians drive to work. The City has also invested in bike facilities in recent years, and bicycling has risen to more than 3 percent of commute trips. Boston residents drive about 4,300 miles per year on average, about half the national average of 8,800 miles.[2]

Nevertheless, the City's greenhouse gas emissions from transportation are still significant. In 2013, transportation accounted for 27 percent of the City's GHG emissions, with nearly the entire motorized transportation system running on fossil fuels. Reductions in emissions have occurred much more slowly than in the electricity sector, which has seen a substantial shift to cleaner fuels. To achieve the City's goal of carbon neutrality by 2050, the City and its business and residents will need to greatly reduce or eliminate the use of carbon-polluting energy sources for all energy uses including transportation.

[2] Boston: 2015 total distance traveled for vehicles registered in Boston of 2.8 billion miles (includes household and commercial vehicles), divided by 646,000 population [2]. U.S.: 2.8 trillion light-duty vehicle-miles in 2016 [3], divided by 325 million population.

3.2 Existing City, Regional, and State Plans and Policies

Transportation in Boston is influenced by policies, plans, and funding decisions made by the City as well as by state and regional agencies. References in these plans to GHG emissions and reduction strategies, as well as GHG-focused studies carried out by regional and state agencies, are described below. Existing plans generally move the City and its neighboring cities and towns in a favorable direction for reducing GHG emissions by focusing on transit, walking, biking, clean vehicles, and improved traffic operations rather than roadway expansion. However, recent analyses for regional and state agencies have suggested that, within current funding and policy envelope constraints, the GHG reduction potential of measures in the direct control of transportation agencies alone is limited to a few percent. This report considers additional measures the City and its partners will need to implement to achieve the goal of carbon neutrality.

3.2.1 City of Boston Plans

The ***Go Boston 2030 Vision and Action Plan*** is the long-term mobility plan for the City of Boston [4].

Go Boston 2030 is a resident-driven plan that identifies both aspirational goals and specific projects. It focuses on issues such as reliable and affordable transit choices, access to job centers, and improving walking and biking. The vision framework for the plan includes "climate responsiveness" (which includes decreasing emissions) as one of its three guiding principles, along with equity and economic opportunity.

Go Boston 2030 sets aspirational goals for mode use in 2030: increasing public transit by one-third, increasing walking by half, and increasing biking fourfold, while reducing driving alone by half. The plan also sets a target of reducing transportation GHG emissions by 50 percent of 2005 levels by 2030, and notes that this will require working with surrounding communities to affect travel beyond the City's boundaries through low-emission vehicles and shared travel alternatives.

The plan identifies a set of "top projects" that include walking and bicycling improvements, various transit investments, Smart Signal Corridors and Districts, and Neighborhood Mobility microHUBS that provide access points to shared transit resources. It also identifies a set of "top policies," including state of good repair to sustainably maintain infrastructure; bus route restructuring; autonomous vehicles; and Vision Zero safety initiatives.

In addition to traditional infrastructure investments such as improving transit and expanding bicycle facilities, the plan calls for a flexible approach to lead the nation in supporting new mobility technology and innovations in shared transportation that reach all Bostonians. Examples include adaptive traffic signals, revisions to the use of curb space, trip planning information and apps, and increasing the use of clean fuel vehicles. The plan calls for policies that provide incentives for more shared travel and increases to average car occupancy. The City is developing policies for autonomous vehicles to ensure that vehicles are shared, are electric, and can improve mobility options for all residents.

The plan also emphasizes affordability, by restructuring transportation costs to address income disparities and mitigating effects of transportation-induced gentrification; promoting active and healthy lifestyles through green corridors, emission reductions, and access to healthcare facilities; and prioritizing the movement of people over cars. Finally, the plan has a focus on equity, including assigning a larger share of capital improvement dollars to underserved neighborhoods to achieve equitable distribution of investment.

Go Boston 2030 is an aspirational plan that will require the support and funding of other partners (such as the MBTA) to fully implement. Capital projects such as improvements to local streets and paths can be implemented through the City's annually updated five-year capital plan. In 2017 the City launched the Imagine Boston Capital Plan to move Boston residents' priorities from idea to action, including investing in the core goals of Go Boston 2030 and other initiatives. The **Fiscal Year (FY) 2019-2023 Capital Plan** identifies $967 million in local, State, and Federal funding to implement the core initiatives outlined in Go Boston 2030, including safer streets, reliable and predictable travel, and quality transportation choices, as well as keeping the system in a state of good repair [5]. Other City plans and policies are relevant to its transportation future. ***Imagine Boston 2030: A Plan for the Future of Boston*** sets a vision for the City across all sectors [6]. It calls for providing significant new mixed-use housing and encouraging job growth in transit-accessible areas at the edges of existing neighborhoods. ***Housing a Changing City: Boston 2030*** outlines a plan to produce 53,000 new units of housing by 2030 [7]. It calls for the City to "prioritize new construction along public transit and increase other options for alternative modes of transportation," including exploring reform of parking standards to accommodate non-automobile centric development, and increasing the bikeability and walkability of Boston's neighborhoods by accelerating implementation of the City's Complete Streets Guidelines.

3.2.2 Regional Plans

Boston's transportation system must be considered within a regional context. The Boston Region Metropolitan Planning Organization (MPO) is responsible for long-range transportation planning and capital programming for the region, including all projects and programs that use Federal funds. The most recent long-range plan, ***Charting Progress to 2040*** (adopted in 2015), sets a long-range vision for programming $2.85 billion in federal highway funds during the next 25 years [8]. The plan represents a shift in focus from previous plans by setting aside approximately half of MPO funding to support transit system, bike, and pedestrian projects, rather than primarily funding major roadway improvements. The plan sets forth the following collective transportation vision:

> *A modern transportation system that is safe, uses new technologies, provides equitable access, excellent mobility, and varied transportation options—in support of a sustainable, healthy, livable, and economically vibrant region.*

The priorities set forth in the plan guide the development of the MPO's **Transportation Improvement Program** (TIP) which identifies funding for specific projects over the next five years and is updated annually. GHG reduction is one among many criteria for selecting projects in the TIP. Projects listed in the TIP are typically projects on the state-owned or funded roadway system (major streets, highways, and bridges) as well as transit (MBTA) and off-street shared-use paths. Local street improvements are typically funded and programmed by the City through its five-year capital plan. Boston projects programmed in the Federal Fiscal Year 2018-2022 TIP include traffic signal and intersection improvements, street improvements and reconstruction (Boylston Street, Rutherford Avenue, and Melnea Cass Boulevard); bridge replacement (North Washington Street); and multi-use path construction (New Fenway path).

MBTA investments listed in the TIP such as vehicle replacement, signals, and elevator upgrades benefit residents of Boston as well as surrounding communities.

In February 2018, the MPO posted a report entitled ***Promising Greenhouse Gas Reduction Strategies for the Boston Region*** [9]. This report follows up on the recommendations of the Boston Region MPO's *2016*

Greenhouse Gas Reduction Strategy Alternatives: Cost-Effectiveness Analysis report [10] and details the results of an effort to identify cost-effective strategies employed by other transportation agencies and MPOs in the Northeast and Mid-Atlantic states. The report identifies nine "promising strategies" with relatively greater cost-effectiveness and/or GHG reduction potential:

- Workplace Transportation Demand Management
- Teleworking
- Individualized Marketing of Transportation Service
- Ridesharing
- Carsharing
- Pedestrian Improvements
- Bicycling Improvements
- Information on Vehicle Purchases (primarily policies to promote electric vehicle purchases)
- Parking Management

The report calls for the MPO to revise its project selection criteria to give more emphasis to GHG emission reductions, and recommends the implementation of tools for the measurement and evaluation of the progress of GHG emission reduction initiatives. The report also notes that GHG reduction is just one among many benefits of these strategies.

MetroFuture is the 30-year plan for the Boston region adopted by the Metropolitan Area Planning Council in 2008. The plan includes a vision for the region's future; goals, objectives, indicators; and an action plan. The plan envisions that more of the region's growth would occur in the region's city and town centers (including Boston) with most new homes and jobs near train stops and bus routes. The plan envisions mixed use, pedestrian-oriented developments and jobs located near housing to increase commuting choices, with expanded transit service and biking and walking opportunities. MAPC is currently undertaking a new effort, **MetroCommon 2050: Shaping Our Region Together**, to update and develop a new plan for the region.

The MBTA is currently drafting a long term investment strategy titled **Focus40: The 2040 Investment Plan for the MBTA.** This plan seeks to position the MBTA to meet the long term needs of the metro-Boston region and make its system more *robust, reliable*, and *resilient.* In addition to supporting the greenhouse gas reduction goals of the region the plan seeks to improve livability, mobility and prosperity. The draft plan focuses on improving transportation options and services around the priority areas of: major employment districts; inner core communities lacking access to transit; and, urban gateways. Potential opportunities identified in the draft report include: expanding rapid transit; adding new services and technologies to the commuter rail, increasing dedicated bus routes; and enhancing the ridership experience.

3.2.3 State Plans

WeMove Massachusetts is the State's long-range transportation plan [11], adopted in 2013 by the Massachusetts Department of Transportation (MassDOT). The plan introduces a performance-based approach to statewide investment. The plan notes that GHG reduction is an important performance measure and that MassDOT will work to develop and refine quantifiable metrics for various goals including GHG emissions reductions that can be tied to funding scenarios. MassDOT's **Capital Investment Plan,** which is updated annually, implements *WeMove Massachusetts* by identifying funding for specific projects. In recent years, MassDOT has begun to estimate GHG reductions associated with CIP projects, including shared-use paths, Complete Streets, transit projects, and intelligent transportation systems (ITS) projects such as all-electronic tolling.

GreenDOT is MassDOT's comprehensive initiative to make the agency a national leader in "greening" the state transportation system by reducing GHG emissions; promoting the healthy transportation options of walking, bicycling, and public transit; and supporting smart growth development [12]. Goals of GreenDOT are to design a multimodal transportation system, including increases in bicycle facilities and improved transit performance; develop healthy transportation options and livable communities; and triple the mode share of walk, bike, and transit. Implementation of GreenDOT has included a focus on Complete Streets to benefit all modes/all users and increasing investment in nonmotorized transportation; support for programs such as travel demand management (TDM) and travel information; reducing emissions from agency operations and construction (e.g., clean fleet and transit vehicles); and requiring regional agencies to measure and reduce GHG emissions consistent with state targets. The statewide GHG reduction potential from GreenDOT actions is estimated to be 1.0 million metric tons (t) of carbon dioxide-equivalent (CO_2e) in 2020 [13], or 1.1 percent of the state's 1990 inventory; smart growth is estimated to contribute an additional 0.4 Mt CO_2e in 2020. MassDOT has subsequently provided guidance to MPOs on assessing and reporting on GHG emissions [14].

In 2015, MassDOT conducted a study to model transportation GHG reduction policies using the Federal **EERPAT** model [15]. One scenario considered investments that MassDOT could make if additional funding was available, including bicycle infrastructure, TDM, increased transit service, ITS, and clean buses. The other major scenario considered policies outside of MassDOT's direct control, including parking pricing, electric vehicles, land use and smart growth, VMT fees, congestion pricing, and an enhanced clean fuels standard. The scenarios found potential statewide GHG reductions of an additional 2 to 5 percent in 2030 and 3 to 5 percent in 2050, compared to continuing the implementation of existing policies.

The **Massachusetts Clean Energy and Climate Plan for 2020** fulfills state requirements to address GHG emissions per the Global Warming Solutions Act of 2008 [13]. The original 2010 CECP, as well as the 2015 update, identify policies to attain a GHG reduction of at least 25 percent below 1990 levels by 2020 and to further work toward a long term goal of an 80 percent emission reduction by 2050. Strategies identified for the transportation sector include federal and California vehicle efficiency and GHG standards, clean/electric vehicle incentives, smart growth, federal and regional clean fuel standards, and GreenDOT transportation actions. The 2015 CECP update calls for the State to set interim targets for 2030 and 2040 as well.

GHG emissions from proposed development projects are also covered by the Massachusetts Environmental Policy Act (MEPA). The **Revised MEPA Greenhouse Gas Emissions Policy and Protocol** requires some types of projects to estimate GHG emissions from the project, including GHG from vehicle trips generated, and to identify and commit to mitigation measures [16].

Finally, Massachusetts has undertaken policy initiatives to support zero-emission vehicles. The state is one of nine Northeast and West Coast states that have adopted California's zero emission vehicle (ZEV) regulations, which mandate increasing sales of zero-emission vehicles through 2025. To support implementation of the ZEV regulations, in June 2018 the state joined eight other Northeast and West Coast states in the release of a new Multi-State **Zero Emission Vehicle (ZEV) Action Plan** for 2018-2021 [17]. The Action Plan, which builds on the 2014 ZEV Action Plan, presents 80 market-enabling action recommendations for states, automakers, dealers, utilities, charging and fueling companies and other key partners to rapidly accelerate consumer adoption of zero emission vehicles, including plug-in hybrid, battery electric and hydrogen fuel cell vehicles. Actions implemented by the Commonwealth have included rebates for the purchase or lease of an electric vehicle (EV), incentives for charging station equipment, and EV test drive campaigns.

4 Baseline Inventory and Forecast

A baseline inventory and forecast of transportation sector GHG emissions were prepared for the City for the years 2016 through 2050. About 2 Mt of greenhouse gases are currently emitted each year as a result of travel starting and/or ending in the City. Three-quarters of the city's GHG emissions come from passenger vehicles, with 15 percent from trucks and 10 percent from transit.

GHG emissions are driven by the total vehicle activity (VMT), fuel efficiency of vehicles, and carbon intensity of fuels used. Employment and population are forecast to increase by 11 and 22 percent, respectively, between 2016 and 2050. However, VMT is forecast to increase by only 3 percent, as a result of shifts in land use patterns and demographics that will reduce VMT per household, and changes in employment and manufacturing patterns that will reduce truck travel. GHG emissions are expected to fall 28 percent by 2030 and 40 percent by 2050, mostly as a result of currently adopted Federal and State fuel economy standards for light-duty vehicles and trucks.

4.1 Scope and Methods

The baseline inventory includes the following surface transportation modes: light duty vehicles, heavy duty vehicles (trucks and buses), rail transit, and water transit (passenger ferries). It excludes intercity passenger rail (Amtrak), air (passenger and freight aircraft using Logan Airport), and intercity water transport (long-distance ferries, cruise, and cargo ships). It also excludes "off-road" sources such as ground support equipment at Logan Airport or port and warehouse equipment such as cranes and forklifts.

The baseline inventory and forecast includes GHG emissions associated with vehicle *trip-ends* in the City. This is in contrast to the City's Community Greenhouse Gas Inventory (2016) which estimated GHG emissions from *vehicle activity* (vehicle-miles of travel, or VMT) within the city's boundaries. Both are acceptable methods according to the ICLEI U.S. Community GHG Protocol [18], but the trip-end method is recommended if suitable data is available, because it relates more closely to transportation-generating activity that occurs within the city's boundaries. In contrast, the in-boundary method includes VMT passing through the City, which the City may have less ability to influence through local policy decisions. The trip-end method works as follows:

- Trips starting and ending within the City - all GHG emissions associated with the trip are included in the inventory.
- Trips with one end in Boston – half of the GHG emissions associated with the trip are included in the inventory.
- Trips passing through Boston without stopping – excluded from the inventory.

In this inventory, due to data limitations the trip-end approach is applied only to light-duty vehicles and trucks. Transit emissions (buses, rail, and water) are assigned based on the proportion of the transit system's operations occurring within the City's boundaries.

Table 1. Transportation Activity Subsectors Used in the Baseline Inventory and Forecast

Key	Subsector
1	**Light-duty vehicles**
1.1	Individual ownership
1.11	Households
1.12	Households – ride-hailing services
1.13	Commercial light trucks
1.2	Fleets
1.21	Taxi
1.22	Rental
1.23	Carshare
1.24	Autonomous fleets *(not used)*
1.25	Municipal
1.26	State
1.27	Transit
1.28	Utility
1.29	Other
2	**Medium and heavy-duty vehicles**
2.1	Medium-duty/single-unit trucks
2.11	Commercial fleets
2.12	Utility
2.13	Refuse
2.2	Heavy-duty/combination trucks
2.21	Commercial fleets
2.22	Owner/operator
2.3	Transit buses
2.31	MBTA
2.32	MassPort
2.33	Other
2.4	School buses
2.5	Intercity buses
3	**Rail**
3.1	MBTA light & heavy
3.2	MBTA commuter
4	**Water**
4.1	MBTA ferry

The inventory is based on a bottom-up estimation of the number of vehicles and miles driven by type of vehicle, as well as fuel efficiency and the mix of fuel types for each type of vehicle. Total vehicle population, activity, and emissions are presented by transportation subsector. GHG emissions estimates are based on fuel consumption by type of fuel, with varying consumption rates and fuel type splits by activity subsector and technology/fuel type. The activity subsectors used in the inventory are shown in Table 1. The technology/fuel types include gasoline and diesel internal combustion engine (ICE), compressed or liquefied natural gas (CNG/LNG); and electricity.

The transportation sector inventory in this study includes GHG emissions from electric power generation for electric vehicles so that the full GHG impact of transportation activity can be understood. EVs currently represent a very small fraction of transportation energy consumption, but this fraction is anticipated to grow significantly in the future. Emissions associated with EV charging also are likely to also be included in the building sector of a comprehensive GHG inventory, and care should be taken not to double-count these emissions when adding together emissions from the different sectors. Currently it is not possible to distinguish electricity use for recharging in buildings from electricity use for the building itself. Unless new metering systems are developed, this will limit the ability to explicitly measure and apply policies to transportation electricity consumption.

4.2 DATA SOURCES

The primary sources of data used in this inventory are as follows:

- The **Central Transportation Planning Staff (CTPS) travel demand forecasting model** was used as the source of travel activity data for on-road light-duty vehicles and trucks. CTPS is the staff to the Boston Region Metropolitan Planning Organization, the body responsible for federally required transportation planning activities in the region. The CTPS model is a network-based model predicting flows of travelers and vehicles between 2,730 zones in 164 Boston metro area cities and towns as well as 377 external zones. It is widely used for policy and regulatory purposes, including development of the long-range transportation plan and transportation improvement program for the region. It has been calibrated to historical data on traffic flows and traveler choices. It is multi-modal and includes auto travel (single and high-occupancy vehicle), transit, bicycle, and pedestrian modes. It also predicts truck trips segmented into three classes (light, medium, and heavy commercial trucks). Vehicle trip tables by origin-destination and distance skims (distance for each origin-destination pair) were obtained from CTPS so that VMT could be calculated and assigned appropriately to the City inventory. Data were obtained for a base model year of 2016, as well as from 2040 model year runs that account for projected changes in population and employment.
- **MOVES input files** created by the state's Executive Office of Environmental Affairs, Department of Environmental Protection (DEP) were used as a basis for vehicle populations for light-duty vehicles and trucks. MOVES (the Motor Vehicle Emissions Simulator Model) is the U.S. Environmental Protection Agency's official model for developing vehicle emissions inventories and conducting regulatory analysis. Vehicle populations are based on state registration data (Department of Motor Vehicles) for vehicles registered within Suffolk County, as analyzed by DEP.
- **National Transit Database** (NTD) and **General Transit Feed Specification** (GTFS) data were used to estimate vehicle populations, VMT, and energy consumption rates for transit. The NTD is a federal repository of data reported annually by transit agencies around the country receiving federal funding. The NTD includes vehicles in the fleet by type, miles and hours of operation, fuel use, and other statistics. GTFS data were used to allocate MBTA system-wide data to the City of Boston based on the proportion of stops within the city's boundaries (45 percent). NTD reporting data for 2016 were used.
- The U.S. Department of Energy, **Annual Energy Outlook** (AEO) was used to estimate the share of each vehicle type by fuel/technology (gasoline, diesel, electric, etc.) and the efficiency of each vehicle type/technology group (miles per gallon) other than transit. The 2018 AEO Reference Case was used for the baseline inventory. The AEO includes forecasts to 2050. The AEO is a nationwide data source and does not include region or state-specific data on vehicle stocks and efficiency.
- **City of Boston** data was obtained on City fleets (municipal vehicles, school buses, etc.) This data included vehicles in the City's fleet as of 2015.

A variety of data sources were used to develop estimates of vehicles and VMT used in specific applications, including ride-hailing services, taxis, rental vehicles, and carshare. Intercity bus activity was estimated from CTPS [19]. The intercity bus mileage included in the inventory is the one-way mileage to the first listed destination.

Table 2 describes the data source or calculation method for each activity subsector for vehicle population, annual VMT, and annual miles per vehicle. In some cases, multiple sources may have provided redundant or conflicting information. CTPS model VMT estimates for passenger vehicles and light, medium, and heavy trucks were set as the control totals, with other sources used to match these totals.

Table 2. Activity Data Sources for Boston Inventory and Forecast

Key	Subsector	Vehicle Population	Annual VMT	Miles per Vehicle per Year
1	Light-duty vehicles	Sum of 1.1, 1.2	Sum of 1.1, 1.2	
1.1	Individual ownership	Sum of 1.11, 1.12, 1.13	Sum of 1.11, 1.12, 1.13	
1.11	Households	MOVES - Sum of motorcycle, passenger car, passenger truck, motor home	CTPS model; sum of AUTO[3]	= VMT/VehPop
1.12	Households - ride-hailing	Estimates from various data sources found on the Internet[4]	Trips estimated from Internet sources (see previous footnote) Assume 5 miles per trip [22]	= VMT/VehPop
1.13	Commercial registration	MOVES - light commercial truck	CTPS model; sum of LightTruck	= VMT/VehPop
1.2	Fleets			
1.21	Taxi	Count of taxi medallions within City of Boston	See note for 1.12	= VMT/VehPop
1.22	Rental	Extrapolated from rental:taxi ratio in Certify report (0.29:0.08)	= VehPop*MiPerVeh	Assume same as daily HH use
1.23	Carshare	ZipCar vehicles located within Boston city limits	= VehPop*MiPerVeh	Assume average of rental/hh and taxi
1.24	Autonomous fleets	*(not used)*	*(not used)*	*(not used)*
1.25	Municipal	Boston City Vehicle Inventory	Boston City Vehicle Inventory	= VMT/VehPop
1.26	State	*(not used)*	*(not used)*	*(not used)*
1.27	Transit	NTD – Demand Response (DR)	NTD * 45% stops in Boston	= VMT/VehPop
1.28	Utility	Boston Public Schools Vehicle Inventory	Boston Public Schools utility vehicles only	Assume same as 1.25
1.29	Other	*(not used)*	*(not used)*	*(not used)*
2	Heavy-duty vehicles		Sum of 2.1, 2.2, 2.3, 2.4, 2.5	
2.1	Medium-duty/ single-unit trucks		CTPS model; sum of MediumTruck	
2.11	Commercial fleets	MOVES - single unit short-haul + single unit long-haul truck	2.1 less 2.12, 2.13	= VMT/VehPop
2.12	Utility	Boston City Vehicle Inventory	Boston City Vehicle Inventory	= VMT/VehPop

[3] An annualization factor of 340 was used to convert CTPS daily model VMT into annual VMT, per guidance from CTPS.

[4] Calculations on Uber driver forums estimate about 20,000 drivers working in Boston area [20]. Certify business travel reports put Uber market share at about 70% [21]. Scaling up for Lyft (12%) and "other" add an extra 5% on top; the remainder out of 105% are taxis (though this number is neglected) gives 24,857 vehicles. Using Certify ratios, estimate 2,485 million ride-hailing trips and 514,000 taxi trips.

Key	Subsector	Vehicle Population	Annual VMT	Miles per Vehicle per Year
2.13	Refuse	MOVES - refuse truck	VehPop*MiPerVeh	Assume same as 2.12
2.2	Heavy-duty/ combination trucks			
2.21	Commercial fleets	MOVES - combination short-haul + comb. long-haul truck	CTPS model, sum of HeavyTruck	= VMT/VehPop
2.22	Owner/operator	*(included with 2.21 due to lack of data)*	*(not used)*	*(not used)*
2.3	Transit buses			
2.31	MBTA	NTD	NTD * 45% stops in Boston	= VMT/VehPop
2.32	MassPort	Derived from Massport GTFS data using peak vehicle requirement	Derived from Massport GTFS data using peak vehicle requirement	= VMT/VehPop
2.33	Other	*(not used)*	*(not used)*	*(not used)*
2.4	School buses	Boston Public Schools Vehicle Inventory	Assume 200k mile/12 year lifespan	= VMT/VehPop
2.5	Intercity buses	Derived from CTPS study intercity bus service[5]	Calculated as annual 1-way mileage to first listed destination	= VMT/VehPop
3	Rail			
3.1	MBTA light & heavy rail	NTD	NTD * 45% stops in Boston	= VMT/VehPop
3.2	MBTA commuter rail	NTD	NTD * 45% stops in Boston	= VMT/VehPop
4	Water			
4.1	MBTA ferry	NTD	NTD * 45% stops in Boston	= VMT/VehPop

The Metropolitan Area Planning Council (MAPC) has also developed a vehicle inventory that includes registered vehicles, miles driven per vehicle (based odometer readings), fuel efficiency estimates, and other data by community for the entire state. The version published at the time of this analysis was based on 2009-2014 registration data [23]. Vehicles are classified into two types – household and commercial (cars and trucks were not distinguished in the public dataset). This dataset was used to develop an alternative inventory of VMT and GHG corresponding to all travel by "resident" vehicles (i.e., registered to an address within the City of Boston limits).

MAPC has also conducted surveys and estimates of ride-hailing, obtained after the estimates in the baseline were developed [24]. MAPC estimates that 3.6 percent of trips originating in Boston and 3.9 percent destined to Boston are by ride-hailing. This closely matches the estimate in the baseline inventory of 3.9 percent of VMT with trip-ends in Boston occurring by ride-hailing.

After the inventory was finalized for purposes of this study, additional or updated data were obtained that would result in modest refinements to the inventory. These include:

[5] Peak vehicle requirement calculated by evenly spacing headways over 18 hour period

- The City identified mode-specific factors for allocating MBTA data from the NTD to the City, including 63.5 percent of regional rapid-transit miles occurring in the City, 58.4 percent of bus miles, 20.6 percent of commuter rail miles, and 25.6 percent of The RIDE trips. This decreases the MBTA bus and rail inventory by about 18,000 t compared to this study's inventory.
- The City noted that its estimate of school bus GHG based on fuel consumption was about 15,700 t or 36 percent lower than this study, as a result of lower miles per vehicle and use of propane fuel in about one-third of buses (propane has about 14 percent lower GHG emissions per unit of energy compared to diesel fuel). The City is planning additional propane bus purchases.
- The City also provided additional/updated data on fuel consumption from municipal vehicles.

4.3 Drivers of Future GHG Emissions

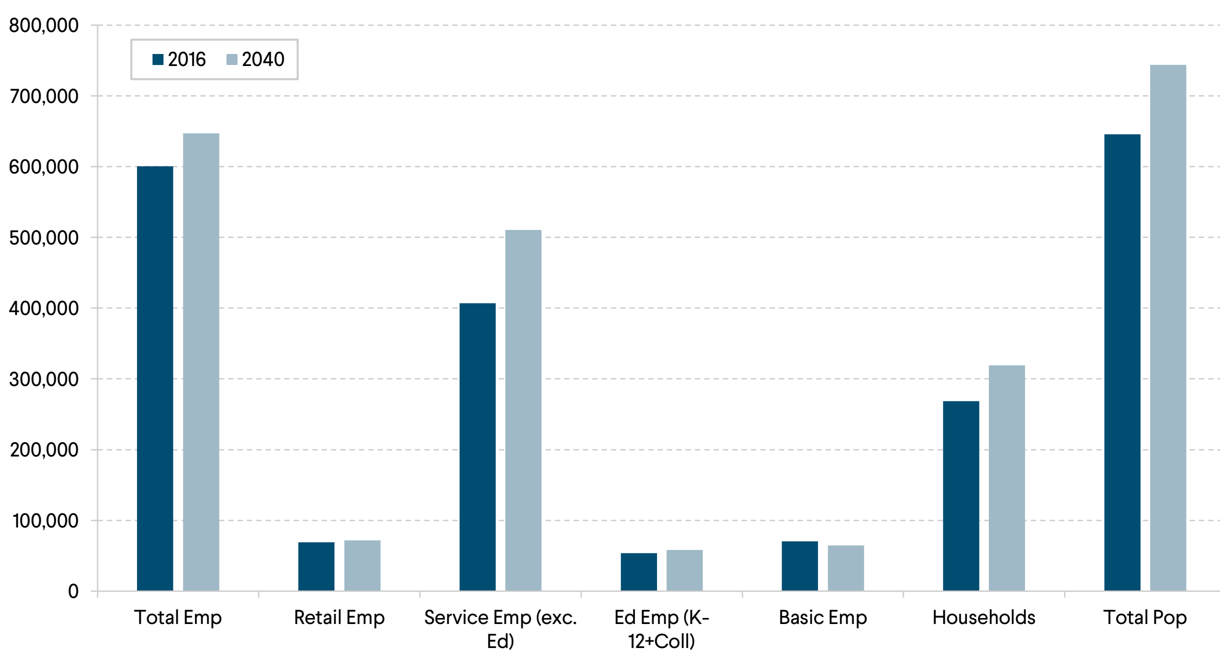
GHG emissions are driven by the total vehicle activity (VMT), fuel efficiency of vehicles, and carbon intensity of fuels used.

4.3.1 Population and Employment

Figure 1 shows population and employment projections prepared by MAPC with input from communities including the City. These are the projections that underlie the CTPS model forecasts. Total employment is forecast to grow by 7 percent between 2016 and 2040, from 600,000 to 647,000 jobs. The service sector is forecast to grow by 20 percent, whereas retail and educational employment show lower growth rates (4 to 8 percent) and basic employment (i.e., industries such as manufacturing that are fueled mainly by external, rather than local, demand) is forecast to decline by 9 percent. Population is forecast to grow by 13 percent, from 646,000 to 744,000. Total households are forecast to grow by 16 percent, from 269,000 to 319,000. If extrapolated, these forecasts suggest a total of 666,000 jobs and 785,000 residents in the City in 2050 – 11 percent and 22 percent higher than 2016 levels, respectively.

Figure 1. City of Boston Employment and Population, 2016 and 2040 Projection

Source: CTPS Travel Demand Model, 2016

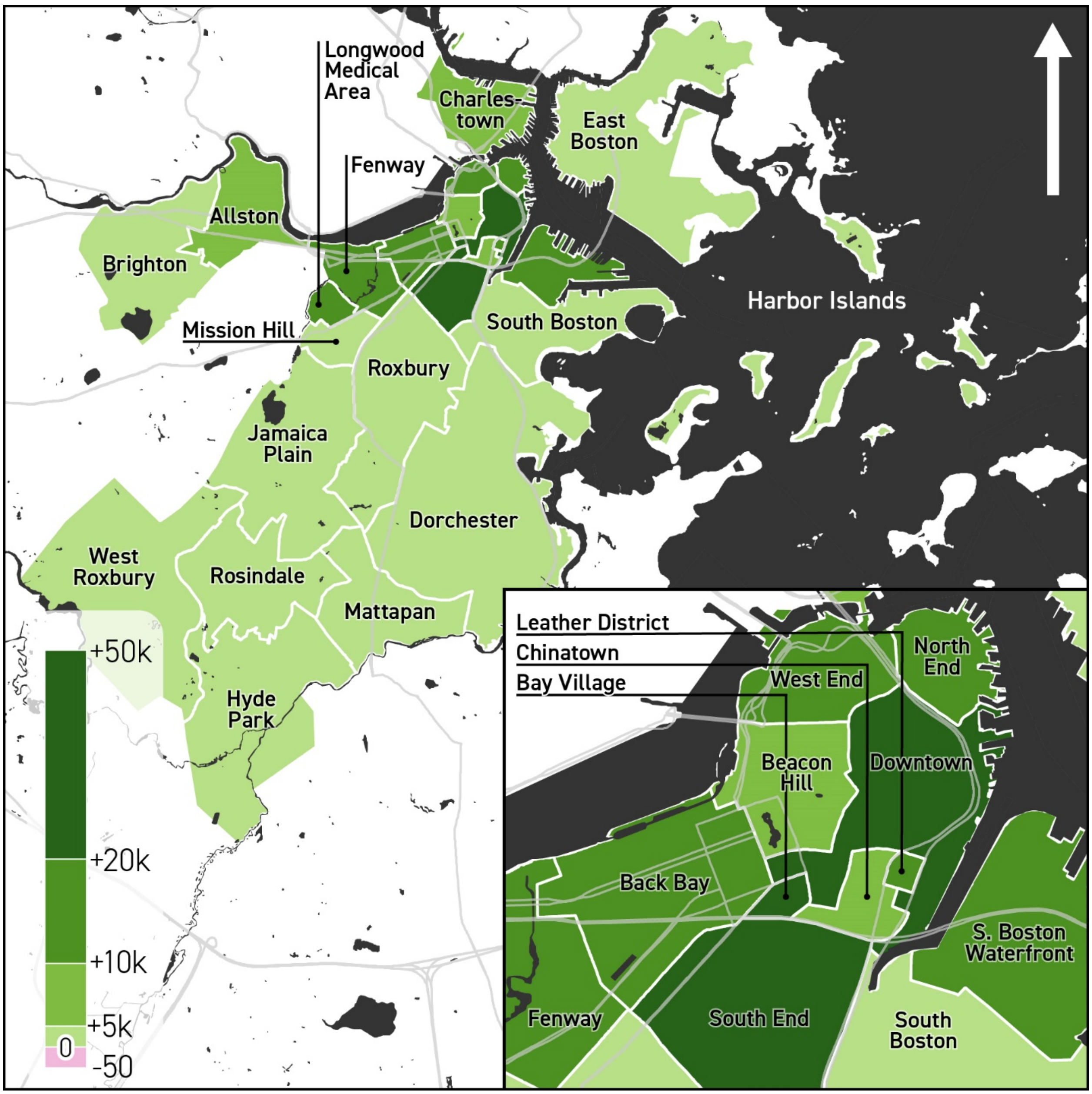


Compared to the entire 164-town modeled area, the City of Boston contains 24 percent of the region's jobs and 14 percent of the region's population. Boston's share of the region is forecast to grow slightly (by about 1 percent) by 2050.

Figure 2 shows where in the City the growth is expected to be distributed. Total population and employment growth between 2016 and 2050 (extrapolated CTPS forecasts) is shown per square mile by neighborhood. The highest intensity of growth is expected to occur Downtown and the South End, with other high-growth areas also including the core neighborhoods of the South Boston Waterfront, North and West Ends, Back Bay, Fenway, and Longwood.

Figure 2. Forecast Population + Employment Growth Intensity by Neighborhood (Change in Population + Jobs per Square Mile, 2016-2050)

Source: CTPS Travel Demand Model, 2016

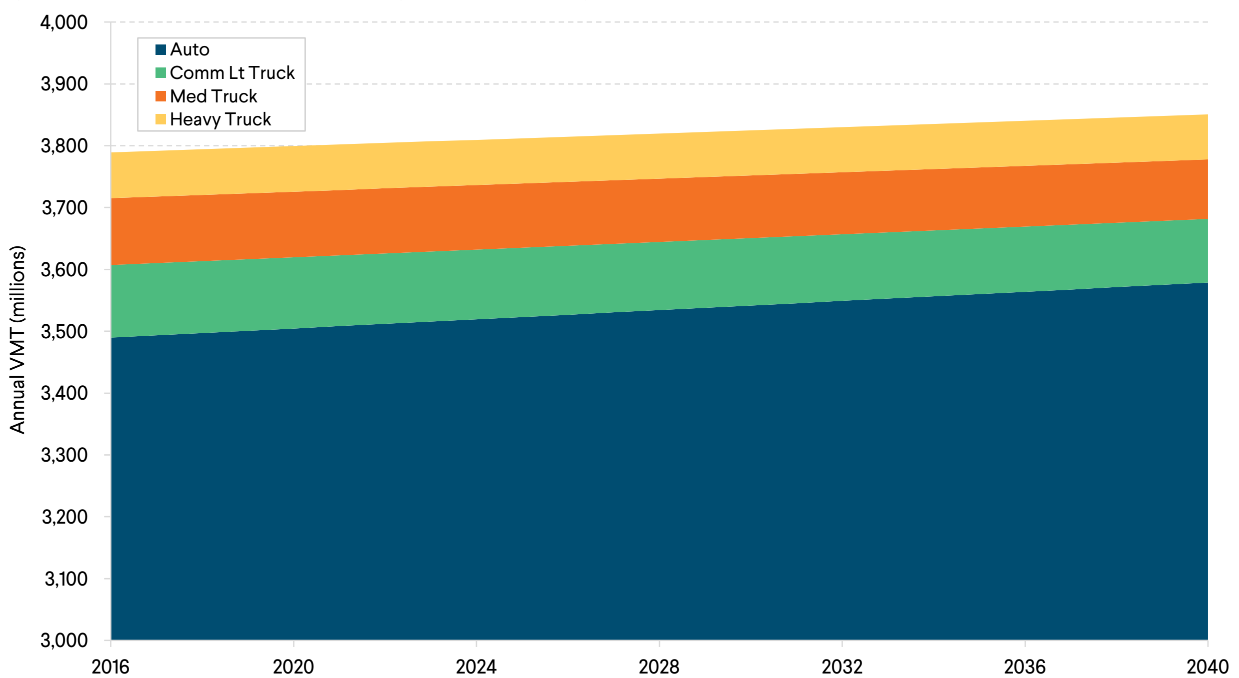


4.3.2 Vehicle-Miles Traveled

Figure 3 shows projected VMT by vehicle type from 2016 through 2040, based on CTPS model data. VMT is forecast to increase by only a very small amount, from 3,790 to 3,850 million, or 2 percent. Light-duty VMT is forecast to increase by 3 percent over this time period, mainly as a result of increasing population and employment.[6] The rate of VMT growth is lower than the rate of population and job growth, suggesting that future growth may be trending into more transportation-efficient location patterns. Light and medium truck VMT is forecast to decrease by about 10 percent, likely due to shifts in the composition of economic activity away from truck-generating employment such as manufacturing; heavy truck VMT is forecast to remain constant. To develop VMT estimates through 2050, the rate of VMT growth between 2016 and 2040 was assumed to remain constant through 2050. Note that the CTPS model was developed based on behavioral data from a survey of household travelers conducted in 2011, so it does not account for any effects of emerging technologies such as ride-hailing services.

Figure 3. VMT Associated with Boston Trip-Ends, 2016 and 2040 Baseline Forecast

Light truck = 2 axle, 4-tire; medium truck = single-unit, 6+ tire; heavy truck = combination truck. Source: CTPS travel demand model, 2016.



4.3.3 Fuel Efficiency

Figure 4 shows the projected efficiency of various vehicle types in miles per gallon of gasoline equivalent (MPGGE).[7] The car and truck projections are for the U.S. vehicle fleet from the 2018 AEO Reference Case,[8]

[6] After the baseline was developed, CTPS released revised data showing a slight *decrease* in light-duty VMT, mainly due to less growth and travel in outlying parts of the region. This change would not substantively affect the conclusions of this report and has not been reflected in the baseline data presented here.

[7] GGE is a unit of energy that is equivalent to the energy stored in a gallon of gasoline. It is convenient when comparing energy use among different types of fuels with different energy densities. One gallon of diesel fuel contains about 1.11 GGE, or the amount of energy in 1.11 gallons of gasoline.

[8] Energy consumption for light truck stock corresponding to the CTPS light truck category is not reported separately in AEO, so the mpg values for all light-duty stock were adjusted by the ratio of “new light truck” mpg to “new light duty vehicle” mpg. The CTPS medium truck category combines the AEO light-medium and medium freight trucks.

which reflects the model years (MY) 2017-2025 light-duty GHG and fuel economy standards [25] and the MY 2014-2018 “Phase 1” [26] and 2019-2027 “Phase 2” heavy-duty standards [27]. These projections assume no change to the existing GHG/fuel efficiency standards as a result of the current Administration’s review of these standards; if these standards were rolled back, future fuel efficiency levels would be lower.

Figure 4. Projected Fuel Efficiency – Gasoline and Diesel Cars and Trucks

Source: AEO Reference Case [28], analysis by Cambridge Systematics

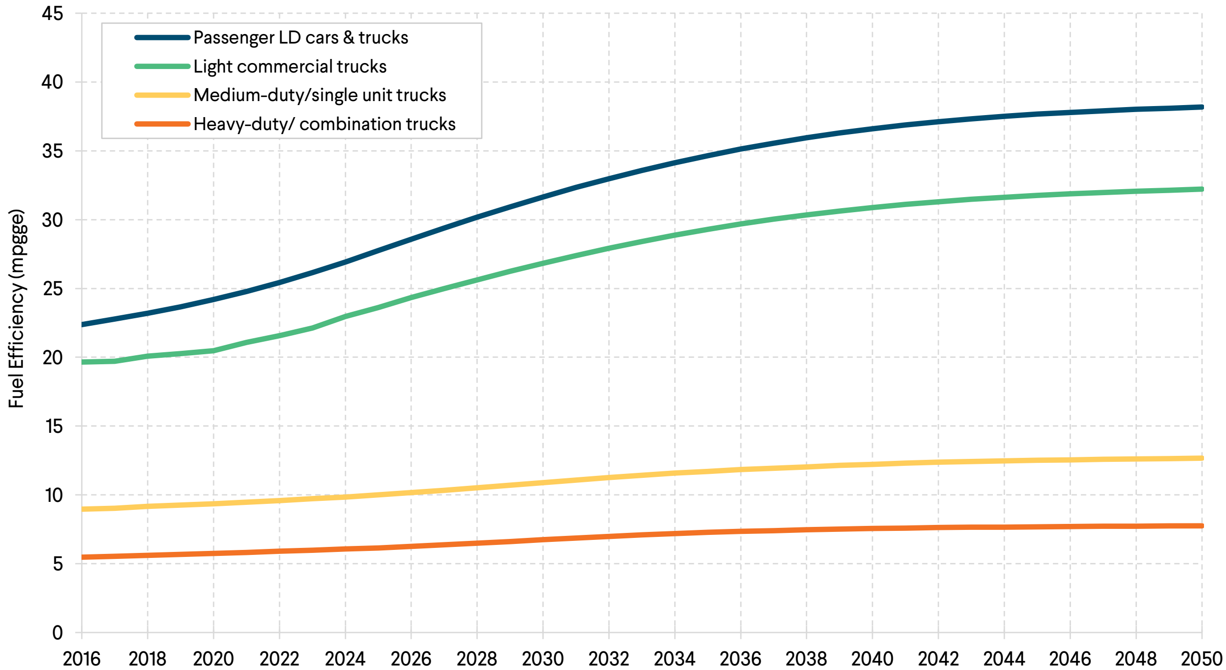
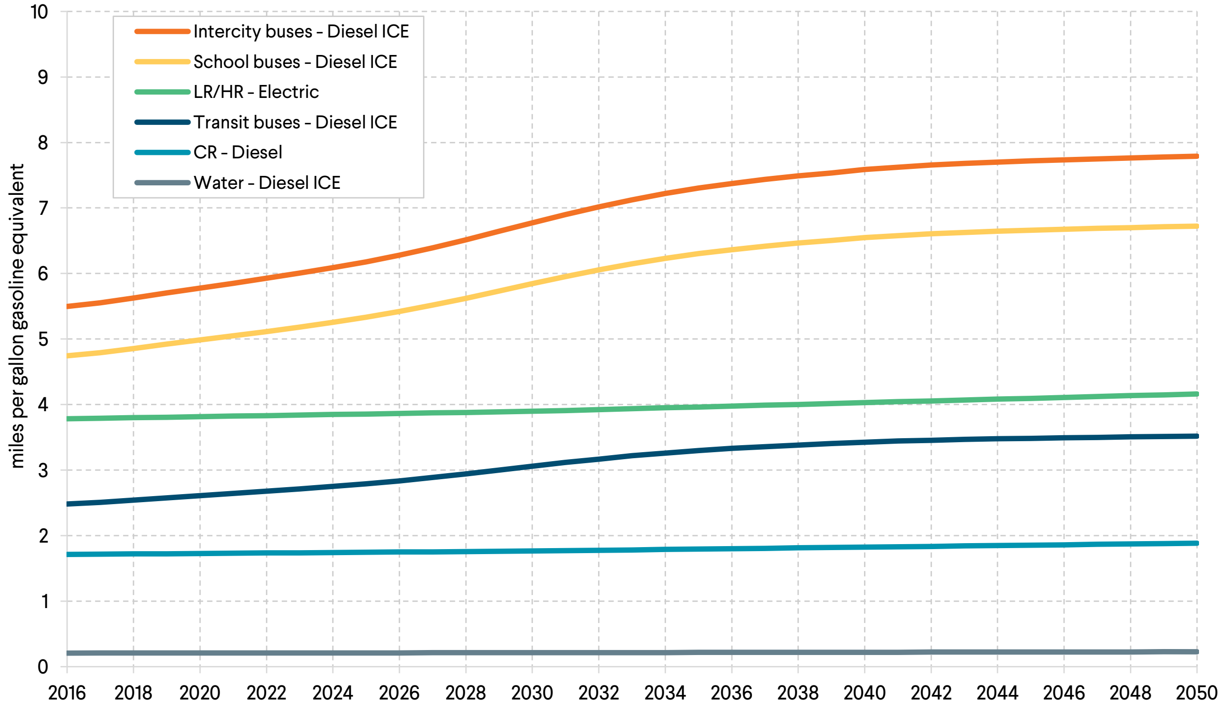


Figure 5 shows the projected fuel efficiency for transit vehicles. The transit vehicle 2016 estimates are based on 2016 energy consumption reported by the MBTA to the National Transit Database. School bus efficiency is based on average fuel economy for school buses from the U.S. DOE Alternative Fuels Data Center (AFDC) [29], adjusted by the ratio of MBTA reported to AFDC transit bus efficiency to account for Boston operating conditions (a reduction of about 10 percent). Intercity bus is based on M.J. Bradley Associates [30]. Transit, school, and intercity bus future year efficiencies are all adjusted from 2016 values based on AEO projected efficiency improvements for trucks (both trucks and buses are subject to the same Federal heavy-duty GHG/fuel efficiency standards). Rail and ferry vehicle efficiency is forecast to improve by 3 percent in 2030 and 10 percent in 2050 compared to 2016.[9]

[9] Rail efficiency improvements reflect advances such as regenerative braking.

Figure 5 Projected Fuel Efficiency – Transit Vehicles

For rail modes a "vehicle" is a single passenger-carrying train car. The relative efficiency of propane school buses operated by Boston Public Schools is assumed to be similar to diesel. Source: National Transit Database [31], M.J. Bradley & Associates [30], Alternative Fuels Data Center [29], and AEO Reference Case [28].



The baseline inventory includes fuel efficiency and market share estimates by fuel type, for the vehicle and fuel types shown in Table 3. There is a small amount of fuel use in other categories (e.g., light-duty natural gas, propane in school buses, ethanol flex-fuel) that is not explicitly considered in this inventory (these vehicles would be assumed to have the same average carbon emissions as the rest of their vehicle class).

Table 3. Baseline Inventory Fuel Technologies by Vehicle Type

Vehicle Type	Gasoline	Diesel	Hybrid gasoline/ electric plug-in	Electric (plug-in or rail/catenary)	Natural gas
Light-duty vehicles	✓	✓	✓	✓	
Light commercial trucks	✓	✓		✓	
Medium-duty/ single-unit trucks	✓	✓		✓	
Heavy-duty/ combination trucks		✓		✓	
Transit buses		✓		✓	✓
Intercity buses		✓			
School buses		✓		✓	
Light/heavy (urban) rail				✓	
Commuter rail		✓		✓	
Water (ferry)		✓			

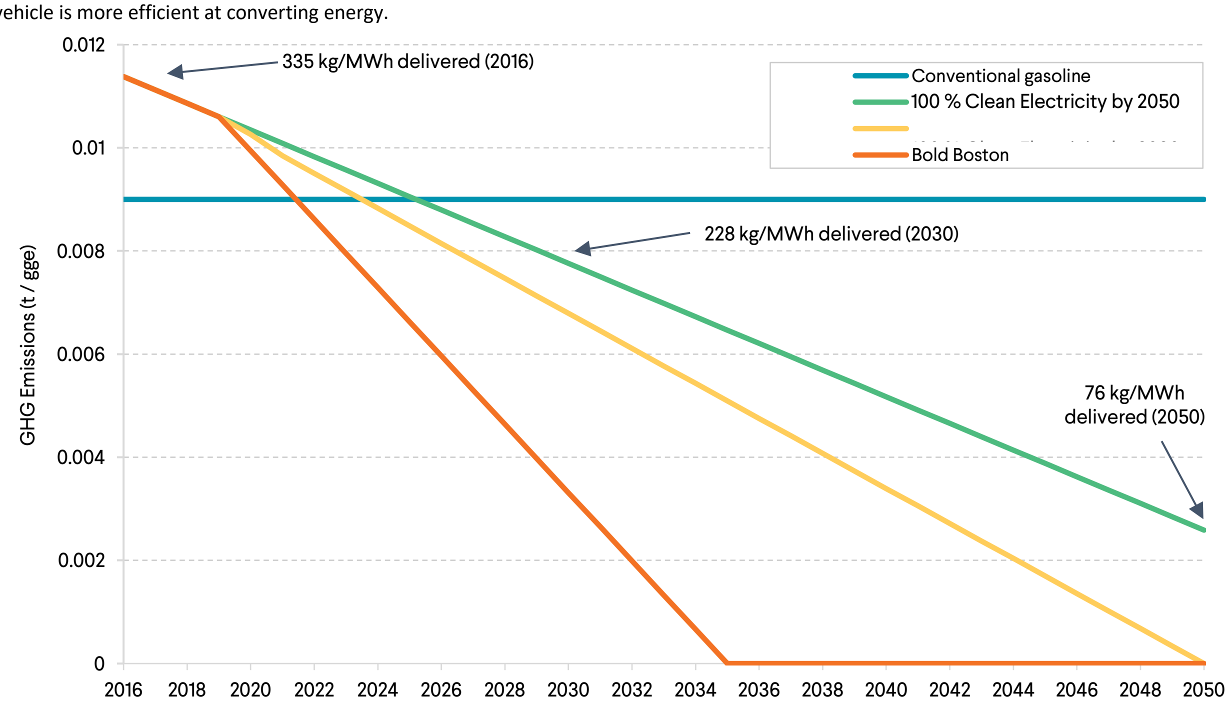
4.3.4 Carbon Intensity

The GHG emissions from electric vehicles (electric cars, trucks, and transit), as measured in CO_2e, will also be affected by the GHG intensity of the electricity grid. Baseline GHG intensity projections were used consistent with the "MA Clean Energy Standard" electricity sector modeling in the Carbon Free Boston study, as shown in Figure 6. This projection shows GHG intensity declining by over 75 percent between 2016 and 2050. This figure also shows GHG intensity for conventional gasoline for comparison, along with the more aggressive "Zero by 2050" and "Zero by 2030" electricity GHG pathways. While the GHG intensity per unit of energy (GGE) in 2016 is greater for electricity than gasoline, an electric vehicle is nearly three times more efficient at using the delivered (plug) energy than an internal combustion engine vehicle, resulting in a net reduction in GHG emissions. The relative benefit of electricity vs. gasoline will increase in the future as the electricity grid becomes cleaner.

The effect of biofuels (e.g., ethanol or biodiesel) on gasoline and diesel carbon emissions is not considered in this inventory. As a result of the Renewable Fuel Standard (RFS2) rule [32] which sets volumetric requirements for biofuels through 2022, today's gasoline includes up to a 10 percent ethanol blend. Biofuels have the potential to reduce life-cycle emissions by producing fuel from plant matter that absorbs carbon when growing. This inventory only considers tailpipe rather than lifecycle emissions, however, as "upstream" emissions and emissions savings are accounted for in other sectors (industry, agriculture) and also largely occur outside of the state. Furthermore, the current practice of blending corn ethanol with gasoline appears to have very little benefit when the life-cycle emissions of corn production and processing are considered [33]. Advanced biofuels could result in substantially reduced life-cycle carbon intensity but their development has lagged compared to targets set in the RFS2 and it is unlikely that the U.S. will meet the total renewable fuel target as outlined in statute [34].

Figure 6. Electricity Grid GHG Intensities Compared to Gasoline GHG

Source: Electricity intensities from Boston University – Institute of Sustainable Energy, May 2018; gasoline = 8.8 kg CO_2/gal plus 2 percent for non-CO_2 GHGs. Note that GHG emissions *per vehicle-mile* will be lower for an electric vehicle than a gasoline vehicle even in 2016 because the electric vehicle is more efficient at converting energy.



4.3.5 Comparison with MOVES Energy Consumption Rates

The project team compared fuel consumption rates from the AEO with energy and CO_2 emission rates from the U.S. Environmental Protection Agency's Motor Vehicle Emissions Simulator (MOVES) model, which is the accepted emissions model for all states except California, which has its own model. MOVES was also run with the objective of developing emission factors for particulate matter ($PM_{2.5}$) and oxides of nitrogen (NO_x) to evaluate air quality impacts.

MOVES2014a was run using input files for Suffolk County obtained from the Massachusetts Department of Environmental Protection in the spring of 2018. The state's input files are a mix of state-specific data (e.g., vehicle populations from registration data) and national defaults (e.g., speed distributions).

Speeds are an important driver of emissions, as vehicles tend to operate most efficiently in the middle (30-60 mph) speed ranges, with higher fuel consumption at lower and higher speeds. Speeds are input to MOVES in the form of a distribution of percent of vehicle-hours of travel (VHT) in 16 speed bins, by road type. The national default distributions in MOVES appear to overestimate speeds in Boston, as average speeds are about 50 percent higher than the average speeds estimated by dividing zone-to-zone travel distances by travel times using the CTPS model data. Speed distributions were therefore manually adjusted to match CTPS peak period average speeds. Ultimately this made little difference as the increase in emissions from more congested (low-speed operation) appeared to be offset by a decrease in high-speed operation. Two speed distributions were tested, one representing the 7-8 a.m. hour and one representing the 11 a.m. - 12 p.m. hour; the emission rates differed by less than 1 percent. A full set of network speed data (from the model or observed sources) would be required to test an actual speed distribution for Boston traffic.

Table 4 compares the AEO-based study inventory and MOVES CO_2 emission rates (inventory rates are adjusted to remove non-CO_2 GHGs for comparability with the MOVES CO_2 rates). The vehicle definitions are not exactly comparable between the two sources. Some differences in emissions are observed, with potential reasons as follows:

- Light duty cars and passenger trucks: MOVES shows about 6-11 percent lower emissions than AEO. One reason is likely a different split of cars vs. light trucks in Boston (more cars and fewer light trucks) than the national average. Also, the MOVES and AEO definitions are slightly different. MOVES includes passenger light trucks under 8,500 lbs. gross vehicle weight rating (GVWR), but excludes commercial light trucks under 8,500 lbs. (weight class 2a), which are in a separate category in MOVES. Differences in speed distributions could also be a factor.
- Commercial light trucks: The MOVES rate is slightly lower than AEO's "light medium" commercial trucks. MOVES includes weight classes 2a (6,000 – 8,500 lbs.) and 2b (8,500 – 10,000 lbs.). AEO only includes class 2b so the emissions rate should be higher.
- Medium-duty trucks: The MOVES rate is higher than AEO. AEO includes "freight medium" (<10,000 lbs. GVWR), not "light medium", which would skew it higher. On the other hand, AEO will exclude single-unit trucks falling in the "heavy" weight classes. Also, MOVES2014a does not include the heavy duty Phase 2 final rule GHG standards, which would make truck emissions from MOVES higher than from AEO, which does account for this rule.
- Heavy-duty trucks: MOVES is significantly higher. While there are some differences in truck categorizations, the main difference is probably that MOVES2014 does not include the heavy duty Phase 2 final rule.

- Transit and school buses: The MOVES rates are significantly lower than based on actual energy consumption reported by the MBTA (National Transit Database) or the Boston Public Schools. This may be due to different operating conditions (lower speeds) in Boston, which decrease efficiency.

The overall inventory for cars and trucks would be about 7 percent lower in 2030 using MOVES emission rates, or about equal in 2050, compared to this study's inventory constructed using AEO data.

Table 4. Comparison of Study Inventory and MOVES GHG Emission Rates

	2030			2050		
Vehicle Class	**Inventory CO_2 g/mi[a]**	**MOVES CO_2 g/mi**	**MOVES vs Inventory**	**Inventory CO_2 g/mi**	**MOVES CO_2 g/mi**	**MOVES vs Inventory**
Passenger LD cars & trucks	276	246	-10.9%	230	216	-6.1%
Light commercial trucks	332	311	-6.0%	284	271	-4.4%
Medium-duty/ single unit trucks	836	991	18.6%	712	985	38.3%
Heavy-duty/ combination trucks	1,341	1,696	26.5%	1,164	1,680	44.4%
Transit buses	2,714	1,299	-52.1%	2,322	1,299	-44.1%
School buses	1,556	902	-42.0%	1,353	901	-33.4%
Total inventory excluding buses (t)	1,069,570	994,702	-7.0%	895,785	891,344	-0.5%

[a] The study inventory includes non-CO_2 GHGs. The "inventory" rates shown here are adjusted downward by 2 percent to show CO_2 only for comparability with the MOVES rates.

4.4 Baseline Forecast Results

Figure 7 shows projected annual GHG emissions from the trip-end inventory, by source type. In 2016, the inventory totaled about 2 Mt CO_2e, with light-duty passenger vehicles responsible for about 1.5 Mt (75 percent), trucks 300,000 t (15 percent), and transit vehicles 200,000 t (10 percent). By 2050 the total is forecast to fall to 1.2 Mt, with the shares remaining about the same. Most of the declines happen by 2035, when fleet turnover almost fully reflects the currently adopted fuel efficiency standards. Figure 8 shows additional detail for 2016 by source type.

4.5 Resident Activity

The year 2015 estimate of resident VMT and GHG based on the MAPC Massachusetts Vehicle Census is 2.8 billion VMT and 1.11 Mt GHG, of which about three-quarters is from household vehicles and one-quarter from commercial vehicles. Compared to the 2016 trip-end inventory for light-duty vehicles described above, the resident vehicle inventory represents 72 percent of the VMT and 69 percent of the GHG emissions. The GHG estimate is based on an average of 21.2 mpg for all vehicle types reported in the Vehicle Census, which compares to 22.4 mpg for light-duty vehicles in 2016 from the AEO (21.8 in 2015). The efficiency of the vehicles driven in Boston may differ due to differences in the mix of vehicles (e.g., cars vs. light trucks) or operating conditions (e.g., lower speeds reducing efficiency).

Figure 7. Baseline Projection of Boston-Generated Transportation GHG Emissions

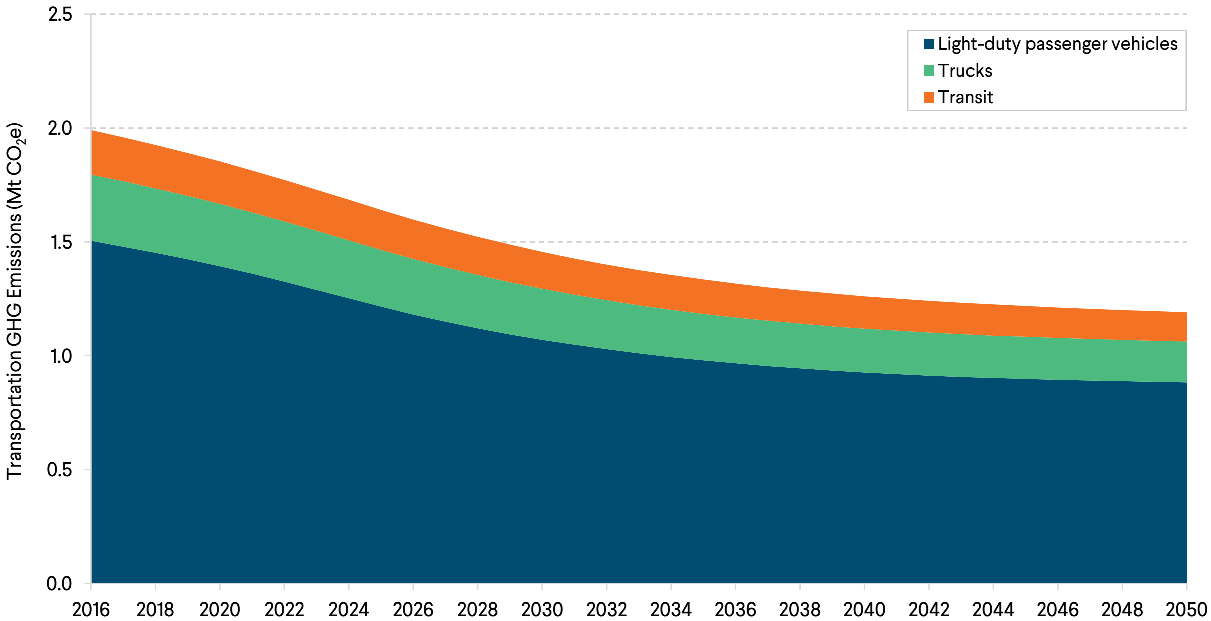
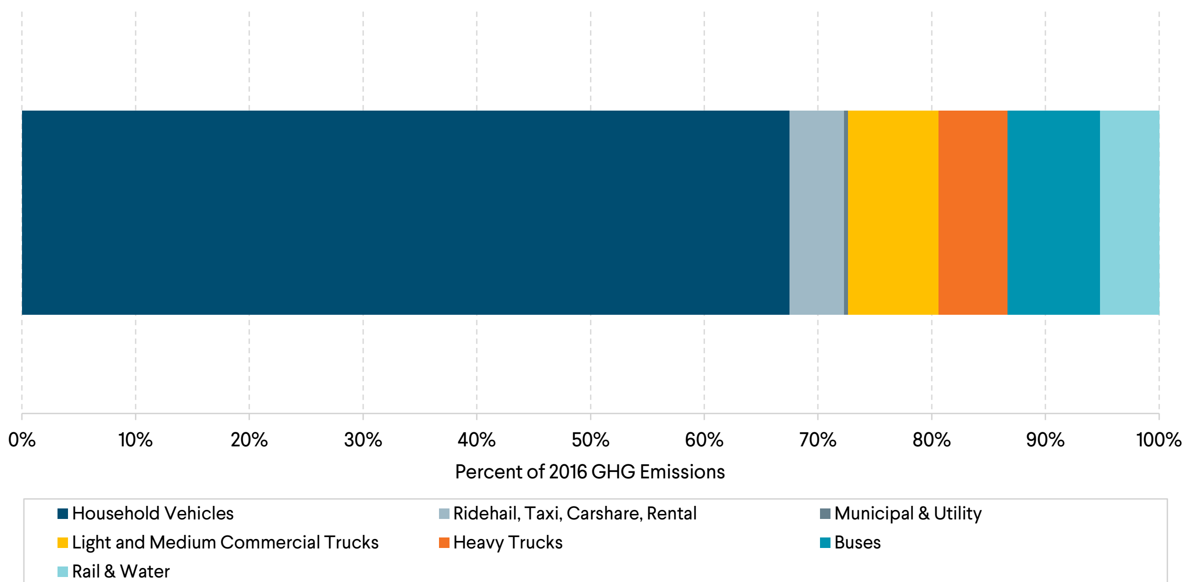


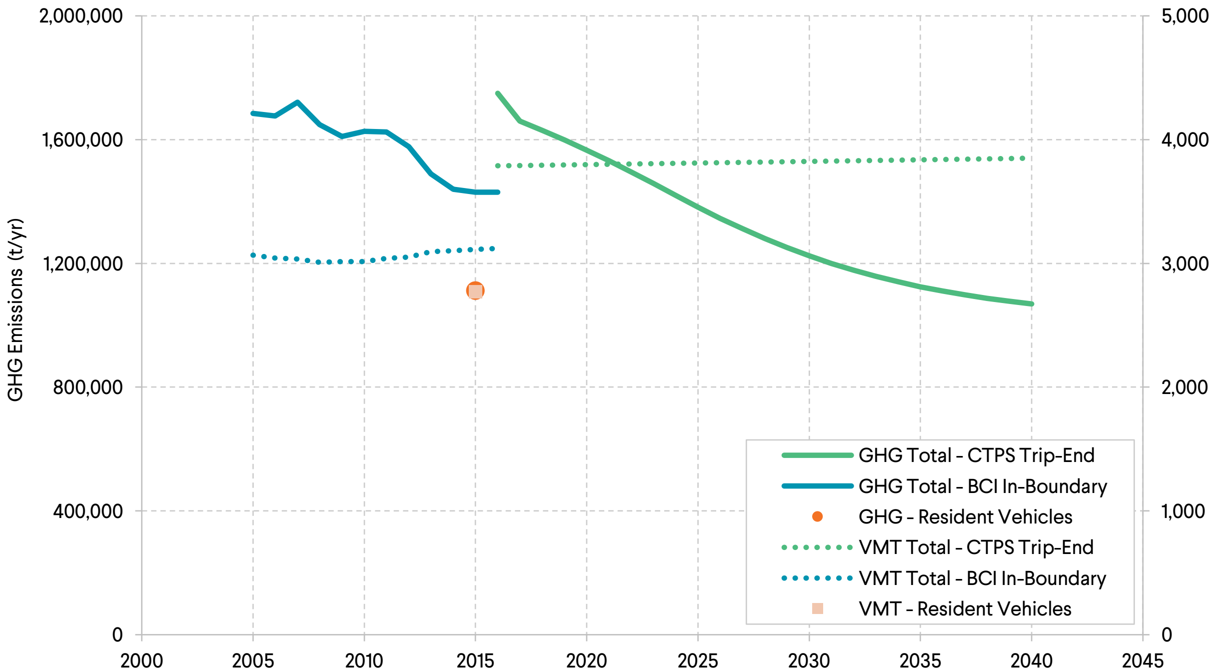
Figure 8. Boston-Generated Transportation GHG Emissions by Subsector, 2016



4.6 Comparison of Inventories

Figure 9 compares previous years' estimates of VMT and emissions from the City of Boston Community Greenhouse Gas Inventory with the trip-end inventory and forecast as well as the resident vehicle inventory (transit emissions are not included in this figure since transit VMT is not part of the CTPS model). The trip-end based VMT and GHG estimates in 2016 are about 21-22 percent larger than the in-boundary GHG estimates in 2015. As this report was written, the City was in the process of updating its 2016 inventory and expected the difference to shift after the update was completed.

Figure 9. Comparison of Boston In-Boundary, Trip-End, and Resident Household VMT and Transportation GHG



The inventories would not be expected to be comparable. The resident inventory includes GHG from travel (VMT) by vehicles registered in Boston, regardless of where their trip takes place. However, it does not include travel by any non-resident vehicles with a trip end in Boston (e.g., commuters to downtown from other communities). The Vehicle Census would include any larger trucks registered in Boston, not just light-duty vehicles. The in-boundary inventory includes VMT by vehicles passing through Boston without stopping (not in the trip-end inventory), but it does not include most of the VMT and GHG emissions from longer-distance trips that start or end in Boston (e.g., commute trips to or from Worcester or Portsmouth, NH). The effect of longer trips ending in Boston appears to more than outweigh the effect of VMT from trips not stopping in Boston.

4.7 VMT BY NEIGHBORHOOD AND COMMUNITY

The large impact of longer trips is confirmed by Figure 10, which shows VMT for trips with at least one end in Boston by the location of the other end of the trip. Trips starting and ending in Boston account for less than one-quarter of the over 10 million daily VMT in the inventory. Trips to communities within the I-95 beltway add another quarter of the total VMT. Trips to communities between I-95 and I-495 account for 40 percent of the VMT in the inventory, with trips outside of I-495 accounting for nearly 10 percent. This means that achieving substantial GHG reductions for Boston-based trips will require working with neighboring communities and state and regional entities to implement clean transportation options, including EV ownership incentives and improved transit and shared mobility options. A zero-carbon transportation future for the City cannot be achieved just by policies that apply within the City's boundaries. The geographies are shown in Figure 11.

Figure 10. VMT for Boston-Based Trips by Location of Other Trip-End

Source: CTPS travel demand model (2016), as analyzed by Cambridge Systematics.

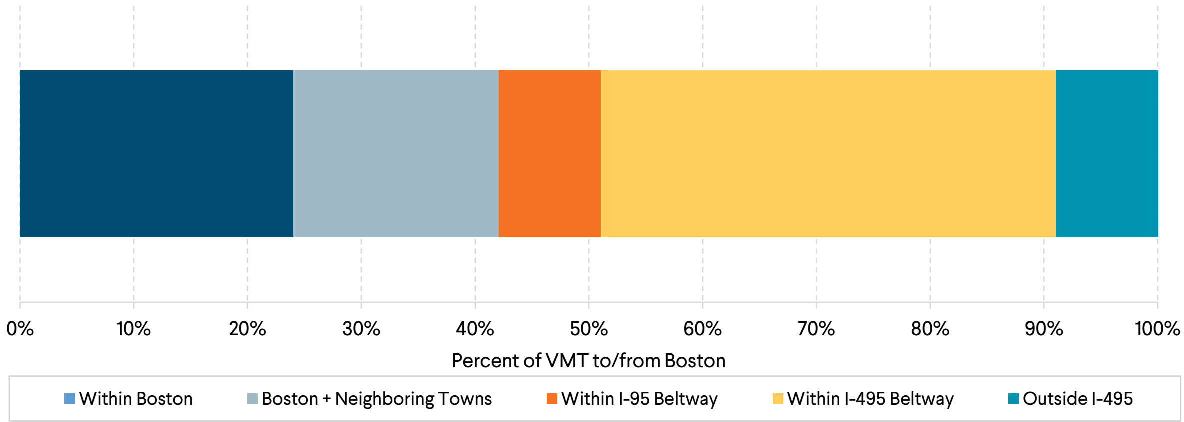
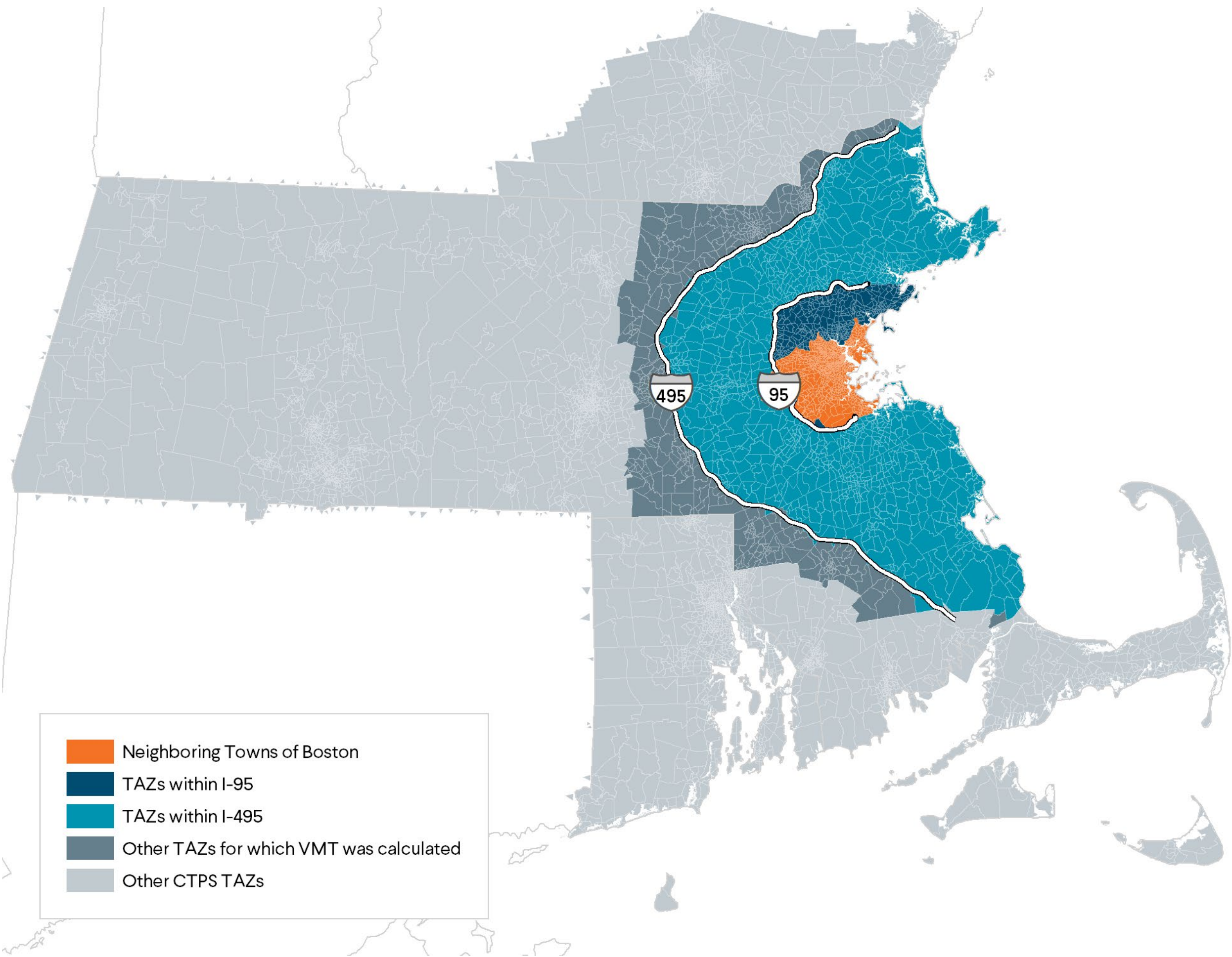


Figure 11. VMT Subregions



VMT can also be examined by Boston neighborhood. Figure 12 shows household VMT generated per capita as predicted by the CTPS model (trip "productions", e.g., from home; this does not include VMT from "attractions" such as workplaces). Figure 13 shows daily VMT produced and attracted by neighborhood, normalized per square mile. Figure 14 shows home-based person-miles of travel (PMT) by neighborhood and trip purpose. Not surprisingly, Downtown Boston creates the most VMT per square mile due to its high concentration of employment, but households in outlying neighborhoods (West Roxbury, Roslindale, Hyde Park) generate more VMT than households in other parts of the City. The outlying neighborhoods of West Roxbury, Hyde Park, Roslindale, and Mattapan have the highest PMT per capita, indicating longer trip distances than the more centrally located neighborhoods. However, below the top four neighborhoods, there is no obvious relationship between geography and PMT per capita. This suggests that land use policies to direct growth into more centrally-located neighborhoods should help to reduce GHG; but that there is a wide swath of the City where land use patterns and transportation options already support low-carbon travel. The data underlying these figures are shown in Table 5.

PMT can also be affected by socioeconomic and demographic factors, such as income and student population, as well as the availability of transportation options. Also, modeled VMT or PMT may not be equal to actual VMT or PMT.

Figure 15 expands the geographic analysis to illustrate the regional relationship between trips into Boston and GHG per trip. The two-color map shows both daily trips to and from Boston and average GHG emissions per trip. Communities farther from Boston generate fewer trips into the City, but trips are longer so each trip contributes disproportionately to GHG emissions.

Figure 12. Home-Based VMT per Capita per Day

Source: CTPS travel demand model (2016), as analyzed by Cambridge Systematics.

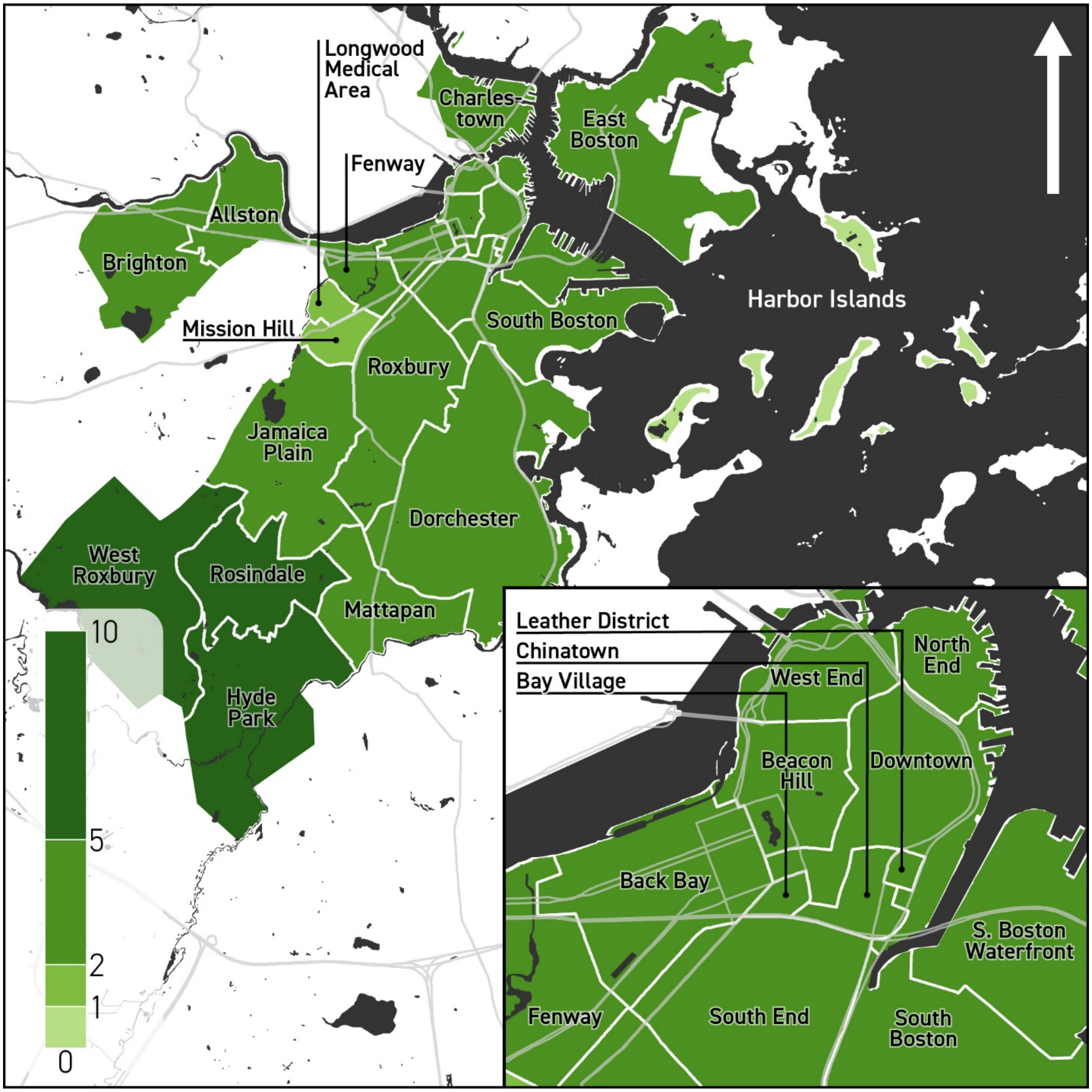


Figure 13. Total Daily VMT Generated per Square Mile

Source: CTPS travel demand model (2016), as analyzed by Cambridge Systematics.

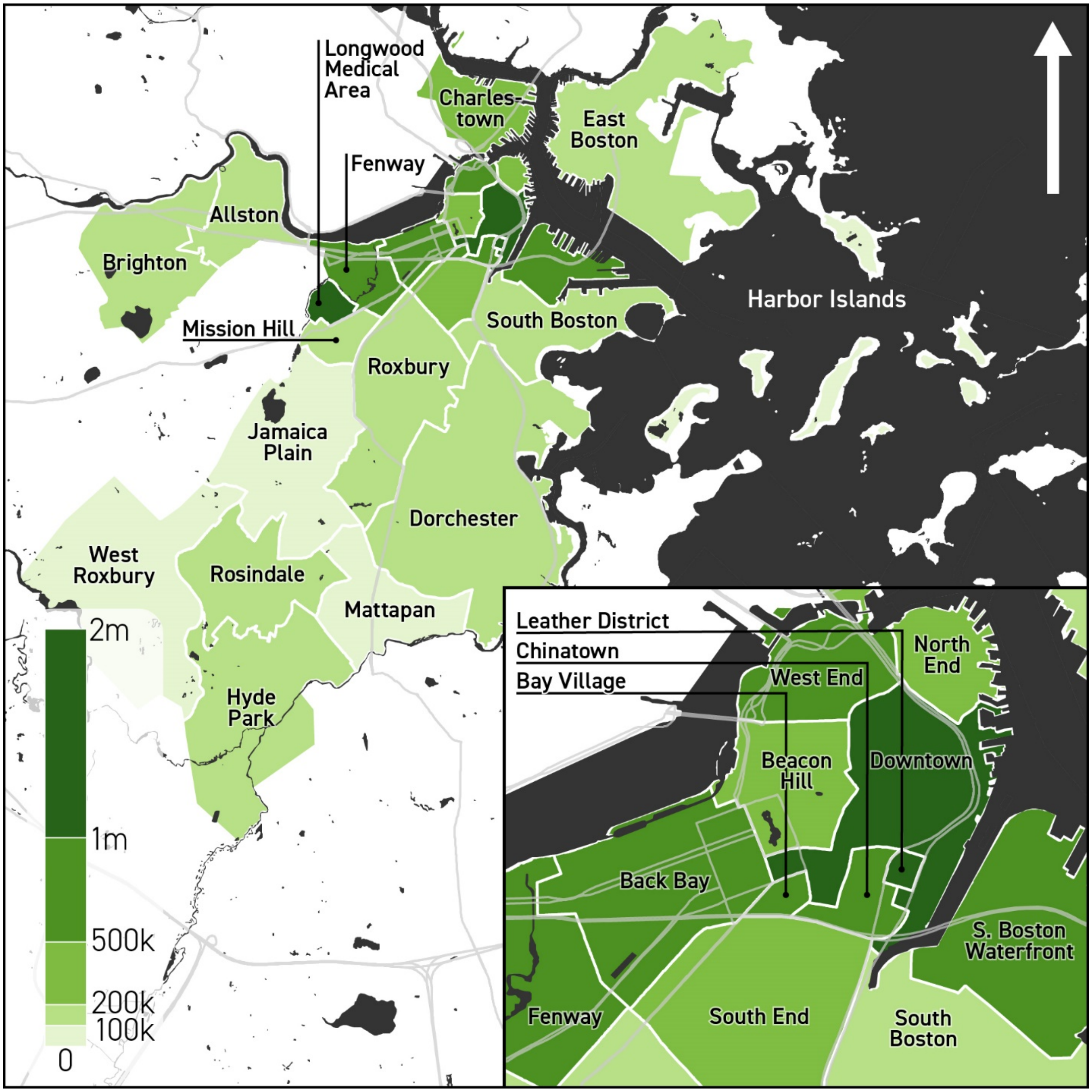


Figure 14. Daily PMT per Capita by Neighborhood and Trip Purpose

Source: CTPS travel demand model (2016), as analyzed by Cambridge Systematics. HBW = home-based work; HBPB+PD = home-based personal business + pick-up and drop-off; HBSR = home-based social and recreational; HBSc = home-based school. ("Home-based" trips either start or end at the home.)

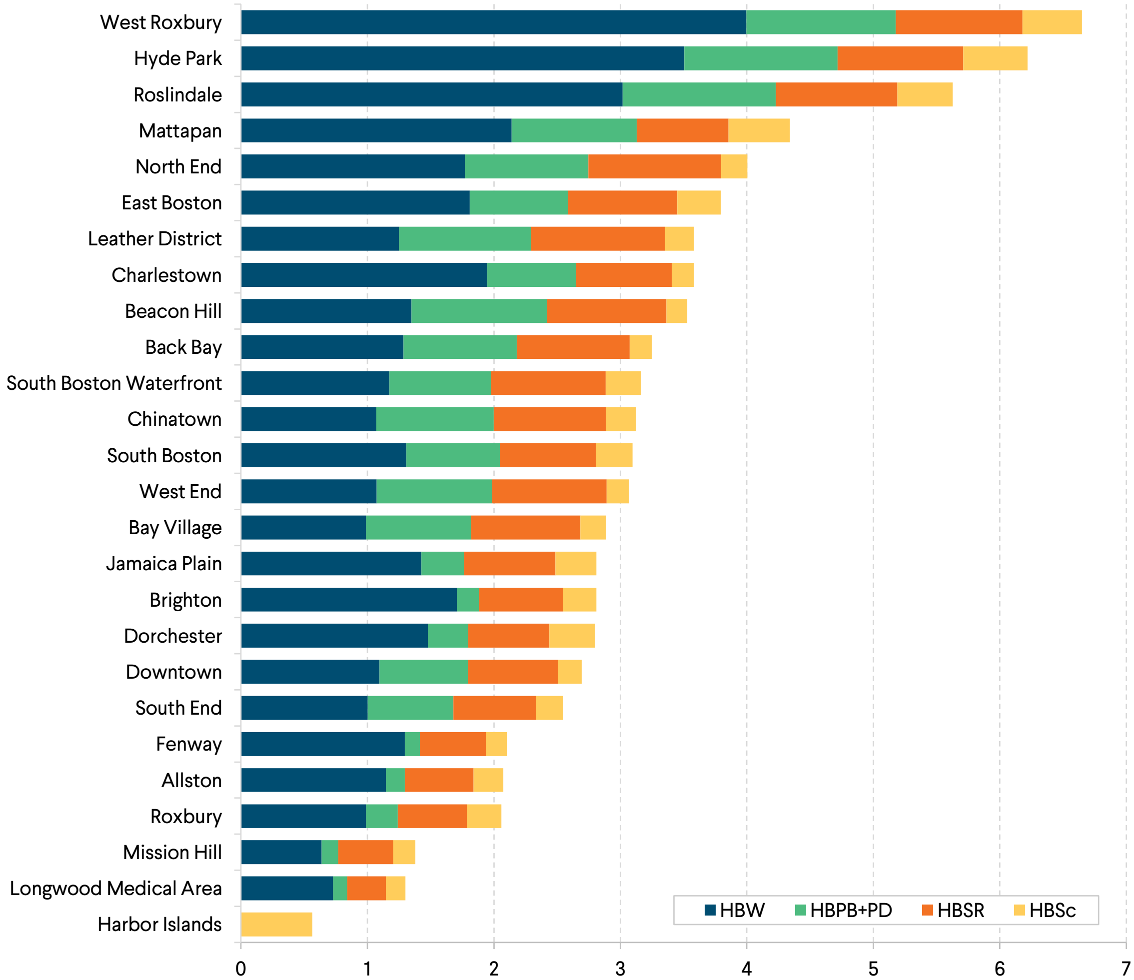
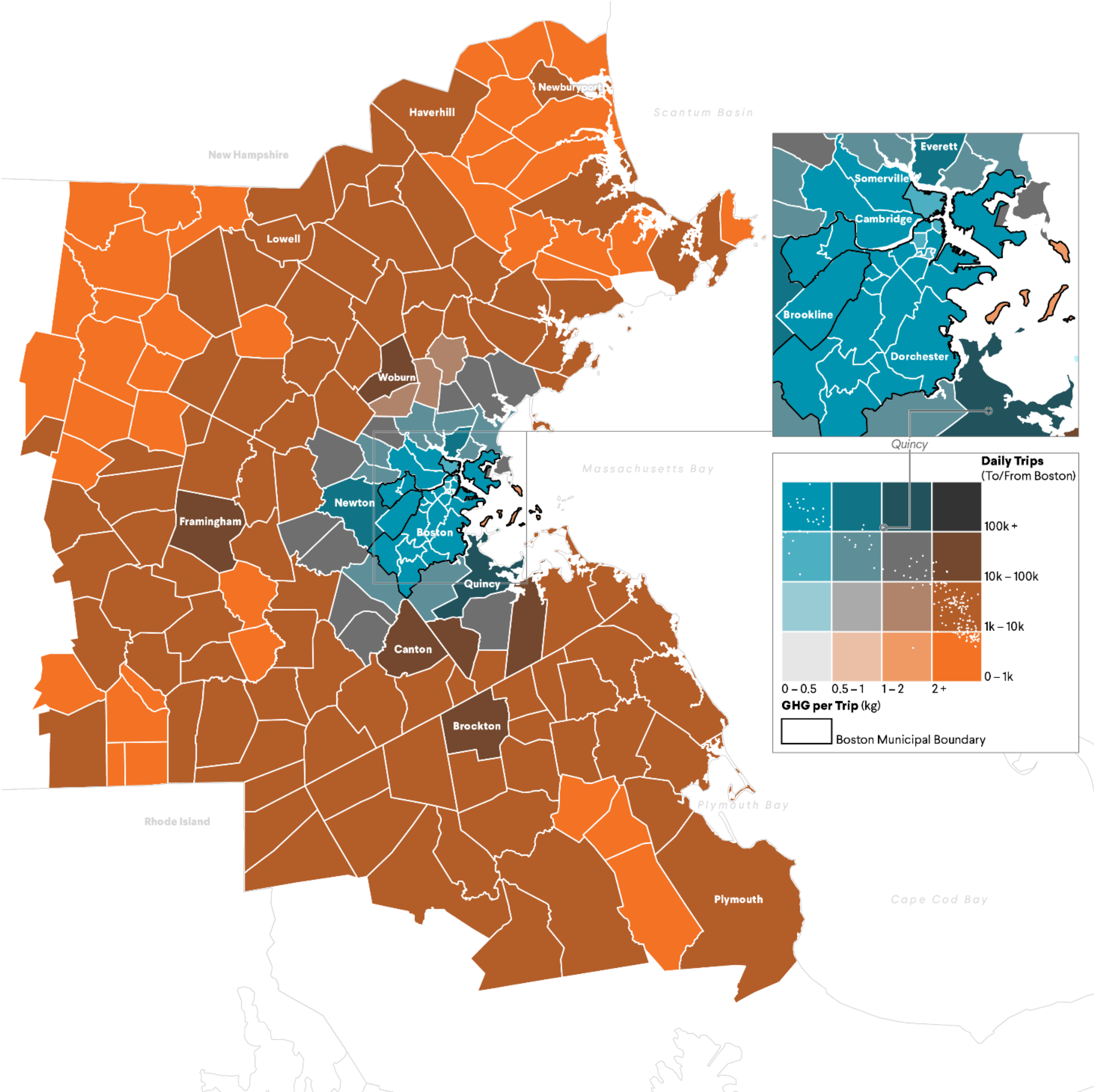


Table 5. Population, Employment and VMT Generated by Neighborhood

	2016					2050		2016-2050 Change	
Neighborhood	Population	Employ-ment	Daily VMT Generated	VMT per Sq. Mi.	HB VMT per Cap per Day	Population	Employ-ment	Population	Employ-ment
Downtown	10,829	153,464	1,303,688	2,099,163	2.9	13,159	163,918	2,330	10,454
West End	6,081	35,857	256,332	861,209	3.3	7,713	39,039	1,632	3,182
North End	11,407	4,374	86,875	438,102	4.2	14,823	4,434	3,416	60
Chinatown	4,630	8,558	84,863	711,602	3.3	5,643	8,599	1,013	41
Leather District	765	3,775	38,330	1,568,489	3.8	1,023	3,958	258	183
Bay Village	1,455	2,646	38,532	929,185	3.1	1,877	3,592	422	946
Beacon Hill	8,977	3,687	101,938	325,946	3.7	11,741	3,683	2,764	(4)
South End	27,835	18,570	237,180	321,917	2.7	35,397	26,889	7,562	8,319
Back Bay	20,212	62,998	562,467	901,492	3.2	27,032	66,518	6,820	3,520
S. Bos Waterfront	2,588	37,563	571,492	588,179	3.4	3,437	48,487	849	10,924
South Boston	36,205	13,620	407,982	181,339	3.3	45,538	13,893	9,333	273
East Boston	39,521	23,705	831,467	176,669	4.0	45,264	24,082	5,743	377
Charlestown	17,970	17,087	402,906	295,866	3.8	22,753	19,572	4,783	2,485
Fenway	36,207	28,760	750,295	856,534	2.1	42,657	32,494	6,450	3,734
Longwood	7,946	47,449	408,358	1,385,643	1.4	8,987	51,627	1,041	4,178
Mission Hill	13,611	5,134	107,303	195,733	1.5	15,889	5,518	2,278	384
Allston	29,213	18,313	308,540	197,755	2.2	37,309	22,511	8,096	4,198
Brighton	48,431	16,779	416,346	144,784	3.0	59,559	18,240	11,128	1,461
Roxbury	52,771	25,354	458,386	139,137	2.2	63,633	29,815	10,862	4,461
Dorchester	113,771	32,639	1,092,621	149,967	3.0	134,112	38,039	20,341	5,400
Jamaica Plain	38,933	14,422	326,447	82,932	3.0	47,847	15,123	8,914	701
Mattapan	22,130	2,892	183,524	86,869	4.6	26,720	3,171	4,590	279
Roslindale	26,797	4,024	289,008	115,202	6.0	32,331	4,101	5,534	77
West Roxbury	28,505	11,415	530,472	96,548	7.1	35,043	11,469	6,538	54
Hyde Park	38,245	7,159	466,468	101,987	6.6	44,946	7,454	6,701	295
Harbor Islands	535	127	1,516	1,177	0.6	535	128	-	1
Total	**645,570**	**600,371**	**10,263,334**	**209,820**	**3.5**	**784,966**	**666,352**	**139,396**	**65,981**

Note: 2050 forecast based on extrapolation of 2016-2040 growth rates in CTPS model. HB VMT = VMT from home based trip productions.

Figure 15. GHG per Trip vs. Boston-Based Trips by Community



4.8 Uncertainties and Their Potential Impacts on the Baseline

This baseline forecast presents one potential future of Boston GHG emissions, assuming the continuation of current policies and trends. There are many factors outside of the city's control that could cause future emissions to differ from the baseline forecast. Some of the key factors include:

- **Energy prices:** Prices substantially higher than the AEO forecast should lead to consumers purchasing more efficient vehicles and/or driving less, thereby reducing GHG emissions. The AEO includes a "High Oil Price" scenario with gasoline prices increasing to over $5 per gallon by 2025 and $6 per gallon by 2050, showing a reduction in light-duty vehicle energy use of 11 percent in 2030 and 24 percent by 2050, compared with Reference Case levels. Figure 16 shows the baseline forecast energy prices; national electricity price forecasts from the AEO were inflated by 50 percent to consider historical price differences between New England and the U.S. (also based on AEO data). Figure 17 shows how the AEO model predicts that light-duty VMT, fuel efficiency, and energy use will respond to higher oil prices. Most of the response is exhibited in reduced VMT rather than increased fuel efficiency. This is because the existing federal GHG standards already drive efficiency to a high level, with the most cost-effective efficiency improvements already applied to meet these standards.
- **Changes in total population and employment:** The baseline forecast is based on one projection of Boston population and employment. Growth may occur at greater or lesser rates than projected. The City of Boston has recently developed revised population projections, reflecting recent trends, that suggest population could increase to 841,000 by 2050 – 30 percent higher than 2016 levels and 13 percent higher than extrapolating the regional 2016-2040 forecast – increasing city-generated travel and GHG emissions proportionately. Job growth above forecast rates would also increase GHG in the Boston inventory. These increases would not necessarily suggest an overall increase in GHG emissions for the state or nation – in fact, they might reduce GHG by locating people and jobs in centrally-located areas with good travel options where they drive less and produce less GHG than housing or jobs in outlying suburbs. However, a population increase would still add GHG to the Boston inventory.
- **Demographic changes:** Even with the same baseline forecast of population and employment, changes in the nature of residents and jobs could increase or decrease GHG. For example, growth in higher-wage jobs could add GHG to the inventory by attracting workers who are more likely to own a car and drive. Higher growth in younger, working-age population might also add to GHG, whereas higher growth in retirement age or student population might reduce it.
- **Changing travel patterns:** The CTPS model forecasts are based on data on how people have recently been observed to travel to work, school, shopping, recreation, and other purposes. Changes such as multiple jobs, home-based work, and Internet-based shopping have been shifting the landscape of travel behavior and will continue to do so in the future, in ways that are not yet completely understood. So will shifts to new mobility options such as ride-hailing and autonomous vehicles. These changes will also affect truck movement, e.g., increasing amounts of commercial deliveries using light and medium trucks.
- **Technological advancements:** The rate of improvement in battery technology (cost per kilowatt-hour) has increased in the past few years compared to past levels, thus providing more credence to optimistic forecasts of rapid electric vehicle market penetration in the 2020-2030 timeframe. Continued advancement of EV or other clean vehicle technology would have the potential to reduce GHG emissions, especially if higher energy prices also support the technology. However, the federal GHG/fuel efficiency standards set a fleetwide standard which includes EVs, so it is not clear how much short-term benefit the advancement of this technology would have in the current regulatory

environment. In the long term, introduction of non-fossil fuel-based vehicles will be essential to achieving deep cuts in carbon emissions.

- **Federal and state policy changes:** The baseline forecast assumes that harmonized (Federal and California) light-duty fuel efficiency standards through model year 2025, and heavy-duty standards through model year 2018, will continue to be implemented. As of August 2018, the Trump Administration had proposed to revise the light-duty standards set for model years 2022-2025. California and other states have the legal authority under Section 177 of the Clean Air Act to set their own standards consistent with California's, and Massachusetts has done so in the past. However, the Section 177 authority is also being challenged by the Trump Administration. If the rollback of fuel economy standards and California's authority to set its own are both successful, GHG emissions from light-duty vehicles will be higher than in the baseline forecast. Federal and/or state policies may also affect the mix of low-carbon fuels. For example, adoption of a low-carbon fuel standard such as that implemented by California could reduce the carbon intensity of fuels consumed even in conventional technology vehicles. There are many other policies that the federal government and/or Commonwealth of Massachusetts could implement that might affect transportation emissions, such as VMT, fuel, or carbon pricing; expanded zero-emission vehicle requirements or electric incentives; and continued advancement of fuel efficiency and GHG standards beyond model year 2025.

Figure 16. Baseline Forecast Transportation Energy Prices

Source: Annual Energy Outlook [28], AEO Reference Case [28]. Electricity price adjusted based on historical data on electricity prices by region. Prices may not be fully consistent with prices used for the analysis of non-transportation sectors.

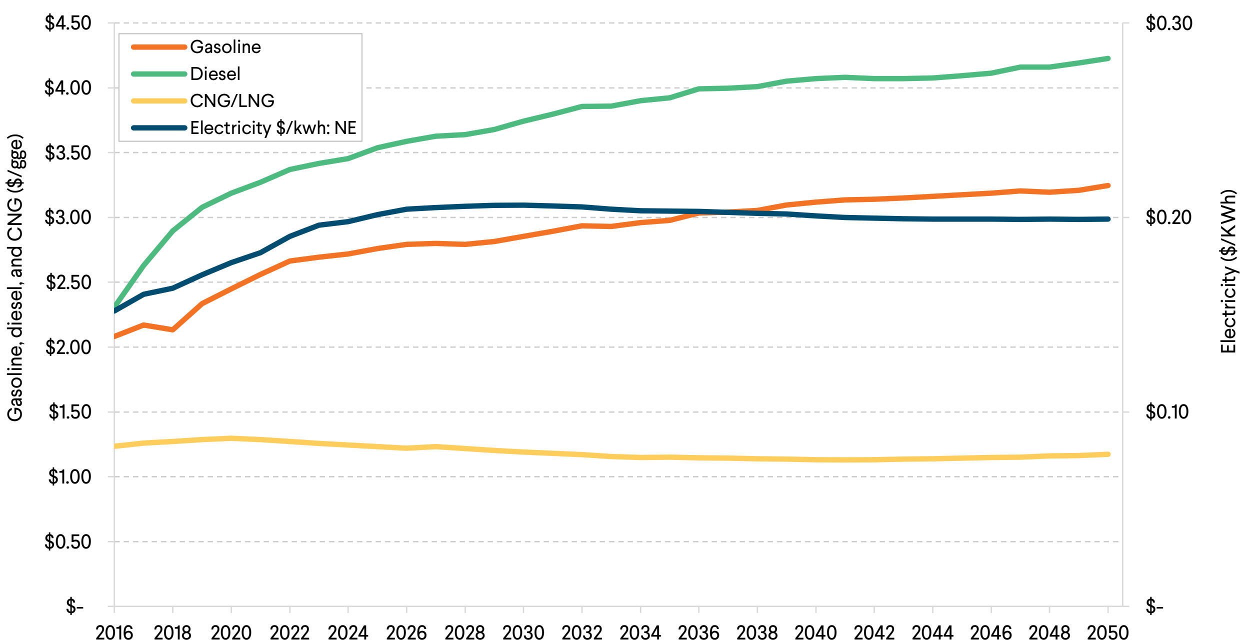
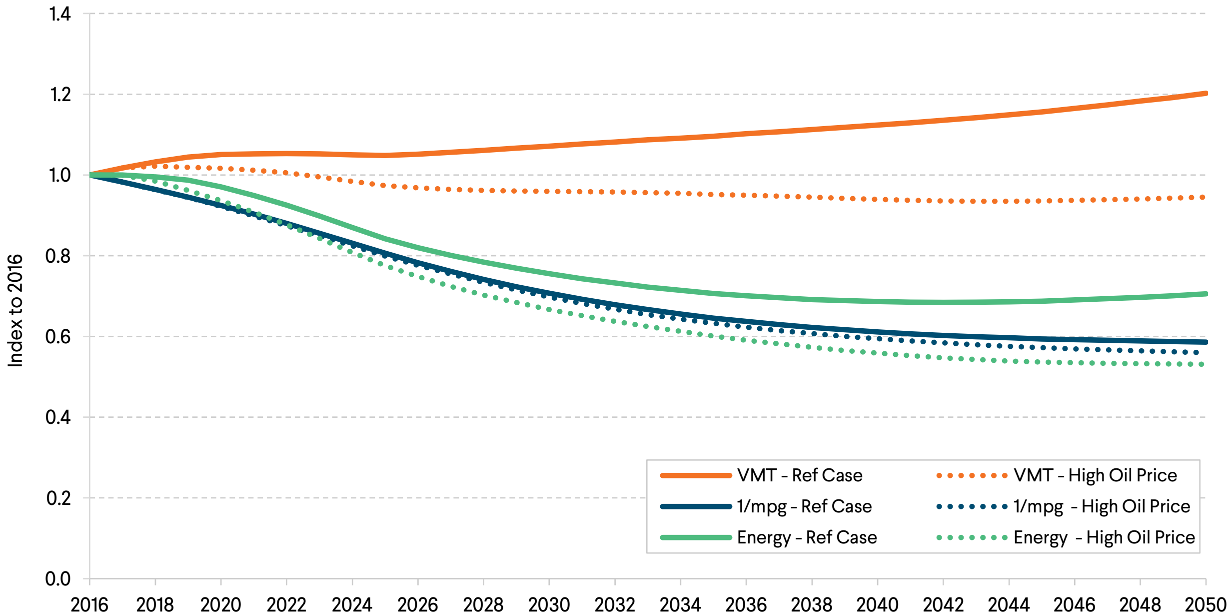


Figure 17. AEO Reference Case and High Oil Price Energy Efficiency Indicators, Light Duty Vehicles

Source: Annual Energy Outlook [28]



5 Transportation Sector Models

Two models were developed to support analysis of transportation strategies for the Carbon Free Boston project:

- A **sketch model** that allows "quick response" testing of key parameters and uncertainties. The sketch model was used to provide the Transportation Advisory Group and key project stakeholders with an initial understanding of the expected magnitude of GHG reductions from different strategies such as EV adoption, transit, and active transportation investment. It was also used as a platform for data and calculations for strategies focusing on vehicle and fuel technology and efficiency, which are not part of the geographic model.
- A **geographic model** that incorporates spatial information on trip patterns and travel times, as well as behavioral information, from the CTPS regional travel demand model. The geographic model was used to conduct more in-depth modeling of strategies affecting travel behavior.

An overview of each model is provided below; more detailed documentation is provided in a separate memorandum. The following sections describe key assumptions and data sources relevant to each policy tested.

5.1 Sketch Model

The sketch model was implemented in Microsoft Excel. The model is not a true behavioral model, but rather incorporates general relationships between strategies and travel and emissions to allow for examining ranges of potential impacts. For example, transit strategies are tested by assuming that new investments will have the same levels of ridership (passengers per vehicle-mile) as current systemwide averages, and that passengers on these new services will be pulled from other modes similar to existing MBTA riders. The sketch model also allows for testing of parameters such as average ride-hailing vehicle occupancy and electric and automated vehicle market penetration levels, to examine issues such as how increased vehicle efficiency might trade off against higher or lower miles traveled per traveler and vehicle occupancy levels. The sketch model is set up to accept inputs and produce outputs for years 2030 and 2050. Outputs include total VMT, total GHG emissions, and total fuel use by type of fuel.

5.2 Geographic Model

5.2.1 Overview

The geographic model is an abstraction of the CTPS travel demand forecasting model implemented in Python. The CTPS model consists of four major steps to producing estimated highway and transit network conditions:

- Trip Generation: a process that estimates the number of trips by purpose (work, school, etc.) based on households by market segment (size, workers, income, etc.);
- Trip Distribution: a process that estimates the destination of the generated trips;
- Mode Choice: a process to estimate the travel mode for each trip; and
- Assignment: a process to 'load' the trips onto the highway and transit networks, effectively determining the routing and congestion levels.

The geographic model implements a simplified version of the CTPS Mode Choice process. The estimated modes in the CTPS model are:

- Auto - segmented by occupancy into drive-alone and shared ride;
- Transit - segmented by access mode (walk or drive); and
- Non-motorized – walk or bike.

In addition to the modes from the CTPS model, the geographic model was extended to include two 'Smart Mobility' modes: ride-alone and shared ride. The ride alone mode represents an on-demand TNC-type service that serves one trip at a time. The shared-ride service represents the on-demand service that may aggregate trips simultaneously.

In application, trip tables at the Traffic Analysis Zone (TAZ) level by purpose and household vehicle ownership from the CTPS model are input to the geographic model along with level of service tables (skims) that represent the travel conditions by mode. Mode choice coefficients are applied to evaluate how changes in the time and/or cost of travel by each mode (e.g., faster transit times) between each origin and destination zone affect how many people use each mode. The geographic model outputs TAZ trip tables by purpose and mode. These outputs are then summarized to present trips, VMT, PMT, active (walk and bike) PMT, and mode shares by Boston neighborhood where the trips are produced (home-based) or attracted (e.g., work or school-based) as well as for four "rings" of communities outside Boston. Model inputs were interpolated or extrapolated to derive 2030 and 2050 values based on the 2040 data used to develop the model. Outputs were postprocessed in Excel to estimate GHG emissions and combined demand scenarios with technology/fuel scenarios.

Scenarios are implemented in the geographic model by modifying the input trip tables and skims and/or modifying the mode choice parameters. For example, policies can be tested by changing the time and/or cost of travel (by mode) for trips produced or attracted to specific Boston neighborhoods, or for any pair of Boston neighborhoods or TAZs.

The model does not include an auto ownership model; however, it can capture the effects of changes in auto ownership since the CTPS model includes different mode choice coefficients for 0 vehicle vs. 1+ vehicle households. The number of households by auto ownership can be changed by the user by zone or neighborhood. The application assumes that for households shifting from 1+ to 0 autos, the total number and distribution of trips remains the same. The model simulates the change in attractiveness of each mode based on the shift in auto ownership. For example, trips from a household with 1+ autos would be more likely to use drive-alone modes.

6 FUTURE POLICY SCENARIOS

6.1 POLICIES AND ANALYSIS APPROACH BY STRATEGY FOCUS AREA

The Carbon Free Boston analysis focused mainly on transportation policies and investment strategies that may be largely influenced by the City of Boston, although some policies – such as carbon pricing, transit investment, and ride-hailing service regulation – may require state and/or regional agency action. Policies were grouped into focus areas and assumptions in the models were changed to represent these policies. Table 6 lists the focus areas and examples of policies for each area, and describes the general approach to modeling each focus area used in both the sketch and geographic model. More detailed assumptions are provided in the discussion of each strategy.

Table 6. GHG Focus Areas and Example Policies

Focus Area	Potential Policies	Sketch Model Approach	Geographic Model Approach
Clean Vehicles	Increase EV infrastructure, e.g., public charging stations; requirements for EV charging in new development; regulatory approaches to encourage provision of EV infrastructure for existing developments. Tax EVs differently from ICEs. EV incentives such as HOV lane access and preferential parking. Ban ICE vehicles from registration. Electrify public vehicle fleets (autos, trucks, buses, commuter rail).	Consider alternative EV market penetration scenarios for light and medium vehicle sectors. Consider alternative electrification schedules for public transit.	Apply clean vehicle results from sketch model to travel reductions from other strategies in geographic model.
Land Use	Update land use/zoning policies to support compact, mixed-use development in transportation-efficient areas, limit dense development in areas not well-served by transit, and reduce parking supply. Use development review process to implement policies.	Shift new population growth from zones with high PMT per capita to zones with low PMT per capita, and recompute PMT and VMT for new population.	Shift new growth into growth focus areas and assume travel patterns are similar to existing residents of those areas.
Transit	Improve bus efficiency and reliability through intersection improvements, dedicated bus lanes, etc. Implement rapid bus and rail projects identified in Go Boston.	Efficiency: assume travel time savings per route-mile based on evidence from other implementations. Investment: assume new services have same average ridership as existing services.	Reduce transit travel time between origin and destination pairs served by Go Boston projects (investment) or citywide (efficiency).
Active Transportation	Improve bikeability through infrastructure (bikeway investments identified in Go Boston and beyond) and supporting programs. Improve walkability through Complete Streets and other pedestrian improvements.	Apply elasticity from other studies on the increase in bike-miles of travel per new bike lane-mile. Alternatively, set a target for increase in % of trips by bike and walk.	Reduce perceived bike travel time between origin and destination pairs served by Go Boston projects (or citywide) to reflect greater attractiveness of bike facilities.

Focus Area	Potential Policies	Sketch Model Approach	Geographic Model Approach
Connected/ Autonomous Vehicles (CAV) in Private Ownership	Implement policies to restrict zero-occupant vehicle travel and encourage or require CAVs to be clean technology (e.g., registration requirements).	Examine scenarios for different levels of market penetration, application of clean vehicle technology, change in travel demand, and efficiency (per mile) compared to human-operated vehicle.	Assume a CAV market share and decrease value of travel time and parking costs for CAVs (unmanaged scenario); apply fees to offset decreases (managed scenario). Increase HH vehicle ownership to represent people who can afford a car but prefer not to or are unable to drive themselves.
Smart Mobility	Implement policies (e.g., trip fees) to increase cost of single or zero-occupant travel and decrease cost of shared rides. Require fleet-operated shared mobility vehicles to be clean technology.	Examine scenarios for different levels of market penetration, application of clean vehicle technology, and vehicle occupancy, for ridehail services (up to 3 occupants) and microtransit (>3 occupants).	Apply a fee to single-occupant ride-hailing trips; reduce costs of multi-occupant trips. Reduce cost of trips to represent labor cost savings from AVs. Reduce auto ownership at high levels of smart mobility adoption.
Travel Pricing	Implement cordon price for vehicles entering central Boston. Increase registration fees. Increase and broaden parking fees. Apply VMT fee (state policy). Apply carbon price to fuel (state policy).	Apply price elasticities from literature to evaluate change in VMT with respect to change in price per trip, VMT, or unit of fuel.	Increase cost per auto trip or per-VMT, for specific neighborhoods or citywide, depending upon policy.
Travel Demand Management (TDM)	Expand outreach to employers and residential property managers to provide travel information and incentives to workers and residents. Require TDM options and incentives at new buildings as part of the permitting/development review process.	Assume increased level of market penetration (# of workers or residents reached with TDM) and response (% VMT reduced) for market reached from literature.	Reduce transit fare for work trips; reduce home-based work trips to reflect TDM program impacts observed in literature.

7 ELECTRIFICATION SCENARIOS

While multiple clean vehicle technologies are possible in the future, such as hydrogen fuel cell and advanced biofuels, battery electric vehicles (BEV) were identified by the City and Carbon Free Boston stakeholders as the technology most likely to be viable on a widespread basis, for most vehicle market segments. The GHG emission benefits of BEVs are a function of the level of market penetration in each vehicle class, efficiency of the vehicle relative to an ICE vehicle, and the GHG intensity of the electricity supply.

BEV technology has been developing rapidly in the past decade. Because the technology is not in widespread use, there is very limited data from which to forecast rates of market penetration or the impacts of different policy incentives, and the rate of future advancement in technology factors that will influence market penetration (especially battery costs) is uncertain. Therefore, multiple EV market penetration scenarios were developed. These are based on the latest industry forecasts, as well as applications of a federally developed model by the CFB consultant team.

7.1.1 Industry Forecasts

The AEO provides projections of light-duty EV market penetration under Reference Case and high oil price conditions. These projections are conservative compared to other recent industry forecasts, showing around 10 percent sales market share in 2030 and no more than 20 percent in 2050. Figure 18 compares forecast sales of light-duty EVs from various sources. Sources including Bloomberg [35] and Energy Innovation [36] place BEV sales market penetration between 20 and 35 percent in 2030 and 50 to 70 percent by 2050. The NREL Electrification Futures Study (EFS) [37] shows even more optimistic penetration rates under their "medium" and "high" electrification scenarios, reaching 60 percent by 2030 and 70 to 90 percent by 2050 (the NREL "low" scenario is comparable to AEO). These are U.S. or worldwide forecasts as noted, and do not reflect Boston-specific conditions.

Fewer sources provide projections of light-duty fleet (stock) or VMT, which is the driver of GHG emissions in any given year. Fleet and VMT market penetration will lag sales since vehicles are typically kept in service for many years. Figure 19 shows fleet or VMT market penetration projections from published sources. Most industry sources show less than 10 percent of VMT in 2030 by electric vehicles, although NREL and the International Energy Agency high policy scenario show over 25 percent given their more advanced EV sales curves.

Figure 18. Light-Duty EV Market Penetration Forecasts (Sales)

Sources: Annual Energy Outlook [28], Bloomberg New Energy Finance [35], Rissman [36], Mai et al. [37], Eichenberg [38], and International Energy Agency [39]. In some cases, raw data were unavailable and data points were estimated by reading graphs.

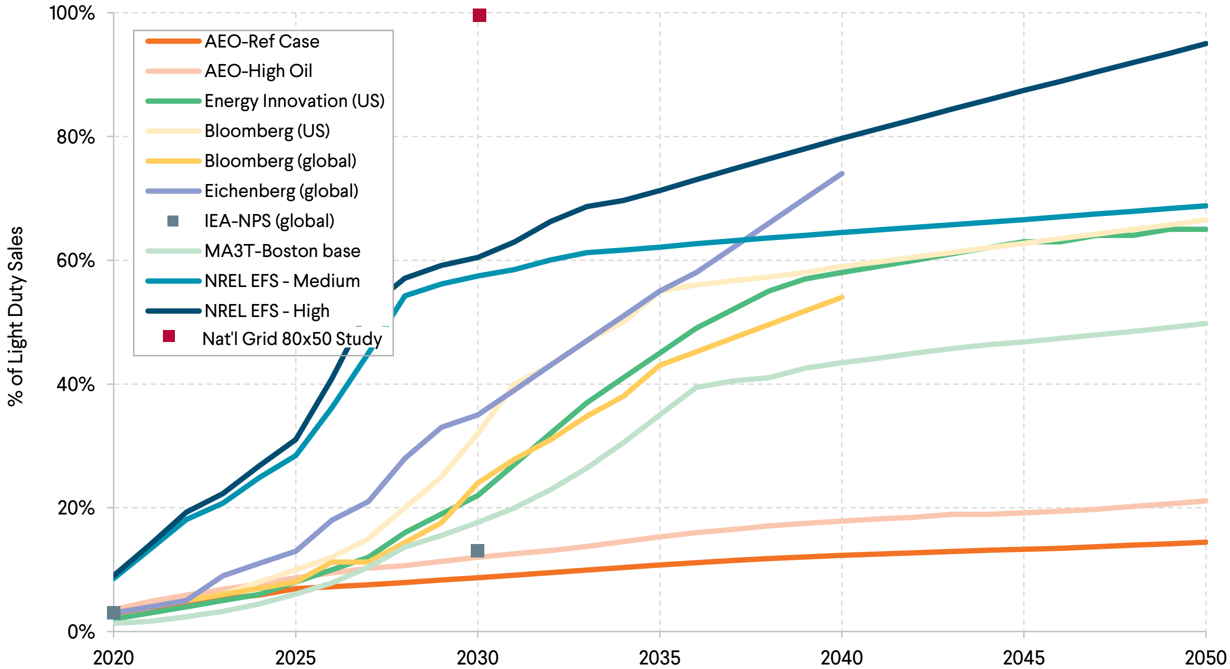
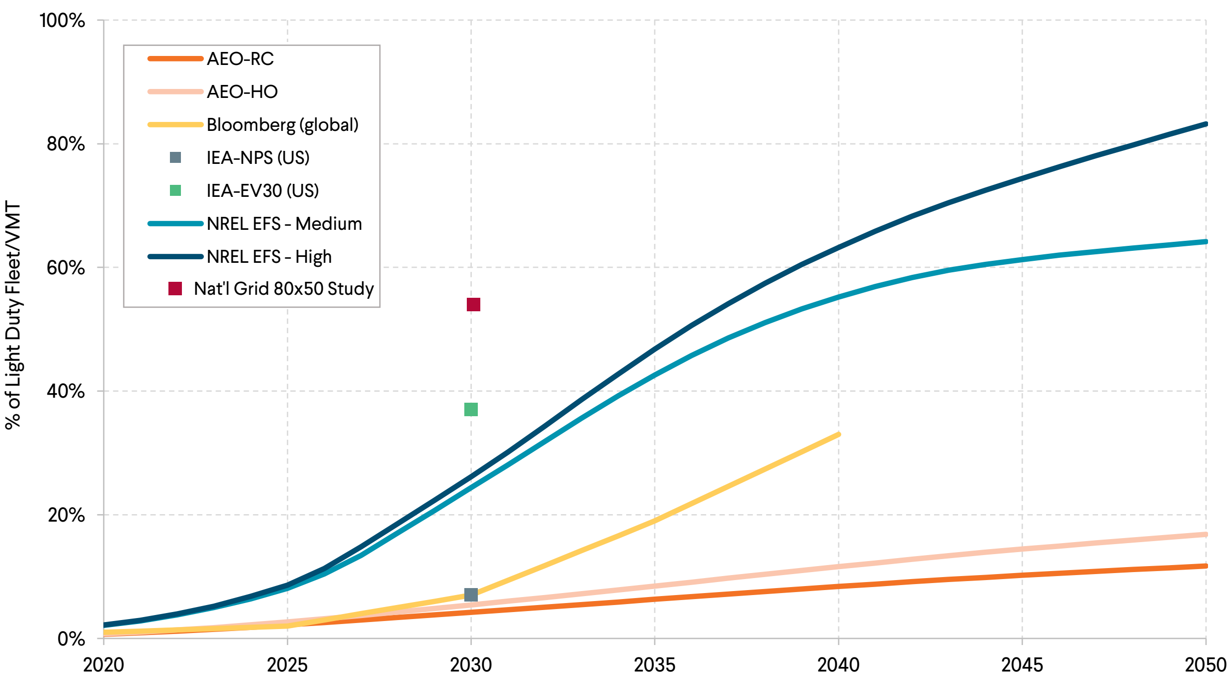


Figure 19. Light-Duty EV Market Penetration Forecasts (Fleet or VMT)

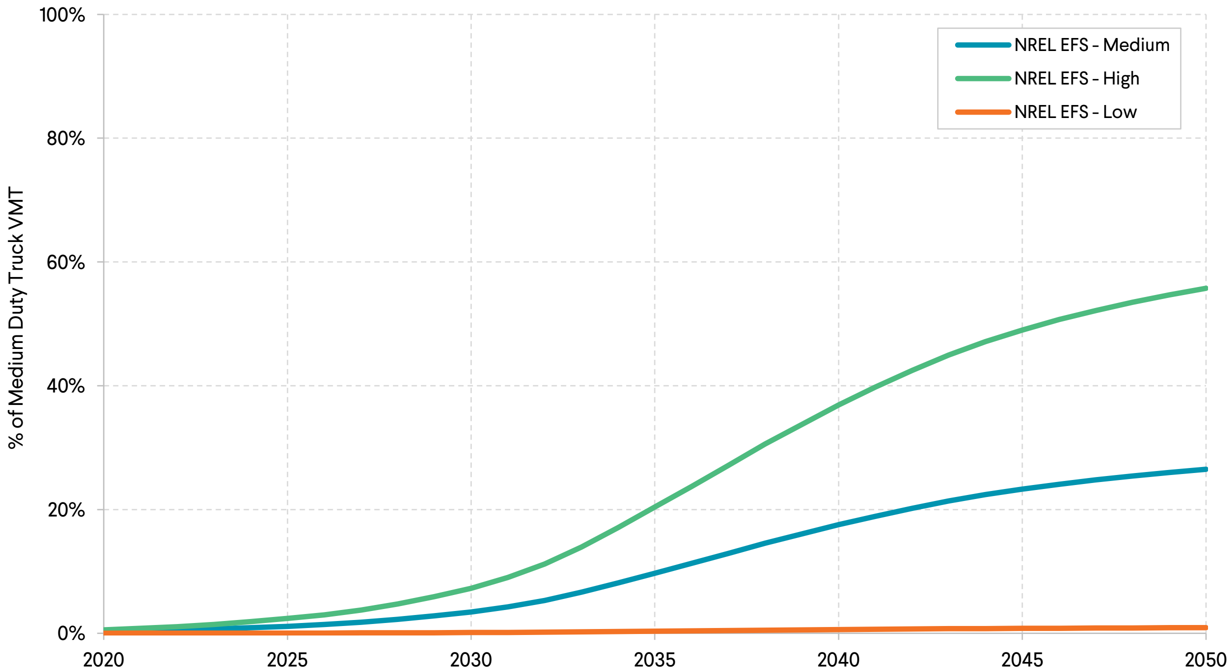
Sources: Annual Energy Outlook [28], Bloomberg New Energy Finance [35], Mai et al. [37], and International Energy Agency [39]. In some cases, raw data were unavailable and data points were estimated by reading graphs.



Only one source – the NREL Electrification Futures Study – was identified than contained projections of medium-duty truck EV market penetration. Figure 20 shows the projected market penetration (share of VMT) by electric MDTs.

Figure 20. Medium-Duty EV Market Penetration Forecasts (Fleet/VMT)

Source: Mai et al. [37]



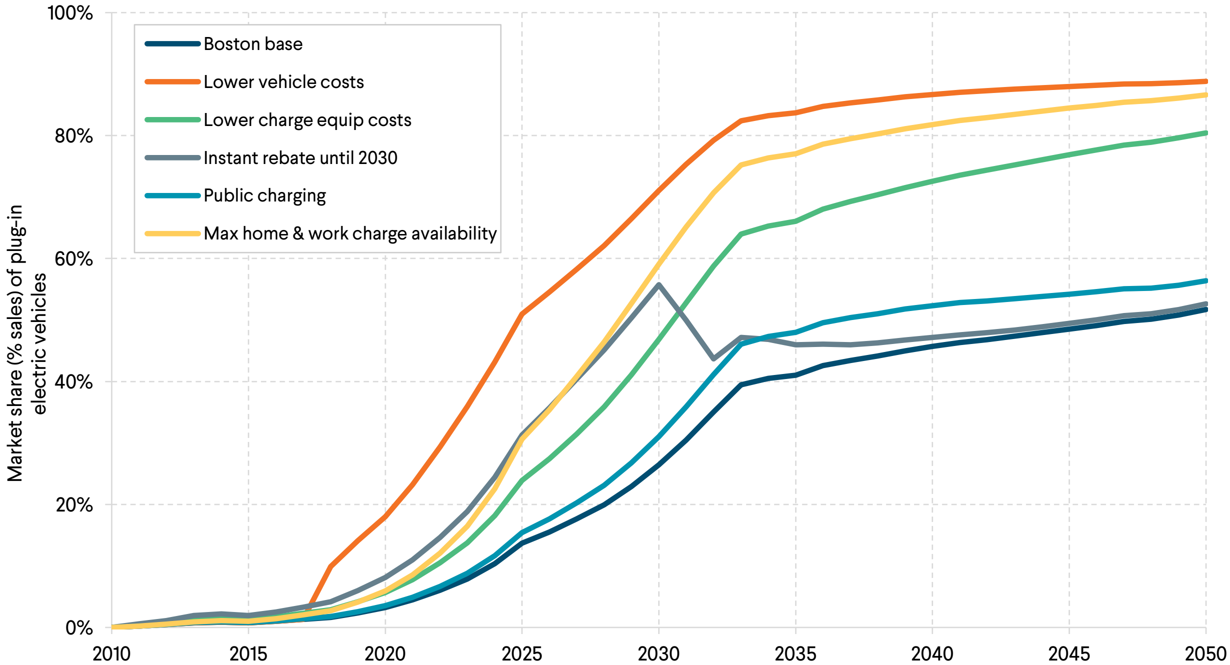
7.1.2 Policy Modeling

To illustrate the potential impacts of Boston-specific factors and policies, the project team applied the Market Acceptance of Advanced Automotive Technologies (MA3T) model developed by Oak Ridge National Laboratory. Implemented in Excel, this model was developed as a tool for analyzing scenarios of demand for various automotive powertrain technologies in response to changes in technologies, infrastructure, energy prices, consumer preferences, and policies. It uses discrete choice methods applied to 1,458 segments of the U.S. consumer market. It was developed circa 2010 and last updated in 2015, and therefore may not reflect the latest information on technology and consumer preferences. However, it was the only publicly available model the project team could identify that is capable of evaluating a full range of policies related to EV implementation. The National Renewable Energy Laboratory (NREL) also has a publicly available tool, ADOPT, but it is primarily focused on technology characteristics and does not analyze the range of policy options desired in this study. The MA3T model includes many vehicle technology types, but the focus of this analysis is on plug-in hybrid electric vehicles (PHEV) and EVs.

The project team first adjusted the MA3T model to reflect a Boston-specific population (most households in the "Central City" area type) and New England energy prices. These changes reduced EV sales somewhat due to less favorable conditions in the Central City (limited charging availability and possibly less economic benefit due to shorter travel distances) and also because New England has comparable petroleum prices but higher electricity prices than the U.S. on average, making EVs less economically competitive.

The project team then tested different policies in the model relating to vehicle technology costs, consumer financial and non-financial incentives, and home, workplace, and public charging availability. Figure 21 shows results from sample scenarios in terms of PHEV + EV sales impacts (scenarios were run independently, not in combination).

Figure 21. MA3T Model: EV Sales Projections



Scenario descriptions:

- *Boston base*: All assumptions embedded in MA3T model, with changes to population by area type to reflect Boston conditions (90% Central City/10% Suburb) and New England energy prices consistent with other elements of the transportation analysis (electricity prices about 50% higher than national average)
- *Lower charge equip costs:* Cost for a home charger reduced from $7,000 to $2,500 (no garage) and from $1,000 to $500 (garage)
- *Public charging:* Increase from 5% availability to 100% availability by 2025
- *Lower vehicle costs:* Reduce vehicle technology costs (cost to manufacturer) by 10 percent (PHEV) to 25 percent (EV) starting in 2018
- *Instant rebate until 2030:* Provide a $5,000 instant rebate ($2,500 for PHEVs) until 2030
- *Max home & work charge availability:* Increase home charging availability from 29% (Central City) or 43% (Suburb) to 100% by 2025; increase work charging availability from 5% to 100% by 2025

The following observations can be made from Figure 21:

- The "Boston base" scenario shows sales of about 25 percent in 2030 increasing to 50 percent in 2050. As compared in Figure 15, this is on the low end of the industry forecasts, which may be reasonable given the difficulty in accessing charging in an environment with large numbers of multi-family residential buildings. Only 40 percent of Boston metropolitan area residents have access to a private garage.[10]
- The model appears to slightly over-predict sales in 2017-2020 compared to AEO and current trends, probably reflecting its lack of recent calibration.
- Lowering vehicle technology costs by 10 percent (PHEV) to 25 percent (EV) starting in 2018, to levels consistent with those estimated in Wolfram and Lutsey [41], advances the curve to an apparently unrealistic degree, with EVs capturing over 50 percent of sales in 2025.
- Providing a $5,000 instant rebate until 2030 ($2,500 for PHEVs) has a significant impact in advancing the curve. However, even with broad market penetration, the benefit is eliminated after the rebate ends, suggesting a permanent cost savings is needed to maintain market penetration.

[10] U.S. Census Bureau, 2013 American Housing Survey, as cited in Salama et al. [40].

- Widespread public charging availability alone has a small impact. This is consistent with studies showing that most charging demand will be at home, with supplemental charging at the workplace and at other destinations.
- Increasing home and worksite charging availability from forecast levels to 100 percent by the year 2026 has a significant impact, on par with the $5,000 instant rebate, raising EV sales to nearly 60 percent in 2030 and over 85 percent in 2050. This suggests an important role for the City in policies that support home and workplace charging.
- Lowering home charging equipment costs from $7,000 to $2,500 (no garage) and $1,000 to $500 (garage) also significantly increases sales, to 45 percent in 2030 and 80 percent in 2050.

Figure 22 shows the EV vs. total EV + PHEV sales fractions for three sample scenarios. The PHEV fraction increases over the long term, and is generally much higher than predicted by AEO (which predicts that PHEVs will make up only 15 percent of the EV market in the long term). However the NREL EFS also shows a high market share of PHEVs, with PHEVs making up the majority of EVs in the “medium” scenario. The high PHEV market shares in the MA3T and NREL models may reflect consideration of range and recharge availability issues at higher levels of market penetration. This is important because to the extent that plug-in vehicles are PHEVs, not full EVs, Boston’s ability to achieve carbon neutrality via clean electricity may be diminished.

The consultant team developed a fleet turnover model to convert sales fractions from the MA3T model into fleet and VMT fractions by year. The model uses data on scrappage rates and miles driven by vehicle age from the Argonne National Laboratory VISION model (2018 release). Even with a more rapid introduction of EVs consistent with the maximum charging availability scenario shown in Figure 16, the VMT fraction of light duty EVs is only slightly more than 10 percent in 2030 (Figure 23). It does reach a long-term rate of nearly 80 percent by 2080. This shows the importance of policies to attain rapid turnover of the vehicle fleet to cleaner technologies in order to meet shorter-term GHG reduction goals.

Figure 22. MA3T Model: EV vs. Total EV + PHEV Sales

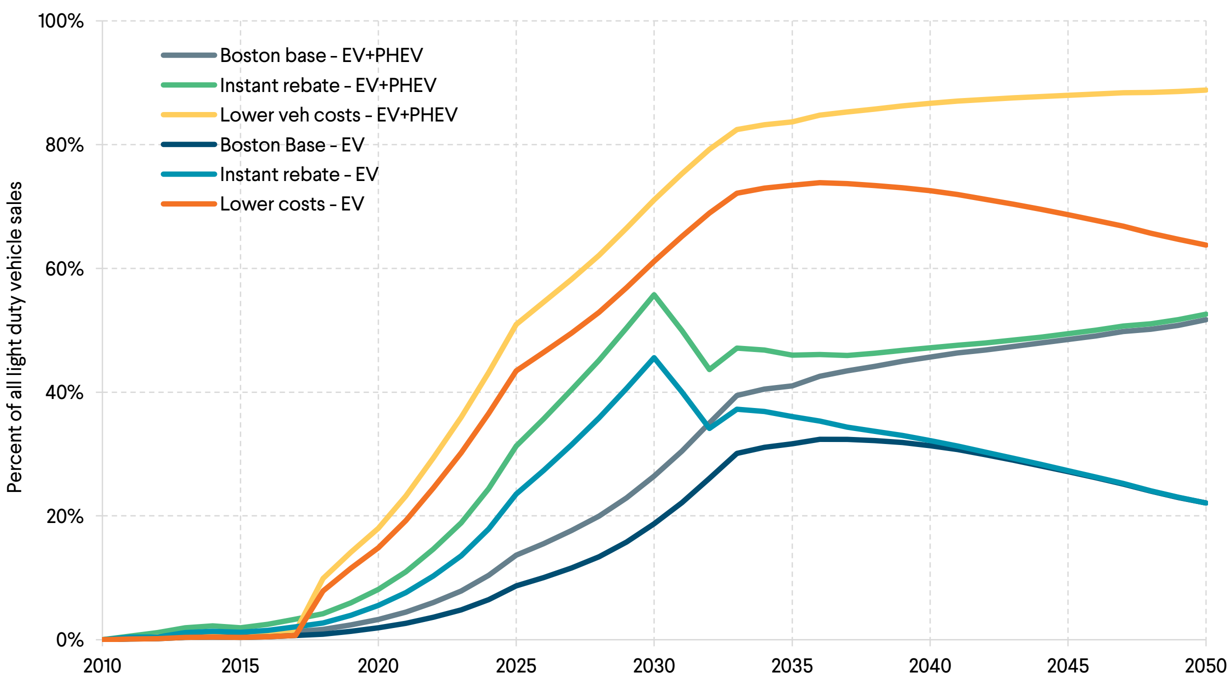
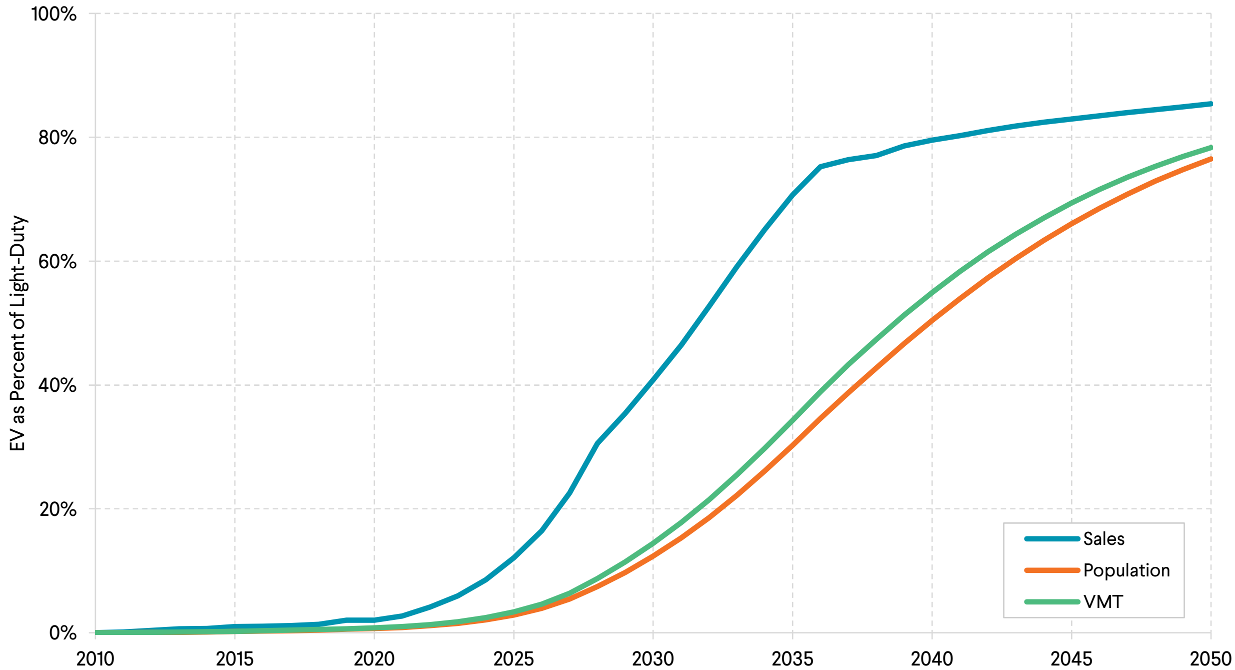


Figure 23. Light-Duty EV Sales, Population, and VMT Fractions for the Boston - Maximum Charging Availability Scenario from MA3T



7.1.3 Electrification Scenarios

Based on industry forecasts and the MA3T model results, the illustrative EV scenarios shown in Table 7 were created. Scenarios 0 (baseline) and 1 are from the 2018 AEO. Scenario 2 is in the range of the Bloomberg and Energy Innovation U.S. forecasts. Scenario 3 is the base run of the MA3T model with Boston conditions. Scenario 4, "MA3T Boston High Impact", assumes maximum charging availability in the MA3T model as well as the more favorable EV/PHEV split from AEO. Scenario 5, "All Electric", contains the same assumptions as Scenario 4 for 2030, but assumes that all light-duty vehicles in Boston are electrified in 2050. Medium-duty vehicles are assumed to be electrified at the same rate as light-duty vehicles in each scenario. The scenarios also vary the rate of transit electrification. In Scenarios 2 and higher, transit and school buses are fully electrified by 2050, with different phase-in rates in 2030. In Scenarios 4 and 5, the commuter rail system is also fully electrified in 2050.

The car and truck percentages could be applied only to vehicles that are resident in Boston, since these vehicles would be most likely to be influenced by City-specific policies, with non-Boston adoption rates held to the baseline. VMT produced in Boston (i.e., by Boston-based households) makes up only about 28 percent of all VMT in the Boston trip-end inventory; the remainder is produced outside of Boston, for trips into the City. A sensitivity analysis was also performed to evaluate the impacts of applying the policy EV scenario market penetration rates to the entire region. While some degree of ownership difference could develop inside vs. outside the City, it seems unlikely that a future would develop in which nearly all vehicles owned by Boston residents are EVs, while nearly all vehicles owned in other communities are conventional ICEs.

The heavy-duty truck, intercity bus, and ferry sectors are not assumed to be electrified. Under most assumptions, the electrification potential of the heavy-duty vehicle sectors is considered to be limited; the NREL "medium" scenario shows only 9 percent of heavy truck VMT to be electrified in 2050 and the "high" scenario shows less than 40 percent. Intercity bus and ferry could potentially be electrified in the long term

(Baruchman [42] reports that the Washington State DOT is beginning to convert vessels to hybrid diesel-electric power). However, these vehicles represent very small portions of the Boston GHG inventory (1 percent for intercity buses and 0.2 percent for ferries). In addition to having limited electrification potential, heavy duty trucks are also mostly outside of the policy domain which the City of Boston is able to influence.

Table 7. Illustrative Electrification Scenarios (2030% - 2050% of VMT)

Subsector	0 - Baseline (AEO Ref)	1 - AEO High Oil Price	2 - Industry Forecast	3 - MA3T Boston Base	4 - MA3T Boston High Impact	5 - All Electric
LDV – EV	4% - 10%	5% - 15%	7% - 49%	3% - 16%	32% - 74%	32% - 100%
LDV – PHEV	1% - 2%	1% - 3%	2% - 8%	4% - 28%	8% - 13%	8% - 0%
MDT – EV	2% - 3%	6% - 17%	8% - 58%	8% - 58%	40% - 86%	40% - 100%
Bus	0% - 0%	5% - 20%	25% - 100%	25% - 100%	66% - 100%	66% - 100%
Comm. rail	0% - 0%	0% - 0%	0% - 0%	0% - 0%	33% - 100%	33% - 100%
Electric grid	MA Clean Energy Standard				Zero by 2050	

Scenarios 0 through 4 also assume electric grid GHG emissions consistent with the Massachusetts Clean Energy Standard projected through 2050. Scenario 5 assumes GHG-free electricity generation in 2050. The assumptions behind the electricity grid intensities are described more fully elsewhere in this report. Figure 5 shows the GHG intensities from various electricity scenarios and compares these intensities to the GHG contained in a gallon of gasoline.

CASE STUDY: ACCELERATING EVS ADOPTION

In an effort to reduce transportation-related air pollution, the Commonwealth of Massachusetts signed a multi-state commitment in October 2013 pledging to have 300,000 zero-emission vehicles (ZEVs) on the road by 2025. The Massachusetts Offers Rebates for Electric Vehicles (MOV-EV) program was launched in June 2014 to promote the production and use of ZEVs. Since its inception, the MOV-EV program has issued over $28.4 million in rebates for more than 13,600 ZEVs across the state. In January 2017, Governor Charlie Baker signed Senate Bill 2505, An Act Promoting Zero Emission Vehicle Adoption, to further support the state's ZEV target by increasing access to public charging stations and ensuring that ZEV will account for 25 percent of annual motor vehicle sales by 2025.

The Commonwealth is not alone in these efforts as public utilities are stepping up to help the state reach its ambitious goals. In December 2017, Eversource was approved by the Department of Public Utilities to pursue a $45 million program to accelerate the adoption of EVs in Massachusetts by reducing the costs associated with EV charging infrastructure. Through this program, Eversource will cover the installation costs and will offer rebates to site hosts in environmental justice communities for the cost of the chargers. In September 2018, National Grid was approved for a similar program of their own amounting to a $25 million investment. Together these efforts aim to support the buildout of roughly 5,000 Level 2 and 150 fast- charging stations in workplaces, apartment buildings, colleges, hospitals, among other locations.

A 2017 report by the National Renewable Energy Laboratory estimated that roughly 42,000 to 90,000 charging stations will be needed to support the Commonwealth's 2025 ZEV goal of 300,000 vehicles. Eversource's and National Grid's combined investment of $80 million will achieve 6 to 12 percent of the needed charging infrastructure but with strategic placement these programs will help accelerate the deployment of ZEVs across Massachusetts.

8 IMPACTS BY FOCUS AREA

GHG, VMT, and other impacts were first evaluated for individual focus areas. Then a set of combined scenarios was developed illustrating potential pathways to a carbon-free transportation system in 2050.

8.1 CLEAN VEHICLES

Clean vehicles that rely on low or zero-carbon fuels are the cornerstone to achieving carbon neutrality without compromising mobility. While research continues on clean fuel technologies such as advanced biofuels and hydrogen fuel cells, the most viable path forward appears to be electrification of vehicles, in conjunction with the development of a clean energy grid. Market projections suggest that anywhere between 40 and 90 percent of light-duty vehicles could be powered by electricity in 2050. Achieving the high end of this range will require local support – such as policies to support home and worksite charging, investment in public charging infrastructure, and other incentives for early adopters – in addition to continued reduction in battery costs, increases in conventional energy prices, and development of clean electricity.

City policies can also support electrification in the light and medium duty truck sectors, mainly used for local commercial travel, and the City can work with state and local partners to electrify transit and school buses. Heavy-duty trucks may need to rely on advanced biofuels, and require state and national level policies. Truck and bus electrification will also provide significant benefits for reducing harmful emissions from diesel exhaust.

8.1.1 Policy Overview

The clean vehicle scenarios represent a combination of policy and market factors. One baseline and five alternative electrification scenarios were tested, as described in the previous section.

8.1.2 Modeling Approach

The sketch model was used to calculate energy and GHG reductions associated with EVs including light-duty vehicles, medium-duty trucks, buses, and commuter rail. Fuel efficiency rates by technology type were taken from the 2018 AEO Reference Case. It was assumed that increasing the fraction of EVs in the fleet would increase the fuel efficiency of the vehicle fleet based on the shift in vehicle technologies. In reality, this may not be the case due to the way Federal fuel efficiency and GHG regulations are structured, in which auto manufacturers are required to meet fleet averages based on vehicle footprints (so that more sales of larger vehicles could decrease overall mpg). It is possible that under this regulatory structure, increasing volumes of EV sales in one location would be offset by less fuel-efficient vehicles sold in another location where EV requirements or incentives are not present. However, more widespread state and local adoption of EV incentives should help stimulate consumer demand and bring down prices, making EVs (and therefore overall fleet fuel efficiency improvements) more viable and cost-effective in the long term.

Plug-in hybrid vehicles were assumed to travel 38 percent of their VMT on gasoline power and consume 62 percent of their energy in the form of gasoline (in 2030; these values differ slightly by year), based on analysis of AEO data on plug-in hybrid energy consumption compared to gasoline and all-electric vehicles.

8.1.3 VMT and GHG Benefits

Figure 24 shows GHG emissions for each EV scenario under baseline travel demand assumptions in 2030 and 2050. Table 6 presents the corresponding numbers and change compared to baseline GHG emissions in each year. Figure 24 and Table 8 assume that households outside of the City continue to adopt EVs at baseline (Scenario 0) rates. Most scenarios show a very modest impact in 2030 but a more significant impact in 2050 as broader market penetration of EVs occurs. Only Scenarios 4 and 5, with their more rapid early market penetration, show significant benefits in 2030. Scenario 3 shows less benefit than Scenario 2 because of the higher fraction of plug-in hybrids in the EV fleet that are still consuming some gasoline. Note that even under the “All Electric” scenario with zero electricity emissions, the GHG change from the 2050 baseline is less than 40 percent due to the contribution of vehicles from outside the City and in the unaffected heavy vehicle sectors. Emissions in 2050 are about two-thirds lower than in 2016.

Figure 24. Emissions by EV Scenario: Baseline Travel, Only Boston Households Affected

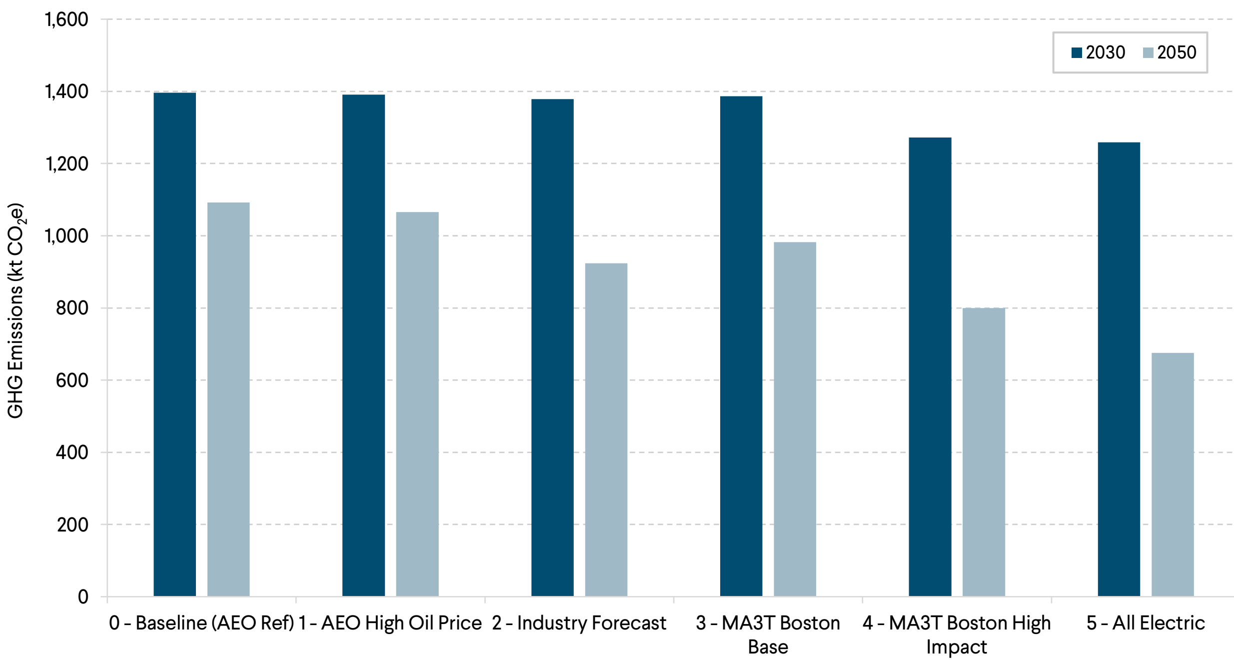


Table 8. Emissions by EV Scenario: Baseline Travel, Only Boston Households Affected

EV Scenario	2030 t CO_2e	% Change vs. 2030 Baseline	% Change vs. 2016	2050 t CO_2e	% Change vs. 2050 Baseline	% Change vs. 2016
0 - Baseline (AEO Ref)	1,396,663	0.0%	-29.8%	1,092,445	0.0%	-45.1%
1 - AEO High Oil Price	1,390,518	-0.4%	-30.1%	1,065,572	-2.5%	-46.5%
2 - Industry Forecast	1,378,610	-1.3%	-30.7%	923,849	-15.4%	-53.6%
3 - MA3T Boston Base	1,386,263	-0.7%	-30.4%	982,297	-10.1%	-50.7%
4 - MA3T Boston High Impact	1,271,862	-8.9%	-36.1%	799,313	-26.8%	-59.8%
5 - All Electric	1,258,593	-9.9%	-36.8%	675,275	-38.2%	-66.1%

Figure 25 and Table 9 show the same results assuming that households outside of Boston adopt EVs at the same rate as Boston households in the scenario. Now in the All-Electric scenario, emissions are reduced by over 90 percent compared to the 2050 baseline or 95 percent compared to 2016 levels, with most of the residual emissions from heavy trucks.

Figure 25. Emissions by EV Scenario: Baseline Travel, All Regional Households Affected

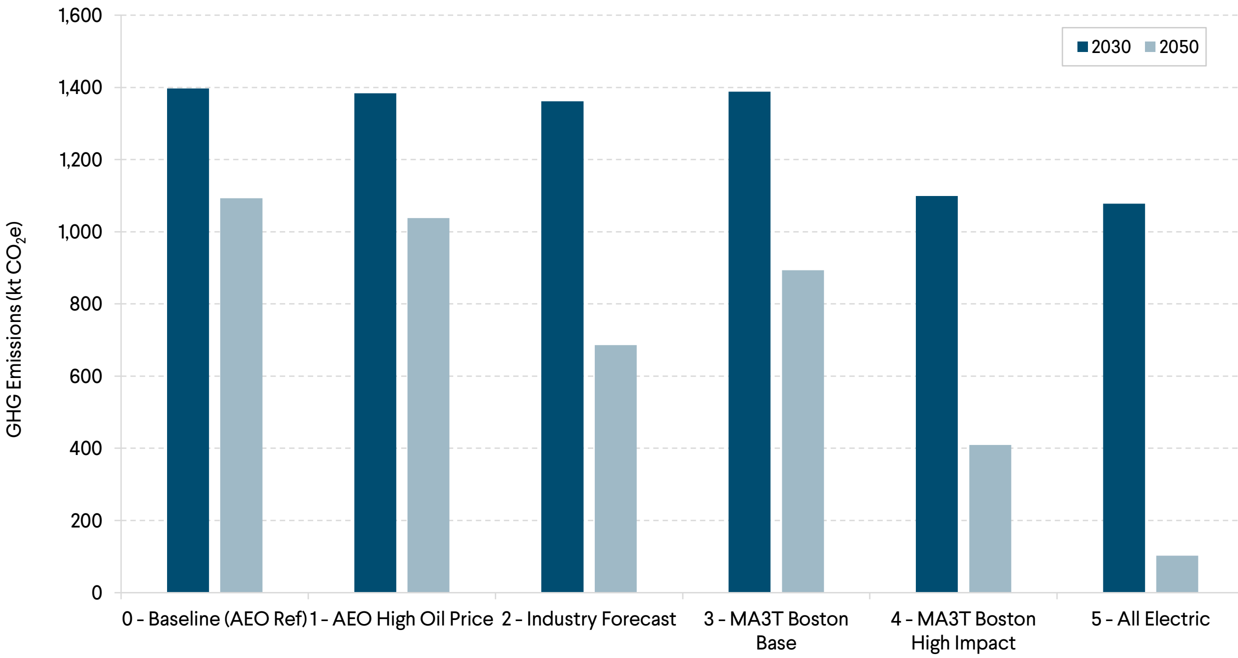


Table 9. Emissions by EV Scenario: Baseline Travel, All Regional Households Affected

EV Scenario	2030 t CO_2e	% Change vs. 2030 Baseline	% Change vs. 2016	2050 t CO_2e	% Change vs. 2050 Baseline	% Change vs. 2016
0 - Baseline (AEO Ref)	1,396,663	-29.8%	0.0%	1,092,445	3.4%	-45.1%
1 - AEO High Oil Price	1,383,169	-30.5%	-1.0%	1,037,990	-1.8%	-47.9%
2 - Industry Forecast	1,361,048	-31.6%	-2.6%	686,242	-35.2%	-65.5%
3 - MA3T Boston Base	1,387,916	-30.3%	-0.6%	893,585	-15.3%	-55.1%
4 - MA3T Boston High Impact	1,099,304	-44.8%	-21.3%	409,463	-61.4%	-79.4%
5 - All Electric	1,077,513	-45.9%	-22.9%	102,342	-90.6%	-94.9%

The possibility was also considered that EVs might increase VMT by reducing the cost per mile of travel (due to cheaper energy costs). This effect is known as "induced demand." Induced demand was tested using the same price elasticity as for the pricing strategies, derived from Annual Energy Outlook data. The 2030 price elasticity would result in a 9 percent increase in VMT per vehicle, for EVs. This increase would marginally reduce the GHG benefits of the EV scenarios. The induced demand impacts are somewhat uncertain and were not considered in the scenario results reported here; however, the sketch model allows the user to include induced demand effects.

8.1.4 Electricity Demand Impacts

Figure 26 and Table 10 show the additional electricity demand that would be generated by the respective EV market penetration rates. These figures represent the additional electricity that would be required by households in the City of Boston, if all charging was done at home. The demand is up to 900,000 megawatt-hours (MWh) per year in 2050, or 0.9 terawatt-hours (TWh). In comparison, the current demand generated by the City is about 6.2 TWh. Therefore, the additional demand represents an increase of about 15 percent over current demand.

Not only the total demand, but also the demand generated during peak periods of electricity demand will influence the requirements for the future electricity grid. This study did not look specifically at what the temporal distribution of EV charging in Boston might be in the future. However, the 2017 NREL EFS made some estimates of expected EV charging by time of day on a national scale. Table 11 shows the NREL estimated hourly distributions for both January and July, and the additional electricity load in megawatts that would be required by hour under Scenario 5 (All Electric) in 2050.

Figure 26. Transportation Electricity Demand by EV Scenario: Baseline Travel, City of Boston Households

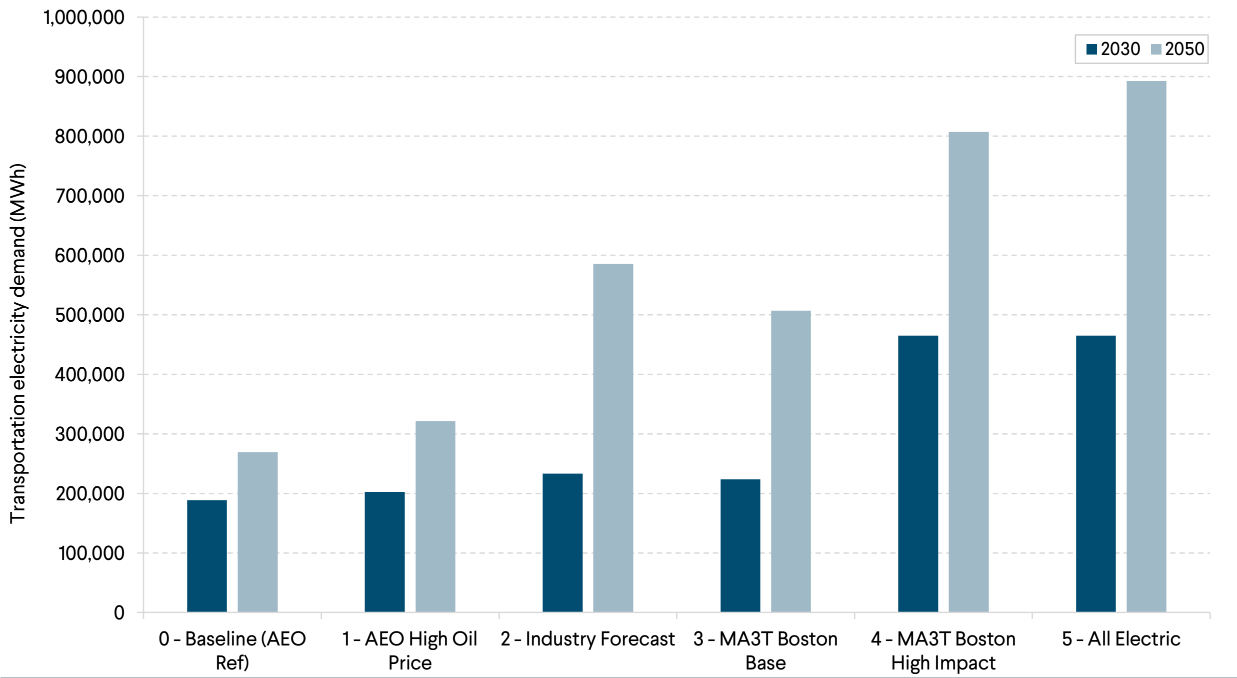


Table 10. Transportation Electricity Demand by EV Scenario: Baseline Travel, City of Boston Households

EV Scenario	2030 MWh	% Change vs. Current All-Sector	2050 MWh	% Change vs. Current All-Sector
0 - Baseline (AEO Ref)	188,502	3.0%	269,100	4.3%
1 - AEO High Oil Price	202,390	3.3%	321,375	5.2%
2 - Industry Forecast	233,271	3.8%	585,291	9.4%
3 - MA3T Boston Base	223,666	3.6%	506,757	8.2%
4 - MA3T Boston High Impact	465,289	7.5%	807,162	13.0%
5 - All Electric	465,289	7.5%	892,465	14.4%

Table 11. Additional Boston Electricity Demand by Hour in 2050, Scenario 5

Hour	2030 January (% of daily)	2030 July (% of daily)	2050 January (MW)	2050 July (MW)
1	5.0%	5.6%	68	76
2	4.5%	4.7%	62	64
3	3.7%	4.3%	51	58
4	2.8%	3.9%	38	53
5	2.2%	3.6%	30	49
6	1.9%	2.7%	26	37
7	2.0%	2.2%	27	30
8	2.0%	2.2%	28	30
9	2.5%	2.6%	34	36
10	3.1%	3.0%	43	41
11	3.6%	3.3%	49	45
12	4.1%	3.7%	56	51
13	4.7%	4.2%	64	58
14	5.2%	4.8%	71	66
15	5.5%	5.2%	76	71
16	6.1%	5.4%	83	73
17	6.6%	5.4%	90	74
18	5.4%	5.2%	74	72
19	4.7%	5.1%	64	70
20	4.5%	4.9%	62	67
21	4.5%	4.4%	62	61
22	5.0%	4.4%	69	60
23	5.2%	4.4%	71	60
24	5.2%	5.0%	71	68
Daily	**100.0%**	**100.0%**	**1,369 MWh**	**1,369 MWh**

8.1.5 Other Impacts

Electric vehicles will reduce air pollution and provide public health benefits. Compared to baseline 2050 levels of electrification, a full electrification scenario is expected to reduce transportation sector emissions of fine particulate matter ($PM_{2.5}$) by 8,900 tons annually or 75 percent. NO_x would be reduced by 258,000 t or nearly 65 percent. Vehicles are becoming cleaner over time, so the emission reductions would be greater in earlier years. The 2050 emission reductions have an estimated value of about $13 million, mainly in avoided health costs. Most of the benefits will come from electrification of medium duty diesel trucks, buses, and trains, which emit these harmful air pollutant emissions at much higher rates than light duty vehicles. There are still some residual emissions from heavy trucks, which are not affected by the strategies evaluated here, and which contribute disproportionately to these emissions on a per-mile basis.

8.1.6 Equity

Electric vehicles cost more up-front, but provide savings in operating and maintenance costs over time. In the early years, EV purchasers are likely to be higher-income consumers, and therefore any subsidies or incentives that benefit EV users will tend to benefit higher-income households. However, as more EVs are phased in and begin to age, the benefits will “trickle down” as lower-income households purchase used EVs and benefit from reduce vehicle operating costs.

Policies to accelerate truck and bus EV adoption should provide equity benefits by reducing harmful emissions in neighborhoods adjacent to truck and bus routes and industrial areas. Policies targeted specifically to support electrification for independent and small business operators could help mitigate any negative equity impacts of fossil fuel and travel pricing strategies.

8.1.7 Policy Discussion

Achieving a clean transportation system requires action in the transportation sector, to support vehicle electrification; as well as action in the electricity sector, to transition to clean energy sources and also increase supply to meet the additional transportation-generated demand. While electricity consumption will increase, the overall amount of energy consumed for transportation will be reduced because of the greater efficiency of electric vehicles. The increase in supply can also be mitigated by demand management measures, as discussed in the following sections.

The ability to electrify the entirety, or even majority, of the Boston transportation system will depend on a variety of factors – some which can be influenced by the City, and some not.

Factors mostly outside the City’s control include:

- **Battery costs** have been declining rapidly, but continued reductions in battery costs – supporting affordable vehicles with at least a 200 mile range – will be required to make EVs economically feasible for a large segment of the household and commercial markets.
- The economics will be strongly influenced by the **relative prices of electricity and petroleum fuels**. With gasoline prices currently at under $3 a gallon, the economics are not favorable; an EV will save the owner only $4,000 over 100,000 miles of use, not enough to make up the purchase price difference. A 50 to 100 percent increase in petroleum prices, without a correspondingly large increase in electricity costs, would make EVs more economically competitive under current vehicle cost projections. Fuel prices can be influenced by state taxes, but policies under recent discussion will have only modest impacts on vehicle purchase and use decisions. For example, a carbon tax of $30 per ton is equivalent to just under 30 cents per gallon, or about $100 a year for a household driving 10,000 miles in a 30-mpg car.
- **Federal and/or state incentives** will continue to have a modest ($1,000 to $2,500) to more significant ($5,000 to $7,500) impact on affordability of EVs in the near- and mid- terms. The absence of incentives will require more favorable technology and/or fuel costs. However, such incentives will not be sustainable at high market penetration rates without a new supporting revenue source.

Factors that the City may be able to influence include:

- **Electrification of city-owned vehicle fleets**, and requirements for city contractors to only use EVs. This is the policy that the City is most clearly able to implement, although it will require additional up-front costs even while saving fuel and maintenance costs over the long term. Maintenance equipment and worker training issues will need to be addressed (e.g., if school bus fleets are converted electricity). However, this will directly affect only a small fraction of the total vehicles operating in Boston.

- The availability of **charging infrastructure,** also known as electric vehicle support equipment (EVSE). This is a modest barrier to homeowners with a garage (adding $1,000 to $2,000 to vehicle purchase costs), but a significant barrier to multifamily residents with off-street parking, where installation costs can range from $5,000 and up and require a supportive property manager or condo association. Recharging is an even more daunting problem for residents who only have on-street parking, where complex policy issues regarding the use of public road space need to be resolved in addition to financing. Public-access charging can help, but home charging is a virtual necessity for mainstream EV buyers given that the vehicle is typically parked at a residence for the longest portion of the day [43]. Policies that the City will need to implement to support access to charging include:
  - Requirements for EVSE installation and/or readiness in all new buildings.
  - Education and outreach regarding EVSE opportunities, options, and requirements, for both homeowners and property managers of commercial and multifamily buildings.
  - Streamlined review and permitting of EVSE installations in existing development.
  - Procurement of private services to install and operate publicly-accessible EVSE at strategic locations.
  - Policies to guide the use of curb space for EV charging.
  - If cost still poses a major barrier after the above policies are implemented, subsidies for charging equipment and installation (possibly financed by related revenue such as registration fees in ICE vehicles).
- **Other incentives for EV ownership, such as:**
  - Differential excise taxes (lower for EVs, higher for ICEs).
  - Access to free or discounted parking in municipal lots and on-street locations, or preferential street parking permits. Parking incentives would need to be created carefully to address potential equity and revenue concerns, and probably limited in quantity as in the long-term free parking will be unsustainable for large numbers of vehicles.[11]
  - Access to high-occupancy vehicle (HOV) lanes. HOV lane access on highways such as I-93 would need to be managed by the state and also demand-limited, although the City could potentially allow EVs to use restricted-access lanes on local streets.[12]

The effectiveness of these policies will depend on their perceived value to consumers (parking cost and travel time savings), as well as their level of confidence that incentives will be sustained in the future. Table 12 compares the cost savings of hypothetical policies over five years of ownership with the additional costs of owning an EV.

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[11] Free workplace parking could be a significant monetary benefit in central Boston. Compared to a cost of $20 per day for 240 workdays, the value would be nearly $5,000 per year, more than enough to offset the additional cost of an EV over a five-year ownership period. However, only about 7 percent of workers in Boston are estimated to pay for parking (per the Massachusetts Household Travel Survey [44]). A savings of $5/day used three days a week would result in a benefit of around $1,000 a year, or $5,000 over five years.

[12] HOV access that saved a driver 10 minutes a day on weekdays, valued at the prevailing average of roughly $13/hour (per U.S. DOT guidance), would be worth about $500 a year, or $2,500 over a five-year ownership period.

Table 12. Hypothetical EV Cost and Cost Savings from Incentives

Cost Factor or Policy	Added Cost (Savings) Over Five Years for Vehicle Purchased in 2020	Source/Key Assumptions
BEV – 200 mile range		
Vehicle purchase	$9,500	Wolfram & Lutsey [41]
Vehicle maintenance	$(400)	Mai et al. [37]
Fuel	$(1,800)	Baseline VMT/vehicle and fuel prices
PHEV - 30 mile all-electric range		
Vehicle purchase	$4,200	Wolfram & Lutsey [41]
Vehicle maintenance	$(200)	Mai et al. [37]
Fuel	$(1,600)	Baseline VMT/vehicle and fuel prices
Other Costs		
Home charging station (garage available)	$1,500	Mai et al. [37]
Home charging station (no garage)	$5,000	Mai et al. [37]
Incentive Values		
Free worksite parking in central Boston	$(25,000)	$20/day, 240 workdays
Free parking at other destinations	$(5,000)	$5/day savings, 3 days/week
HOV access	$(2,500)	10 minutes/day savings on weekdays, $13/hr value (USDOT)
Differential excise tax	$(500)	$100/year difference vs. ICE

- **Consumer and fleet operator education** regarding EV purchase options and ownership issues. State and regional agencies have already developed resources on these topics, although there may be Boston-specific policies and information that should be communicated. The City could also work with larger operators of private truck and bus fleets to encourage and support electrification.
- **Regulations prohibiting internal combustion engine vehicles** in some or all uses and/or locations, e.g., through restricted use areas or vehicle registration policies. This could be a highly effective policy but may also carry significant economic and equity implications that would need to be investigated and mitigated (e.g., making Boston a less attractive place to do business, or imposing a greater burden on low-income drivers). Scenario 5 effectively implies an outright ban on ICE vehicle sales, registrations, and entry to the city at timepoints that is sufficient to effectively eliminate ICE vehicles from use in Boston by 2050. Such strategies have been proposed to different degrees by various countries and cities including Britain, France, India, Norway, Los Angeles, Mexico City, Seattle, Copenhagen, Barcelona, Vancouver, Milan, Quito, Cape Town, and Auckland. Both the various third-party forecasts cited above and our EV adoption modeling fail to demonstrate a pathway to 100 percent EVs by 2050 through expected market conditions or through soft incentives. This may be changing, as some automobile makers have started to commit to 100 percent electric fleets, but it is likely that a strong regulatory signal at the city-level – such as those mentioned above – would be required to eliminate ICE vehicles for vehicle classes that could be electrified. Implementing such a ban would necessitate the deployment of sufficient EVSE within the urban environment and the ability to provide reliable alternative modes of transportation to those who may be priced out of vehicle ownership due to the requirement. Some of these impacts could be mitigated through a phased approach that starts with a relatively small area of the City and expands over a period of years on a publicized schedule.

- **EV-supportive policies and investments by other communities** in the region will play a significant role in affecting the makeup of vehicles traveling to and from Boston. The City can play a lead role in working with neighboring communities and regional and state agencies to develop consistent EV-supportive policies.

One thing that is certain is that in order to achieve widespread electrification, the City will need to do what it can through policy and regulatory means to ensure that vehicle owners have access to home charging opportunities in all types of residential buildings. Additional outreach and incentives (financial or non-financial) will help encourage early adopters and get consumers comfortable with the technology, but will need to be balanced with available resources and other considerations such as equity.

8.2 LAND USE

Land use policies play an important role in managing travel demand and improving accessibility. Adopted regional forecasts show Boston's population growing by 13 percent by 2040. Boston residents located in compact, walkable neighborhoods near transit drive half as much as those in more dispersed, less transit-rich neighborhoods. Regional forecast growth patterns already appear to be shifting Boston's new residents and jobs into slightly more efficient patterns, as Boston-based VMT is not forecast to increase at the same rate as population and employment. A scenario analysis that shifted more of Boston's growth into centrally-located, transit-rich neighborhoods suggested that further changes to growth patterns could reduce VMT by an additional 3 percent.

As illustrated in Section 1.3, Boston residents already generate less VMT and GHG emissions per capita than residents of more outlying communities. Recent trends have led the City to expect over 115,000 new residents by 2050, considerably more than in the adopted regional forecasts. As the City implements policies to absorb a greater share of regional growth in transit-oriented communities, net regional GHG emissions will decline, even as they increase within the City.

8.2.1 Policy Overview

Land use changes can reduce VMT and GHG emissions by locating people and jobs in transportation-efficient locations with good transit access, walk and bike networks, and where trip lengths are short because destinations are close together. "Transportation efficient locations" are typically characterized by a mix of uses (e.g., neighborhood commercial within an easy walk of residential areas), moderate to high densities, street connectivity, and good pedestrian infrastructure.

Most Boston neighborhoods already have strong transportation-efficient characteristics, and vehicle travel per capita is therefore lower than in it is in lower-density, more auto-oriented parts of the region. Thus the efficiencies gained from compact land use patterns just within the city are probably smaller than policies that focus regional growth in urban centers (such as Boston). Still, accommodating future population and job growth in transit-oriented, centrally-located neighborhoods would be expected to reduce VMT. Furthermore, accommodating a greater share of regional growth in Boston should reduce regional GHG emissions, even if it increases GHG from Boston residents and workers.

Principles of transportation-efficient land use planning include:

- Land use policies, zoning changes, density bonuses, and use of the development review process to support compact, mixed-use development in areas well served by transit;

- Limiting the amount of development in areas not well-served by transit;
- Planning for a balance between jobs and housing in neighborhoods across the City, so that people can live close to where they work; and
- Supporting reduced car ownership and use through other land use policies, such as eliminating minimum parking requirements, applying parking caps, and requiring pedestrian-friendly building and site design.

8.2.2 Modeling Approach

In the sketch model, an alternative growth scenario was created in which population growth was increased in neighborhoods with lower VMT per capita than average, and decreased in other neighborhoods. In the alternative scenario, new residents were assumed to have the same VMT per capita as existing residents of the same neighborhood. The baseline discussion provides estimates of home-based VMT by neighborhood for all Boston neighborhoods, as well as baseline forecast growth by neighborhood.

In the geographic model, two alternative land use scenarios were tested:

1. New residential and employment growth was redirected from forecast locations into locations identified as priority growth areas in Imagine Boston 2030.
2. New residential and employment growth was redirected from forecast locations into centrally-located, transit-rich neighborhoods.

Under both scenarios, new residents and workers were assumed to have the same trip patterns as existing residents and workers in the neighborhood.

8.2.3 VMT and GHG Benefits

In the sketch model, a scenario that redirected all population growth into lower-than-average VMT neighborhoods reduced VMT and GHG emissions by about 0.3 percent in 2030 and 0.7 percent in 2050. The modest impact is due to the generally low VMT per capita across most neighborhoods and the relatively modest forecast growth levels. Using the City of Boston’s higher growth projections would increase benefits proportionately. The effects of shifting the locations of employment can be complex and were not evaluated with the sketch model.

In the geographic model, a scenario to reallocate 50 percent of new growth from the forecast location into Go Boston priority growth areas (removed from non-priority zones and added to priority zones in proportion to baseline forecast growth) *increased* VMT, by up to 1 percent regionwide in 2050 (2.5 percent in Boston alone). This may indicate that the tested growth pattern is no more transportation-efficient than the baseline projected pattern. The current growth forecasts already show most growth going into centrally located neighborhoods with strong transit accessibility (Figure 13). Land use scenario evaluation can be complex, with trip patterns depending on the location of both residential and job growth.

The second scenario, which directed three-quarters of new population growth into centrally-located, transit-rich neighborhoods, reduced regional Boston-based VMT by about 3 percent and VMT for trips just within Boston by about 6 percent. This suggests that transportation-efficient land use patterns can help to reduce GHG emissions beyond the benefits anticipated in baseline forecasts. The growth assumptions for this second scenario, compared to the baseline 2050 growth forecast, are show in Table 13.

8.2.4 Other Benefits

Transportation-efficient land use patterns can improve access to jobs, services, and other destinations, and add needed housing supply, without increasing the volume or energy consumption of travel. Population and job growth in walkable and bikeable neighborhoods will help to increase physical activity, resulting in health benefits and related health care cost savings.

8.2.5 Equity Implications

Land use strategies that increase housing in central Boston neighborhoods should reduce housing costs by expanding the supply, benefiting households at all income levels. Land use policies can be crafted to specifically support equity objectives, e.g., through inclusionary zoning (i.e., requirements to set aside a certain fraction of units in a new project for lower-income households), linkage fees, or other provisions to increase the supply of affordable housing. On the other hand, mitigating policies may be needed to protect existing residents (particularly renters) against the effects of gentrification and rising housing prices in particular neighborhoods.

8.2.6 Policy Discussion

The City of Boston already in recent years has worked to increase development in targeted areas, especially near transit, to accommodate housing demands and support economic growth. Further refinement of policies may be considered in the following areas:

- Reduction of parking requirements to accommodate shifting market preferences for zero auto ownership and reduce housing costs;
- Zoning provisions to increase housing supply especially of smaller, more affordable housing units; and
- Expanded implementation of TDM requirements (see TDM strategy).

Growth also needs to be supported by transportation systems that can handle the added capacity. However, it should also be kept in mind that growth that occurs outside of Boston will put even more strain on the transportation system, since people will have fewer transportation options and will drive longer distances. Centrally-located, transportation-efficient growth will minimize the regional GHG impacts of economic development.

Table 13. Alternative Land Use Scenario Growth Assumptions

Neighbor-hood	2016 Pop	2050 Pop Base	2050 Pop Scen	Base Pop Change	Scen Pop Change	2016 Emp	2050 Emp Base	2050 Emp Scen	Base Emp Change	Scen Emp Change
Back Bay	20,212	27,032	34,152	34%	69%	62,998	66,518	66,518	6%	6%
Charlestown	17,970	22,753	19,364	27%	8%	17,087	19,572	19,572	15%	15%
Dorchester	113,771	134,112	116,559	18%	2%	32,639	38,039	34,618	17%	6%
Downtown	10,829	13,159	27,556	22%	154%	153,464	163,918	172,839	7%	13%
East Boston	39,521	45,264	40,915	15%	4%	23,705	24,082	24,082	2%	2%
Hyde Park	38,245	44,946	38,942	18%	2%	7,159	7,454	7,454	4%	4%
Jamaica Plain	38,933	47,847	41,721	23%	7%	14,422	15,123	15,123	5%	5%
Mattapan	22,130	26,720	22,827	21%	3%	2,892	3,171	3,171	10%	10%
Mission Hill	13,611	15,889	20,581	17%	51%	5,134	5,518	5,518	7%	7%
North End	11,407	14,823	14,892	30%	31%	4,374	4,434	4,434	1%	1%
Roslindale	26,797	32,331	27,494	21%	3%	4,024	4,101	4,101	2%	2%
Roxbury	52,771	63,633	59,741	21%	13%	25,354	29,815	27,333	18%	8%
South Boston	36,205	45,538	45,266	26%	25%	13,620	13,893	13,893	2%	2%
West Roxbury	28,505	35,043	29,202	23%	2%	11,415	11,469	11,469	0%	0%
Harbor Islands	535	535	535	0%	0%	127	128	128	1%	1%
Allston	29,213	37,309	40,365	28%	38%	18,313	22,511	20,292	23%	11%
Brighton	48,431	59,559	51,219	23%	6%	16,779	18,240	17,439	9%	4%
Chinatown	4,630	5,643	6,024	22%	30%	8,558	8,599	8,599	0%	0%
Leather District	765	1,023	1,462	34%	91%	3,775	3,958	3,958	5%	5%
Longwood	7,946	8,987	16,310	13%	105%	47,449	51,627	51,627	9%	9%
South Boston Waterfront	2,588	3,437	16,528	33%	539%	37,563	48,487	48,487	29%	29%
Beacon Hill	8,977	11,741	11,765	31%	31%	3,687	3,683	3,683	0%	0%
West End	6,081	7,713	10,263	27%	69%	35,857	39,039	39,039	9%	9%
South End	27,835	35,397	41,775	27%	50%	18,570	26,889	26,889	45%	45%
Bay Village	1,455	1,877	2,152	29%	48%	2,646	3,592	3,592	36%	36%
Fenway	36,207	42,657	47,359	18%	31%	28,760	32,494	32,494	13%	13%
Total	**645,570**	**784,966**	**784,966**	**22%**	**22%**	**600,371**	**666,352**	**666,353**	**11%**	**11%**

8.3 TRANSIT

Transit investments provide relatively modest GHG reductions but also provide substantial "co-benefits" in the form of improved mobility and accessibility for all population groups. Considering the region's already overtaxed transit system, transit investments are also essential to supporting population and job growth in centrally located Boston neighborhoods that will reduce regional GHG emissions. Transit fare reductions can also play a significant role in encouraging mode shift. The City of Boston will need to work with the MBTA and other regional stakeholders to develop transit improvement and funding solutions to realize these benefits.

A comprehensive program of low-cost transit improvements, such as signal priority and queue jump lanes to improve bus travel times and reliability, could reduce GHG emissions by 400 t CO_2e, assuming the use of clean-technology transit vehicles. Adding higher-cost expansion of rail and rapid bus services, including projects called for in Go Boston 2030 and draft plans of the MBTA's Focus 40, could reduce GHG emissions by at least 2,000 t CO_2e. These are direct mode shift effects only and do not include GHG benefits of clustering development around transit (considered under the land use strategy), or reducing roadway congestion. Providing free transit fares for walk-access transit trips, and half-price fares for drive-access trips, could reduce GHG emissions by nearly 30,000 t CO_2e and reduce VMT to and from Boston by nearly 4 percent.

8.3.1 Policy Overview

Three groups of transit policies were tested (in addition to electrification of transit vehicles as discussed previously):

- Improving **bus efficiency and reliability** through intersection improvements, dedicated bus lanes, and other relatively low-cost operational improvements on MBTA key bus routes;
- Implementing the **rapid bus and rail projects** (Table 14) identified in Go Boston and draft plans of the MBTA's Focus 40. These identify approximately 42 miles of new rapid bus service and 35 miles of new urban rail service that residents indicated as high priorities; and
- Providing free fares for walk-access transit (mainly bus and subway), and reducing fares by 50 percent for drive-access transit (mainly commuter rail and ferries).

Table 14. List of Significant transit projects identified in GoBoston 2030 and the draft Focus 40 plan

Project	Stations Involved
LMA to JFK Rapid Bus	JFK/Umass Red Line station, Uphams Corner Indigo Line station, Dudley Square Silver Line station, Roxbury Crossing OL station, LMA T station
Fairmount Indigo Line	South Station,Newmarket,Uphams Corner,Four Corners/Geneva,Talbot Avenue,Morton Street,Fairmount,Readville
Mattapan to LMA Rapid Bus	Mattapan
Seaport to Dorchester / Widett Urban Rail	Silver Line Way station, Widett Circle
North Station to South Boston Waterfront Rapid Bus	Silver Line Way station, South Station,Post Office Square, North Station
I-90 Newton Urban Rail	Newtonville, Boston Landing, West Station, Yawkey Station, Back Bay, South Station
West Station to Kendall Rapid Bus	West Station, Kendall MBTA
West Station to Harvard Square Rapid Bus	West Station, Harvard MBTA
West Station to LMA Rapid Bus	West Station, LMA T Station

8.3.2 Modeling Approach

Operational Improvements

In the sketch model, the method for evaluating operational improvements is similar to that applied in a study for the Transportation and Climate Initiative, a coalition of 11 northeast and mid-Atlantic states and the District of Columbia [45]. Operational improvements were modeled including queue jump lanes, transit signal priority, stop consolidation, and bulb-outs at bus stops. The collective effect of these improvements is to improve travel time and reliability by moving buses through intersections faster and reducing delay at bus stops. These were assumed to be implemented on the 155 miles of "key bus routes" (as defined by the MBTA and measured using GTFS data) currently within the City of Boston. Key assumptions include:

- A travel time savings per route of 3 percent in 2030 and 5 percent in 2050 (see Cambridge Systematics, Inc. [45] for a detailed explanation);
- An average of 408 runs per week per route (GTFS data);
- An average speed of 10.4 miles per hour (MBTA bus vehicle revenue-miles divided by vehicle revenue-hours as reported in the National Transit Database [31]);
- An average ridership of 13 passengers [31];
- A ridership travel time elasticity of -0.8 (i.e., a 10 percent reduction in travel time leads to an 8 percent increase in ridership) (literature sources referenced in Cambridge Systematics, Inc. [45]); and
- Of new riders, 45 percent would have driven or used a shared mobility service (based on MBTA systemwide rider survey data [46]).

GHG benefits were considered both from reduced bus idling, and from reduced automobile VMT due to increased ridership.

In the geographic model, system-wide operational improvements were tested with the assumption of a 5 percent average decrease in transit travel time across the entire system.

Go Boston and Focus40 Investment

The impact of new rapid bus and rail services was tested in the sketch-model by assuming these services would have the same average load factor as existing MBTA services (13 for rapid bus and 26 for rail, per the 2016 NTD) and frequencies similar to existing high-capacity services. This would add 86,000 annual revenue-hours of new bus service and 192,000 annual vehicle revenue-hours of new rail service at build-out. The projects were assumed to be 50 percent built by 2030 and 100 percent built by 2050. A sensitivity test was done to examine the impact of bus fuel type (diesel vs. electric). No change was assumed to existing transit services or ridership.

In the geographic model, travel time savings by TAZ pair were estimated for in-vehicle travel time and out-of-vehicle (walking to transit stop, waiting for service) for each of the Go Boston projects. The time savings was then amortized by 30 percent to account for the unknown distribution of specific origin and destination locations and the potential competing transit services.

Fare Reductions

Fare reductions were evaluated using the geographic model. Transit monetary costs for all trips into and/or out of Boston were eliminated for walk-access trips and reduced by 50 percent for drive-access transit trips. This approach was taken, rather than applying mode-specific assumptions, because the model does not distinguish transit trips by transit mode, but it does distinguish trips by access mode. However, drive access usually corresponds to longer-distance trips by commuter rail, ferry, subway from outlying stations, and some commuter bus services.

8.3.3 VMT and GHG Benefits

The GHG benefit of operational efficiencies was estimated to be very modest, up to 400 t CO_2e per year using the sketch model (less than 0.1 percent of regional inventory). The benefit of new service was found to be larger but still modest, up to 8,200 t CO_2e per year in 2050 using the sketch model, or between 650 and 2,100 t CO_2e per year using the geographic model, depending upon the EV scenario.[13]

The relative impact of transit investments on automobile VMT will be larger; the geographic model predicts that the Go Boston transit investments will reduce auto VMT by 0.5 percent regionwide and 1.3 percent just within the City of Boston. However, some of the GHG benefits of auto VMT reduction will be offset by increased transit GHG emissions, unless new services are fully electrified and powered through a very low- or zero-carbon energy generation mix.

Reducing or eliminating transit fares provides more significant benefits, reducing VMT by 3.8 percent for regional trips or 2.7 percent for trips within Boston. This results in a regional GHG reduction of nearly 30,000 t CO_2e in 2050. Note that this estimate does not consider any GHG emissions from additional service required to accommodate increased ridership. The fare reduction scenario would increase regional transit trips by nearly 18 percent in both the peak and off-peak periods, which would likely necessitate an increase in service, at least on peak-period routes that are at or near capacity. One way to phase in this policy with less impact on service would be to reduce fares only for off-peak periods or directions of travel.

[13] And not including the 2050 "All Electric" scenario, for which the GHG benefits of demand reduction will always be zero.

8.3.4 Other Benefits

Transit investments and service improvements rarely look favorable from a GHG cost-effectiveness perspective. However, they provide important mobility benefits, moving large numbers of people along corridors that cannot be efficiently served by private vehicles. The modeled operational improvements would collectively save bus riders 2.7 million hours of travel time a year without increasing operational costs. The new Go Boston services would serve 75,000 new daily trips, increasing transit ridership by over 5 percent. Almost four-fifths of the ridership increase would occur in the off-peak periods when more capacity is available on the region's transit system.

If Boston's high-capacity transit system did not exist, the impacts on the transportation system would be significant. VMT would increase by over 10 percent, leading to over 10 million additional hours of vehicle delay with an economic value of $127 million, as well as increased GHG emissions.[14] Boston's transportation system is strained to capacity and additional investment in high-capacity transit will be needed to support future growth [47].

8.3.5 Equity Implications

Transit improvements provide city-wide access to jobs and services for those who cannot or prefer not to own their own vehicle. According to the 2015-17 MBTA Systemwide Passenger Survey, 42 percent of bus riders and 26 percent of rapid transit riders are low income [46]. One-half to two-thirds of riders on a number of bus routes that serve Boston neighborhoods are low-income. Transit travel time and reliability improvements in these neighborhoods will help residents get to jobs, shopping, school, medical appointments, and other activities on time, and free up time for other activities.

Free or reduced fares would result in a financial benefit to transit riders of $1.6 billion annually. The precise equity impacts would depend on the source of revenue used to provide the fare subsidies.

8.3.6 Policy Discussion

Most of the investments identified in Go Boston will need to be implemented through the MBTA's capital planning and with the support of federal and state funding. The City is a stakeholder in developing state and regional transit funding plans, but not the primary decision-maker, and existing funding sources are not adequate to implement the aspirational program of investments outlined in Go Boston. Rapid bus improvements (such as the recent Silver Line extension to Chelsea) are typically lower cost than rail improvements and more likely to be feasible in the short- and mid-term, although new rail service using existing tracks may also be cost-feasible.

As the owner and operator of local streets, the City has more leverage over bus efficiency improvements. Efforts are currently underway to pilot "rapid bus" improvements in a number of locations in the Boston area by testing exclusive lanes, signal priority, and other features. However, implementation will still require cooperation with the MBTA, MassDOT (on state roads), and potentially neighboring cities and towns on

[14] VMT based on systemwide transit passenger PMT (National) and alternative mode of travel from 2017 MBTA rider survey. Delay impact from historical (not Boston-specific) relationship between vehicle-travel and delay. Monetary value based on U.S. DOT value of travel time guidance.

routes that cross borders. Broad implementation of bus service improvements will require careful deliberation by the City and its residents regarding the most appropriate use of scarce road space.

Fare policy is set by the MBTA. Any significant change in fare policies would need to be coordinated at the state level with new revenue sources for the MBTA (such as the road pricing policies evaluated in this report) to make up the gap in funding from the reduced fare revenue.

8.4 Active Transportation

Walking and biking investments, like transit, provide relatively modest GHG reductions but also provide substantial “co-benefits” in the form of low-cost mobility and improved public health. A city-wide network of protected bike lanes and pedestrian improvements through “Complete Streets” roadway design could reduce regional, Boston-based GHG emissions by about 2,000 t CO_2e. Since these investments primarily serve short trips, the benefits will occur mainly within the City’s boundaries. Increasing regionwide bike use by three to four times from current levels, which might require expanded use of electric bicycles, would reduce GHG emissions by about 1 percent.

The public health benefits of active transportation have been proven to be significant. Health care cost savings alone are estimated at $0.21 per mile walked or biked, yielding an annual savings of $8 million with the referenced improvements. A more comprehensive measurement of benefits, considering the reduced mortality due to improved health, would place the valuation at about $60 million.

8.4.1 Policy Overview

Active transportation policies tested include investment in priority bicycle facilities identified in Go Boston 2030, and city-wide pedestrian improvements. Go Boston identified an additional 52 miles of on-street and separated bike lanes and shared-use paths throughout Boston neighborhoods, as well as the application of Complete Streets policies so that streets safely serve all modes and all users. An additional scenario was tested assuming a comprehensive set of bicycle facility improvements throughout the city and neighboring communities.

8.4.2 Modeling Approach

In the sketch model, bicycle investments were modeled by assuming an increase of 200,000 annual bicycle-miles of travel per new mile of bicycle facility, based on elasticities of bicycle demand in the literature and sample calculations at various levels of investment.[15] A range of investments was tested, from the Go Boston level of 52 new miles to a more extensive network of 250 new miles of protected bike facilities, which would roughly cover the entire city with bike routes spaced a half-mile apart. Alternatively, the tool can be set to a user-input target bicycle mode share. Pedestrian improvements were modeled by setting an assumed incremental share of trips less than 2 miles converted to walking. Pedestrian and bike improvements can also support emerging “micromobility” options such as electric bikes and electric scooters, that could make these forms of travel more attractive to a broader population. New bicyclists are assumed to be pulled 45

[15] For comparison this equates to about 250-300 new bicyclists a day using a facility, for a 365 day annual average.

percent from driving, similar to the prior drive mode share[16] used for new transit riders based on MBTA rider survey data [46].

In the geographic model, bicycle investments were modeled by decreasing the travel time between areas served by Go Boston projects by 42 percent. The travel time reduction is to approximate the perceived benefit of separated bicycle facilities as observed in other studies [48]. Pedestrian investments were modeled by increasing the "pedestrian environment factor" by 10 percent citywide. This factor is a component of the nonmotorized mode choice model that was calibrated as part of the original CTPS model. It is based on the availability of walking features and is impacted by the vehicle volume and speeds as well as truck routes.

A "Low Cost Mobility" scenario was run with the geographic model combining active transportation and transit operations. Bicycle travel times between all locations in the region were reduced by 42 percent, in addition to the pedestrian improvements in the City, and transit operational improvements were assumed to reduce transit travel time by 5 percent across the service area.

8.4.3 VMT and GHG Benefits

The sketch model predicts that the Go Boston bike investments will reduce VMT and GHG modestly, by about 0.1 percent at Go Boston investment levels or up to 0.5 percent (5,000 t CO_2e in 2050) for a city-wide network with half-mile spacing. These correspond to between 8 million and 50 million new miles biked in 2030, with the larger figure representing approximately double the estimated current amount of bike travel. Expanding bike use far beyond these levels might require greater use of electric bicycles to reduce travel time and effort for longer trips. Converting an additional 5 percent of trips less than 2 miles to walking (current share: estimated 33 percent) would decrease GHG by 0.3 percent in 2030. It should be noted that the GHG reductions are expressed relative to the *regional* inventory, whereas only City of Boston investments are assumed in this assessment; investments in other cities would increase the regional impact.

The geographic model predicts that the city-wide active transportation investments will eliminate 89,000 daily VMT, nearly all within the City of Boston, corresponding to 2.9 percent of the VMT from trips starting and ending in Boston (or 0.9 percent of regional VMT). This corresponds to a similar GHG reduction of 4,000 to 8,000 t CO_2e per year under most EV scenarios (less in 2050 under the clean vehicle scenarios 4 and 5), or about 0.6 percent of baseline transportation sector GHG emissions in 2030 and 2050.

The Low Cost Mobility scenario (including City-wide walking and regional biking and transit operations) was predicted in the geographic model to reduce light-duty VMT by 3.3 percent in 2050 and GHG emissions by 26,000 t CO_2e or 2.4 percent of the inventory, assuming baseline vehicle technology.

Assuming that some fraction of bikes are electric has a minimal impact on GHG emissions, as the energy consumption of e-bikes is quite low relative to automobiles (estimated to be 0.017 kwh/mi).[17]

8.4.4 Other Benefits

Like transit, walking and biking investments may show only modest GHG reductions, but they also provide important mobility benefits, allowing more people to reach destinations using low-cost modes. The

[16] "Prior drive mode share" is defined as the percentage of transit riders (or bicyclists, or shared mobility users) who would have driven a vehicle if the alternative mode had not been available.

[17] 0.5 kwh per 30 miles [49].

geographic model predicts that for the Go Boston active transportation investments, PMT by active modes within the City of Boston would grow by 120,000 daily miles or 11 percent. Bicycling and walking can sometimes be faster than any other mode of travel for shorter trips in the most congested areas of Boston. Bike and walk investments also provide significant public health benefits by promoting physical activity and thereby reducing heart disease, diabetes, and other illnesses. The health care cost savings from physical activity has been estimated to be about $0.21 per mile walked or biked.[18] This represents a benefit of over $8 million per year at the modeled increase in walk and bike PMT. These benefits would be up to $60 million per year if non-health care costs of reduced mortality and morbidity were included at a value of approximately $1.50 per mile total.[19]

Figure 27 shows the change in active PMT by neighborhood for the Go Boston investments scenario. The percent change is greatest in the more outlying neighborhoods (up to 20 percent), although these neighborhoods are also starting from a much lower baseline of walking and biking.

8.4.5 Equity Implications

Walking and biking are the lowest-cost forms of travel, with walking virtually free and bicycling costs estimated at only 2 cents a mile compared to up to 55 to 60 cents a mile for driving a car or around $1.70 to $2.75 per trip using public transit. Improving conditions for walking and biking can therefore benefit low-income travelers who may be looking for a low-cost travel option but are uncomfortable biking or walking with heavy traffic.

8.4.6 Policy Discussion

Walking and biking investments are largely under the City's control, as it has jurisdiction over all local streets and a significant say in the design of state roads. Furthermore, regional (Boston MPO) and state (MassDOT) policies also support Complete Streets and any road work funded by the state must accommodate bicycle and pedestrian users. Availability of adequate funding is one barrier to implementing this policy; simple changes (e.g., lane striping) can be made over time as road work is performed, but more complicated changes (such as constructing off-street or separated paths) may increase project expenses compared to simple road rehabilitation or reconstruction.

Other supportive policies, such as adequate bicycle parking, enforcement of traffic laws for all road users, and bicycle skills education for cyclists and motorists, are also important to complement infrastructure

[18] Gotschi analyzed three investment plans in Portland, Oregon [50]. Bicycle health benefits are estimated using a per-capita health care costs of $544 annually attributable to inactivity (i.e., less than 30 minutes of activity per day), which he derives from three literature sources published in 1987, 1996, and 2001, with values adjusted for inflation. New bicyclists are assumed to realize these benefits by increasing physical activity from 15 to 45 minutes daily. Gotschi also cites the World Health Organization's Health Economic Assessment Tool (HEAT) for cycling, which uses a relative risk estimate for all cause mortality of 0.72 for 3 hours of bicycling to work per week, from a large Danish cohort study. Gotschi's resulting estimates of cumulative bike miles and cumulative health care savings between 1991 and 2040 equate to about $0.18 in benefit per additional bike mile of travel, which was inflated to a 2016 value of $0.21 per mile. The estimate does not include air pollution or traffic safety impacts.

[19] Rabl and de Nazelle estimate that switching from driving to bicycling for a 5 km one-way commute 230 days per year provides physical activity benefits worth 1,300 Euros [51]. Converting to U.S. units this equates to a benefit of about $1.11 per mile of bicycling. However, this study is based on valuation of a life saved. The New Zealand Transport Agency's Economic Evaluation Manual provides a value of $1.92 per mile (converted to 2008 dollars) for improved health and reduced congestion from active transport [52]. About 10 percent of this value is due to congestion reduction, 3 percent to safety, and 87 percent to health, making the health benefit $1.72 per mile. Analysis by Cambridge Systematics using the World Health Organization Health Economic Assessment Tool also finds avoided mortality values in the range of $1-2 per mile walked or biked.

improvements. However, the data are not available to quantify the impacts of these policies separate from bike facility investment.

One significant policy issue that will require further consideration in the future is the **prioritization of road space** for different users (auto travel, buses, cyclists, pedestrians, and car parking). The projects proposed in Go Boston will expand Boston's bike infrastructure, but not to the levels seen in some of the world-leading cities of northern Europe, which see bike mode shares of 20 to 40 percent or more, although these cities also have population densities seen only in Boston's core neighborhoods, as well as much higher fuel and auto ownership costs. To achieve substantial bike mode share in Boston (e.g., 10 percent or more, representing an increase of at least four times from current levels) would at a minimum require a comprehensive network of bike facilities mainly separated from traffic. Given Boston's space-constrained streets, this would require re-prioritizing street space away from cars (i.e., reducing travel and/or parking lanes). This may become more feasible over time as shared mobility services, automated vehicles, and other technology advancements make it possible to do this without overly impacting mobility for non-cyclists.

CASE STUDY: BIKING IN BOSTON

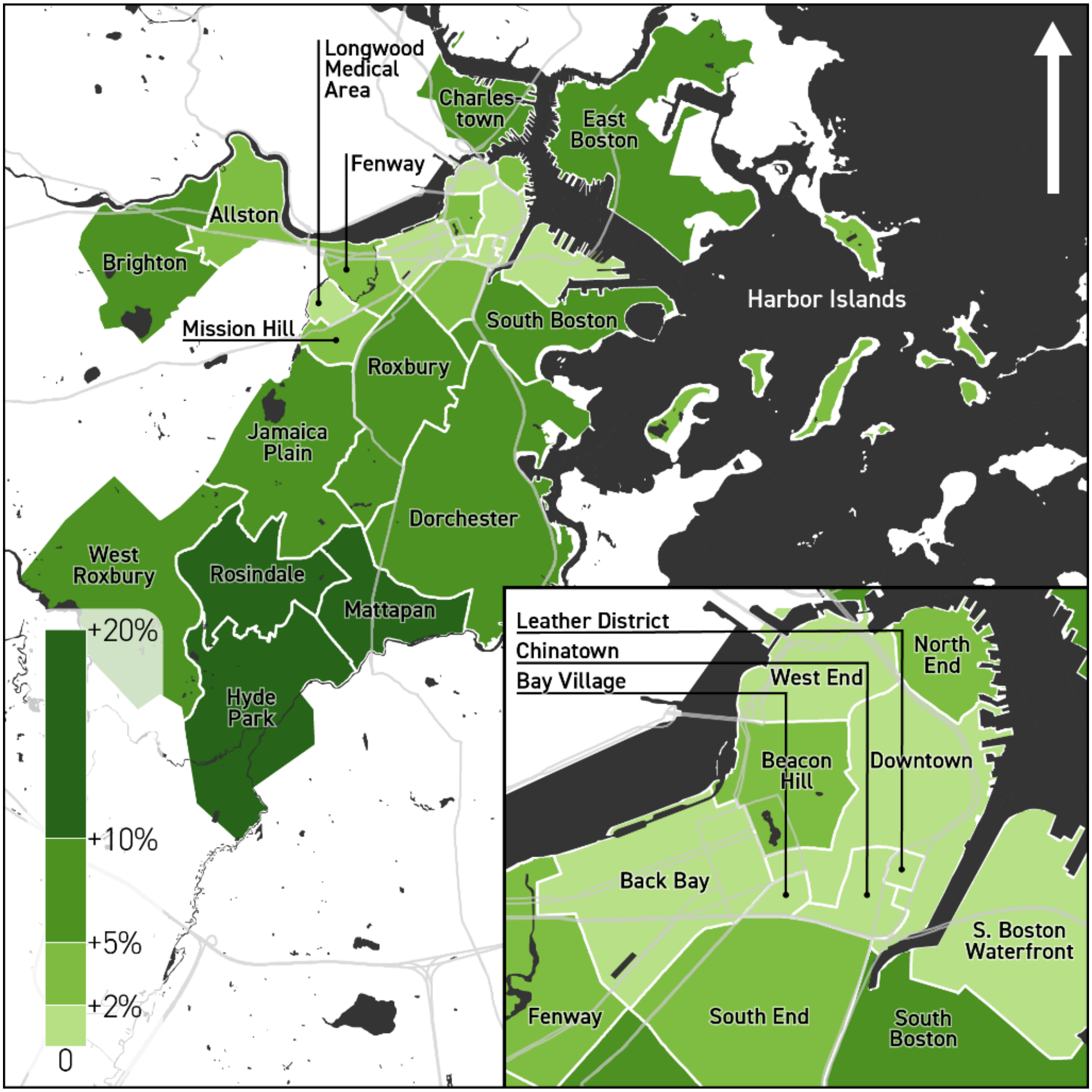
Cycling activity and bicycle infrastructure has steadily become more prominent in Boston in recent years. Currently 2-3% of Boston residents are estimated to commute via bike daily [53]. The city of Boston though its bike count program, has counted 40,000 daily bike travelers at 62 key locations [54].

With its discordant street layout and variable climate, Boston may not seem like a cyclist's paradise, but the there are many opportunities to create an ecosystem that is safe, convenient and carbon-neutral. The foundation of such an ecosystem is sufficient roadway bicycle facilities. Dedicated bicycle lanes, including those offering a protective divider have been installed in the City and its neighboring communities in recent years. These have the potential to increase both the safety and speed of a bicycle commute. Efforts to clear these lanes of snow and debris ensure that cyclists can continue to commute through the winter. Bike share programs, such as Blue Bikes, have also made cycling more accessible to the City's residents. In 2018 the Blue Bikes program significantly expanded, leading to a large increase in ridership that has spawned 1.7 million trips. At an average trip length of 1.2 mile, Blue Bikes has provided the city's residents with a convenient and zero-carbon last mile solution.

Despite these investments, several fatal accidents in recent years demonstrates that there is more work needs to be done. A number of these accidents occurred in heavily trafficked areas that lack sufficient bicycle facilities.

Investments in bicycle facilities are unlikely to have a large carbon savings. However, a healthy cycling environment has the potential to save lives, increase physical activity, reduce demand on the public transit system, and shorten commute times. Promoting a system that leads to such benefits improves the quality of life within the city, attracting more people to live a low carbon lifestyle within the city.

Figure 27. Active PMT Increase by Neighborhood, Go Boston investments



8.5 AUTONOMOUS VEHICLES IN PRIVATE OWNERSHIP

Autonomous (self-driving) vehicles have the potential to transform transportation in ways that are not yet fully understood. AVs owned by private households are likely to increase vehicle-travel, as travel becomes less onerous, and people unable or unwilling to drive can use a personal vehicle. However, they should also make travel more energy-efficient per mile. The City and/or State may need to implement policies (such as pricing) to manage AV travel, especially to limit or discourage zero-occupancy vehicle (ZOV) use for unproductive purposes (e.g., to avoid parking charges).

There is considerable uncertainty over when AVs will be ready for deployment on public roads, and over what timeframe economics and consumer acceptance will support broad market penetration. Sources suggest that up to 10 to 20 percent market penetration could be achieved by 2030, and 40 to 60 percent by 2050. We estimate that latent demand (induced VMT) could be in the range of 10 to 20 percent, assuming that ZOV travel is managed, although this is highly uncertain. On the other hand, research suggests that self-driving vehicles could be on the order of 10 percent more energy-efficient than a human driver at low to moderate market penetration levels, or 15 to 20 percent at high market penetration levels as vehicles “platoon” and congestion is reduced. Under these conditions, AVs in private ownership would have little net effect on GHG emissions. They should have net positive emissions benefits if AVs use clean technology (e.g., electric drive) at a greater rate than the overall vehicle fleet.

8.5.1 Policy Overview

This “strategy” is actually a combination of a scenario assessment (introduction and increased market penetration of autonomous, or self-driving, vehicles) and testing of policies to regulate those vehicles and how they are used. This strategy addresses autonomous vehicles in private ownership, i.e., that would be purchased by a household and substitute for a privately-owned human-operated car or light truck. The autonomous vehicles may or may not be “connected” (i.e., communicating with other vehicles and/or the local infrastructure). It is also possible that they would be driven by a human operator part of the time.

AVs will cost more than a human-operated vehicle, at least in the foreseeable future, but will likely cost less to operate per mile because of lower fuel and insurance costs. Many experts believe that AVs will first be introduced as part of corporately managed shared-vehicle fleets (e.g., Uber or Lyft) to provide shared mobility services. The use of AVs in shared mobility services is considered in the “smart mobility” strategy.

AVs have the potential to either increase or decrease GHG emissions. In private ownership, they are likely to increase VMT (1) as some people travel more because travel is less onerous, (2) by expanding vehicular mobility to people who are not able or willing to drive themselves (e.g., elderly, disabled, or children), and (3) by allowing vehicles to drive themselves empty (e.g., to find a parking space or pick up a family member), also known as zero-occupancy vehicle travel. However, GHG emissions per vehicle-mile are likely to be reduced, since AVs will operate more efficiently than a human driving a car. AVs are also likely to increase the capacity of the street system by allowing vehicles to travel at closer headways and reducing congestion-causing crashes, which should also reduce energy use and emissions. The net effect of all these impacts on systemwide GHG emissions is not yet known.

Policies to regulate AVs to minimize potential increased VMT and GHG impacts are still in their infancy. Some options that have been considered include:

- Restrictions or pricing on zero-occupant vehicle travel;
- Requirements for AVs registered in the city to be clean technology (e.g., electric or other zero-emissions);
- Additional registration fees or excise taxes to discourage ownership or raise revenue to support mitigation measures; and
- Prohibitions on private AV ownership and use.

8.5.2 Modeling Approach

The sketch model is set up to allow testing of the impacts of the various uncertainties described above. The key uncertainties and ranges of options tested are described in Table 15.

Table 15. AV Key Assumptions

Key Input	Suggested Value(s)	Source/Notes
Market penetration (% of vehicle stock)	Up to 10-20% in 2030 Range of 40-60% by 2050	Based on source cited in Litman [55] for moderate cost premium
Increase in travel per vehicle	10-20% (5-10% for latent travel demand, maybe another 5-10% to account for ZOV travel)	Latent demand based on sources cited in Litman [55]
CAV energy efficiency improvement relative to human-operated vehicle	~10% at low to moderate market penetration levels (<30-40%), 15-20% at high market penetration levels	Various studies on eco-driving and connected vehicles [56]
AV technology	EV (regulated) or light-duty fleet composition (unregulated)	

In the geographic model, the impact of unmanaged private AV ownership was tested with the following input changes affecting private vehicle travel throughout the Boston region:

- 20 percent market penetration (2030) or 50 percent (2050);
- 25 percent reduction in the value of in-vehicle travel time;
- \$0.05/mile reduction in operating cost;
- 75 percent reduction in parking cost (assuming the AV can drive to a cheaper, remote parking spot); and
- 10 percent decrease in zero-vehicle households.

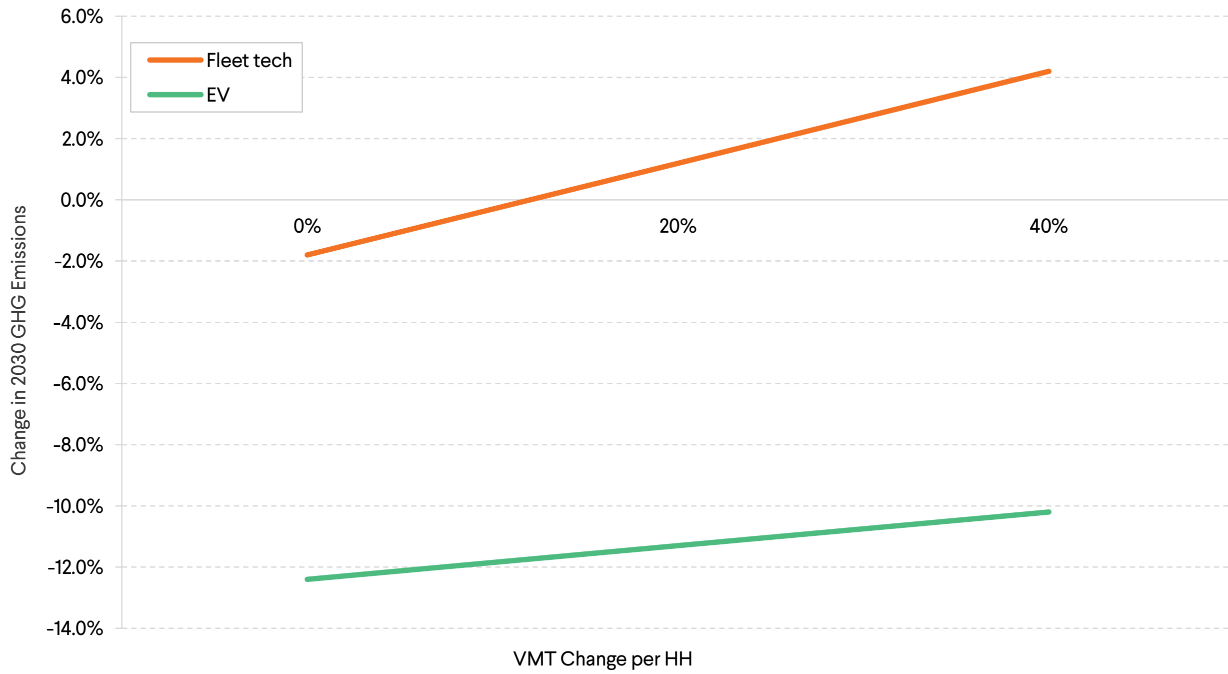
A “managed” scenario was also tested, in which user fees were applied to offset the travel time, operating cost, and parking cost savings. The reduction in zero-vehicle households was retained. Note that these cost changes and offsets are assumed to apply to all trips starting and/or ending in the City of Boston.

8.5.3 VMT and GHG Benefits

The geographic model predicts that the unmanaged CAV scenario increases light-duty VMT by 2 percent in 2050 for 20 percent market penetration and 6 percent for 50 percent market penetration. Not surprisingly, the managed scenario limits the VMT increase to a much smaller 0.5 percent. Assuming a 10 percent efficiency increase per VMT but no requirements for clean vehicle technology, GHG emissions increase by up to 1 percent in the unmanaged CAV scenario. For the managed scenario, emissions decrease from the 2030 or 2050 baseline by 1 to 3 percent.

Figure 28 illustrates the effects of changing the assumptions about the VMT increase per household and the CAV technology, for market penetration of 25 percent and efficiency improvement of 10 percent, based on the sketch model. At the fleet average technology, no change in VMT provides a 2 percent decrease in transportation GHG emissions; GHG increases if the VMT per household goes up by more than 12-13 percent. If all CAVs are required to be electric, GHGs will be reduced by at least 10 percent, even if VMT per household increases substantially. (This is assuming the very modest baseline levels of electrification in 2030; higher levels of baseline electrification will reduce the GHG benefit of clean CAVs.)

Figure 28. CAV Sensitivity Analysis



8.5.4 Other Benefits

CAVs in private ownership have the potential to provide mobility benefits for people by making travel easier, but this will also reduce VMT and possibly pull travelers from other modes. The geographic model suggests that a 20 percent CAV market penetration will have a very modest negative impact on transit ridership and nonmotorized travel, reducing each by 2-3 percent. The increase in VMT under the unmanaged scenario could marginally increase air pollution (assuming mainly ICE technology). Safety would presumably improve due to the prospective safety benefits of self-driving cars. Congestion could increase or decrease depending on how operational efficiency gains trade off against increased VMT.

8.5.5 Equity Implications

CAVs may be helpful in expanding private mobility options for people who cannot easily drive, such as seniors or persons with certain disabilities. However, these benefits will mainly accrue to wealthier people who can afford the added cost of a self-driving vehicle (although purchase costs may be offset by lower insurance costs). The long-term costs of CAV technology and the incidence on different income groups are not yet known.

8.5.6 Policy Discussion

While the perceived benefits of AVs to travelers are at this point not well understood, it is likely that unmanaged AVs in private ownership will increase VMT and potentially GHG emissions. Pricing and/or other policy levers to internalize external costs should be investigated, including metering of travel to price AV travel according to vehicle occupancy. An outright ban on private AV ownership could also be considered, or restrictions on AV operations under selected conditions; however, it seems preferable to investigate policy options that can leverage the potential mobility, safety, and environmental benefits of AVs while mitigating negative impacts.

8.6 Smart Mobility (Shared Vehicle Services)

Smart mobility options, which may involve ride-hailing services, microtransit, and “micro-mobility” options such as electric scooters and bikes, have transformative potential. In particular, the introduction of automated vehicles in ride-hailing services would have the potential to greatly expand service and lower costs in this emerging industry, providing a more competitive alternative to vehicle ownership.

Ride-hailing that serves primarily single-passenger trips will likely increase VMT and GHG emissions, as some riders are drawn from transit, walking, and biking, and due to the extra fuel used in “repositioning” vehicles to serve other customers. Reductions in auto ownership will provide an offsetting benefit, although the auto ownership impacts of current and future services are not well understood. In the future, smart mobility services will reduce GHG emissions only if they are used mainly by multiple occupants <u>and</u> they rely on clean vehicle technology. Similarly, microtransit has potential to reduce GHG, but only if clean vehicles are used at relatively high occupancies. State and city policy changes will be needed to allow, and define the conditions for, operation of driverless vehicles. City and state policies can also shape the evolution of these services, for example, by charging higher fees on zero- or single-passenger travel, and by requiring vehicles operated in fleets to meet advanced emissions standards.

8.6.1 Policy Overview

While the term “smart mobility” encompasses a host of technology-enabled mobility solutions, the focus in this report is on shared vehicle services, specifically ride-hailing (a light-duty car or truck carrying up to three non-owner passengers) and microtransit (a van or small bus carrying four to 15 passengers). While shared mobility services are currently operated by humans, in the future, they could be provided by fleets of self-driving vehicles operated by for-profit or nonprofit organizations.

Like the autonomous vehicles strategy, the smart mobility (SM) strategy as defined here is a combination of externally driven technology scenarios and local management policies. As noted in the baseline documentation, shared mobility services (including ride-hailing, taxis, and carsharing) are currently estimated to make up around 5 percent of VMT in the Boston inventory. The baseline forecast did not assume any change in this level, since reliable forecasts of smart mobility use are not currently available.

Smart mobility services may increase or decrease VMT and GHG emissions. VMT will increase due to the requirement of SM vehicles to reposition themselves to pick up another user after completing a trip (deadheading). However, they can support decreased private vehicle ownership which has been shown to reduce VMT per household. The average occupancy (number of riders per vehicle) of an SM service is also a key driver of the overall effect on GHG. Currently, the technology of SM vehicles is similar to private vehicles; however, the rise of corporately owned AV fleets would support the wider use of electrification technology (hybrid or all-electric) because the intensive use of these vehicles would reward the operating cost savings.

Potential policies to leverage benefits and manage the GHG impacts of smart mobility include:

- Policies to permit operation of automated vehicles for shared-mobility services under defined conditions;
- Trip or VMT-based fees that are scaled according to vehicle occupancy;
- Requirements that fleet-operated smart mobility vehicles be clean technology;
- Requirements that fleet operators “cross-subsidize” trips to increase the cost of ride-alone and decrease the cost of shared-ride trips;
- Restrictions on the extent of operation of zero-occupancy AVs.

8.6.2 Modeling Approach

In the sketch model, hypothetical scenarios of increased SM market penetration rates were assumed. The sketch model was also used to examine the effects of changes in technology (fleet average or all EV), vehicle occupancy for work and non-work travel, the VMT added by trip circuity (i.e., going out of the way to serve multiple passengers) and deadheading (repositioning between rides), the drive mode share of riders if they did not use smart mobility, and changes in household auto ownership.

SM does not exist as a mode in the CTPS model, so for the geographic model, the mode was calibrated with a mode-specific constant roughly reflecting current conditions. The model was also used to examine how much SM usage rates might increase if the attractiveness of the service provided was comparable to a privately owned vehicle (i.e., mode choice is based only on the difference in travel time and cost). Ride alone and shared ride options were modeled separately; the cost per trip was decreased and the travel time increased for shared ride vs. ride alone options. Costs for current services were estimated by reviewing published formulas for Uber and Lyft fares as well as recent trip receipts. Household vehicle ownership (percent of zero-vehicle households) was manually adjusted. Key assumptions for SM are shown in Table 16.

Table 16. Smart Mobility Key Assumptions

Key Input	Suggested Value(s)	Source/Notes
Market penetration	10-30%	
Baseline vehicle occupancy	Shared vehicles: 1.1 – work trips; 1.6 – non-work trips Microtransit: 6.0	Shared vehicles: Average occupancies for all work and non-work travel from the 2009 National Household Travel Survey. Microtransit: average person-miles of travel per VMT for Vanpool mode from the National Transit Database.
Prior drive mode share	41%	Respondents who said they would have traveled by private vehicle or taxi if the ride-hailing service were not available [57].
Circuity/deadhead factor[a]	1.3 – 1.6	Analysis of RideAustin dataset by CS - 35% deadhead by distance; 19-21% of trip lengths out-of-service for ridehail, taxis at 44% [58]; 69% added VMT in Denver [59]; ratio of 1.6 total miles to passenger miles average from Chicago, New York City, San Francisco [22].
Cost per trip of shared ride relative to ride alone	-30%	Estimate

Key Input	Suggested Value(s)	Source/Notes
Time per trip of shared ride relative to ride alone	+30%	Estimate
Household vehicle ownership change	-0.2 vehicles/HH[20]	Change in vehicle ownership for carshare participants in a nationwide survey [60].

[a] Defined as the ratio of total vehicle VMT to VMT that would be required to transport individual passengers directly between their origin and destination (i.e., if each passenger drove alone).

8.6.3 VMT and GHG Benefits

Based on the sketch model, Figure 29 and Figure 30 illustrate how GHG emissions would change as vehicle occupancy increases above current levels and prior drive mode share goes up or down. Figure 29 assumes that smart mobility vehicles are the same as the baseline fleet in 2030; Figure 30 assumes they are all electric. Both figures assume a 10 percent shared mobility mode share. An occupancy increase of 0.2 means the work trip occupancy would increase from 1.1 to 1.3 persons per vehicle and non-work from 1.6 to 1.8 persons per vehicle. Figure 31 shows how GHG would change for different assumptions about auto ownership, vehicle technology, and occupancy, for a constant 41 percent prior drive share and 10 percent market penetration. The assumed circuity/deadhead factor in all figures is 1.5.

Figure 29 shows that under the baseline assumptions, a 10 percent shared mobility mode share will increase GHG by about 4 percent. GHG impacts at different smart mobility mode shares would scale proportionately. To decrease GHG emissions, vehicle occupancy would need to increase by 0.8 persons per vehicle – a rather extreme change as it would mean an average of nearly 2 people in a work trip vehicle and nearly 2.5 in a non-work trip vehicle. If the SM users were pulled mainly from driving instead of other modes, the GHG increase would be smaller but, most likely, still positive.

Figure 30 shows that if all SM vehicles were electric, GHG would show essentially no change under current prior drive mode share assumptions. The occupancy has less effect on the emissions change in this situation due to the higher efficiency of EVs. Figure 31 shows that if the 10 percent shared mobility use supported a 5 percent decrease in auto ownership, GHG emissions could decrease with baseline technology if occupancy was increased by only 0.2 persons per vehicle, and would decrease more (about 4 percent) if all SM vehicles were electric. (In the sketch model, a 5 percent decrease in auto ownership was assumed to decrease non-shared mobility VMT by 5 percent.)

[20] The evidence regarding impacts of smart mobility on auto ownership is very limited and to date the most robust studies have looked at carsharing impacts. For example, Martin and Shaheen surveyed carsharing members throughout the United States and found that of the households surveyed, the average vehicle ownership was 0.47 before joining a carshare service and 0.24 after [60]. This is a nearly 50 percent reduction, but starting from a lower level than the average U.S. household. In a study of the San Francisco City CarShare program, Cervero and Tsai found that when people joined, nearly 30 percent reduced their household vehicle ownership [61]. A recent nationwide survey found that household vehicle ownership is similar for non-transit, ride-hailing users vs. the rest of the car-centric population (only 3-5 percent not owning a vehicle), but that 24 percent of respondents who used both transit and ride-hailing services did not have a vehicle in the household. Nine percent of ride-hailing users indicated they had disposed of one or more household vehicles [62].

Figure 29. Change in 2030 GHG Emissions for Shared Mobility, Fleet Average Technology

Note: Assumes overall shared mobility mode share of 10 percent.

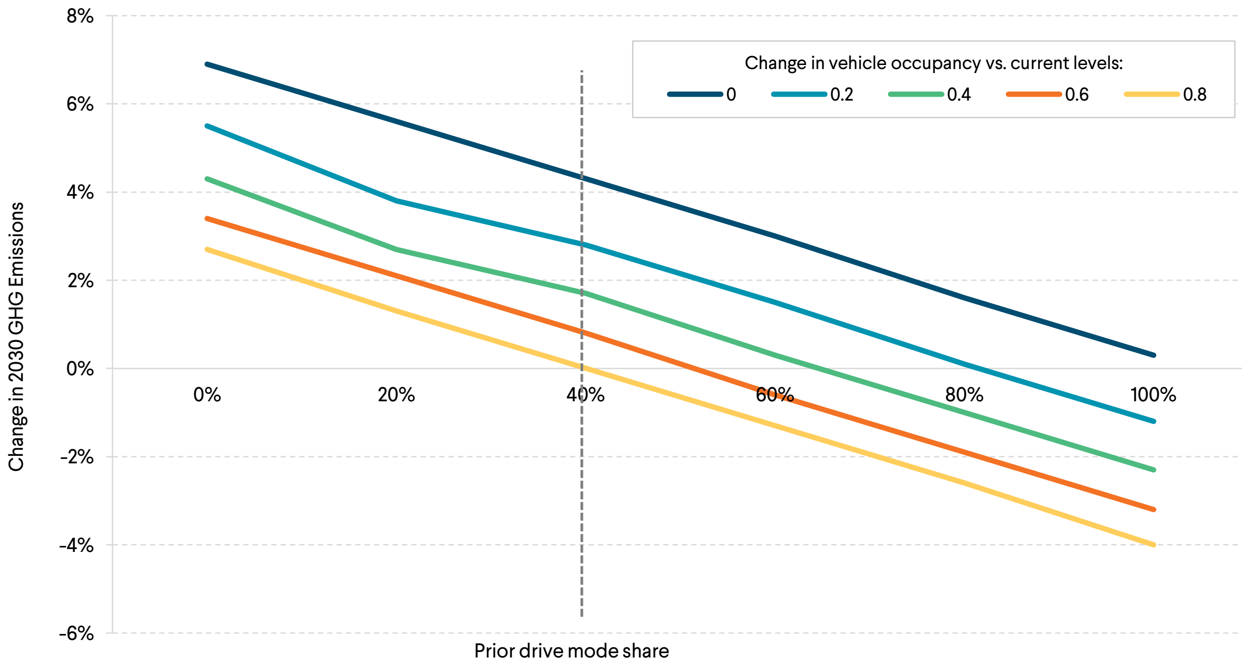


Figure 30 Change in 2030 GHG Emissions for Shared Mobility, EV Technology

Note: Assumes overall shared mobility mode share of 10 percent.

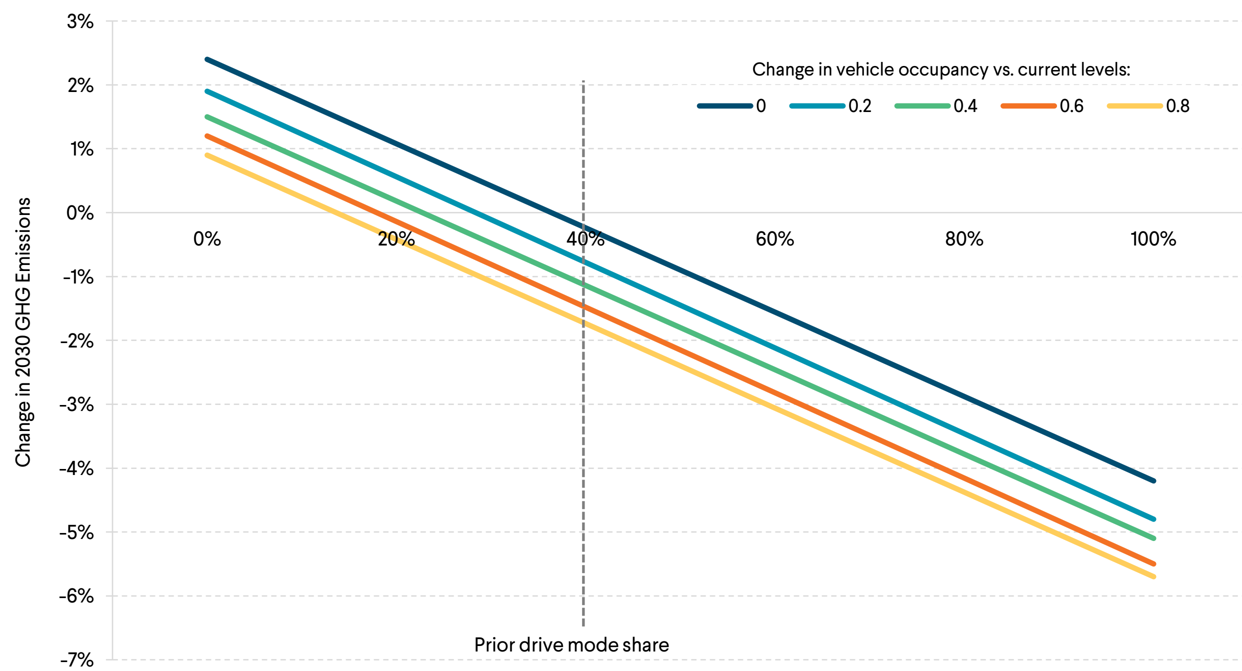
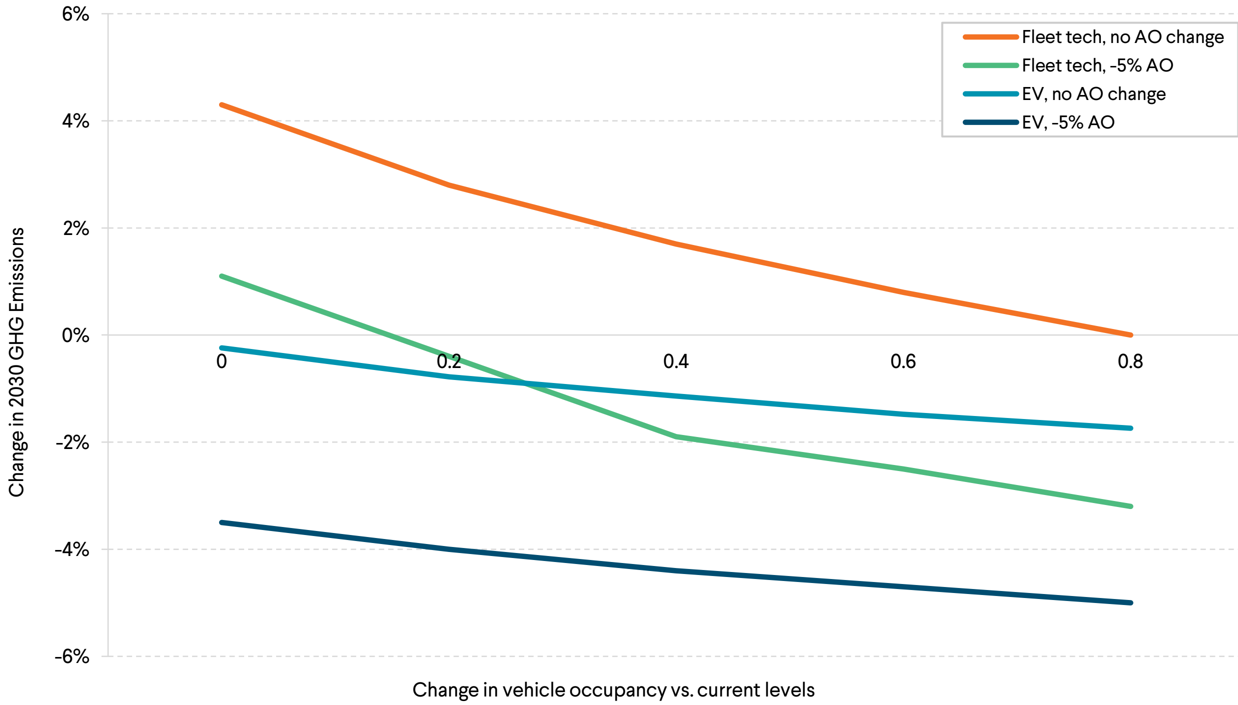


Figure 31. Change in 2030 GHG Emissions for Shared Mobility, by Technology and Auto Ownership (AO)

Note: Assumes overall shared mobility mode share of 10 percent.



SM was also evaluated using the geographic model. One scenario assumed a modest (6 percent) increase in SM mode share and a negative SM modal constant that limits its attractiveness for many travelers (e.g., because of the additional hassle of using an app, ability to store personal possessions in one's own vehicle, risk of riding with a stranger, or simply unfamiliarity with the service). With no management policies in place and no auto ownership effects, direct VMT would increase by about 3 percent, with total VMT increasing about 5 percent assuming a 1.3 deadhead/circuity factor. GHG emissions would go up by about 3 percent from the 2030 baseline. Applying policies to subsidize shared ride trips (reduce cost by $1/mile) through surcharges on ride alone trips (increase cost by $1/mile) would only marginally affect the VMT increase. If the SM vehicles were electric, automated vehicles, GHG emissions would be reduced by 1-2 percent.

To test more extreme assumptions, another scenario was evaluated in which SM is assumed to be similar in attractiveness to driving, and in which widespread availability of SM services would decrease auto ownership by 20 percent. With this assumption, the smart mobility mode share would be about 28 percent, roughly equally split between ride alone and shared ride. Direct VMT (i.e., carrying passengers) would be reduced by 8 percent regionwide, with larger percentage reductions occurring for longer distance trips and almost no change for trips just occurring within the City of Boston. After accounting for deadheading/circuity, the VMT reduction would be less than 1 percent and the GHG reduction would be under 1 percent with existing technology, or 22 percent with clean technology (and non-SM vehicles at baseline technology levels).

Microtransit was evaluated using the sketch model, but not included in the geographic model. At a market penetration of 5 percent of trips and average occupancy of 6 persons (over the entire daily drive cycle of the vehicle), it is estimated to reduce GHG emissions by 2.8 percent in 2030 if EVs are used; if vehicles are the same technology as the average MDT fleet GHG emissions would increase by 1.3 percent. Raising the average occupancy to 8 persons provides a 3.6 percent reduction in 2030 with EVs and an 0.6 percent GHG reduction with standard technology.

8.6.4 Other Benefits

If using conventional vehicle technology, smart mobility would have impacts associated with any VMT increase, including modest increases in air pollution and crashes. The use of AV and EV technology would mitigate these negative impacts.

SM tends to pull travelers from transit and nonmotorized modes, with potential negative public health impacts. The increase in SM use under the 28 percent market share in the geographic model would pull trips from both transit (net 10 percent decrease) and nonmotorized (net 17 percent decrease), even with the reduced auto ownership. The transit decrease would occur almost entirely in the off-peak periods, when trips would decrease by 25 percent; there would be little change in peak period transit ridership.

8.6.5 Equity Implications

Evidence suggests that existing SM services have provided mobility benefits to lower-income travelers by providing a relatively low-cost mobility option that is available when transit, nonmotorized, or other rideshare options are not convenient.[21] These benefits may increase in the future if AVs bring down the cost of SM operation. However, policies must ensure that services are equitably provided to low-income and minority neighborhoods as well as to all travelers, including those with disabilities.

8.6.6 Policy Discussion

SM services can be a core component of a climate mitigation and transportation management strategy. SM services can serve as last mile solutions, increase accessibility, and lower congestion. To achieve these goals, SM services must use clean vehicles, pull people mainly away from solo point-to-point driving, and/or be shared rides. If SM services are unable to do so, they will likely increase emissions and congestion. Requirements for clean vehicle fleets are one public sector approach to steer SM in a GHG-reducing direction. Pricing incentives can also help steer people towards shared rides, and experts have speculated that operators of SM-AV fleets will have incentives to maximize revenue which means maximizing vehicle occupancy. However, even a fairly substantial price incentive or cross-subsidy was found to have only a moderate effect on the proportion of ride alone vs. shared ride use. For example, in the geographic model a $1 per mile cross-subsidy from ride-alone to shared-ride decreased the number of ride-alone trips by about one-fifth, from 1,091,000 to 865,000, with a slightly larger increase in the number of shared-ride trips (from 1,164,000 to 1,437,000) – reducing the ride-alone fraction of SM trips from 43 to 38 percent and decreasing VMT by 3 percent.

Broader scale market penetration of these services and better ridematching and travel-optimization algorithms may help overcome the inherent travel time/convenience penalty associated with ridesharing. Integrating multi-mode trips (e.g. share-ride to transit, or walk to a pick-up point) with SM apps and algorithms could reduce costs, time, and emissions. Successful deployment of such SM services will require

21 A Boston area survey [57] found that reported incomes of ride-hailing users are similar to the region overall, and a substantial number of trips are made by people from households earning less than $38,000 per year.

partnerships between transportation network companies, the MBTA and the City of Boston to identify areas for optimization.

8.7 Pricing Vehicle Travel

Travel pricing has the greatest potential impact of any travel demand reduction policy. Appropriate pricing can help travelers internalize the costs of their decisions and steer them to the most efficient alternative for each trip. A “cordon price” of $10-15 per day for entry into central Boston, similar to pricing implemented in London, Oslo, and Singapore, could reduce GHG by 2 to 3 percent and VMT by up to 4 percent in 2050, accounting only for mode shifts and not for any changes in the overall patterns of trips or activities. A parking fee equivalent to $5 per trip could reduce VMT by nearly 12 percent within Boston and 8 percent regionally, reducing 2050 GHG by 61,000 t CO_2e or 5.6 percent. At the state level, a $30 per ton carbon fee could further reduce GHG by 1.5 percent and a $0.20 per mile VMT fee could reduce GHG by 2.3 percent. Collectively, the combined impacts of aggressive pricing, including a cordon charge, $5 parking fee, $0.20 per mile VMT fee, and free or reduced transit fares, could reduce VMT by at least 18 percent.

Pricing policies provide a significant revenue stream that could be reinvested in clean transportation and/or used to reduce other forms of taxation. Pricing needs to be implemented with caution so that low-income households are not overly burdened. Pricing can be done equitably by reinvesting revenues in transit, biking, walking, and other travel alternatives; providing discounts for low-income travelers; or providing tax breaks for low-income households that offset the higher cost of travel.

8.7.1 Policy Overview

Pricing has been found in other studies to be one of the most effective policies at managing travel demand. Currently the cost of a private vehicle trip is less likely to be recognized by travelers than fare-based transit or commuter rail trip. Pricing can help travelers internalize the external costs of a trip. While it does impose an additional cost on travelers, it also generates revenues that can be reinvested to improve the transportation system, or to support equity objectives (e.g., through subsidies or tax rebates to low-income households). A variety of pricing mechanisms are available, some of which are already implemented at the state or local level in Massachusetts. The City’s pricing policy options include:

- Working with the Commonwealth to support **new statewide or regional pricing mechanisms** such as a carbon fee or VMT fee. (In the long run some form of alternative funding will be necessary to replace dwindling gas tax revenues.)
- Working with the Commonwealth to introduce **congestion pricing** by varying tolls by time of day on existing tolled facilities.
- Introducing a **cordon charge** for driving into central Boston (with the cordon area to be determined), similar to cordon charges implemented in London, Oslo, and Singapore. The charge might vary by time of day and by type of traveler (e.g., passenger vs. commercial vehicle, resident or non-resident.) This would likely require cooperation with MassDOT and, if charges are implemented on Interstate highways, permission from the Federal government.
- Expanding **curbside parking pricing management** (such as piloted in Back Bay) to ensure availability of parking at all times, reducing fuel wasted in parking searches while also encouraging use of other modes. This could include expanding metered spaces, expanding meter hours, curtailing holiday discounts, dynamic pricing of parking spaced based on demand.

- Charge for resident **on-street vehicle parking permits,** with a graduated cost scale for additional permits procured by a household. This could help discourage auto ownership although the burden would fall entirely on residents without access to off-street parking.
- Applying a surcharge on existing **paid parking** or a fee on any parking space. A surcharge on existing paid parking would affect a minority of trips; according to the 2011 Massachusetts Household Travel Survey, less than 7 percent of workers traveling into Suffolk County (by any mode) pay for parking and less than 2 percent of non-work trips involved paid parking.
- Selectively **discounting or exempting** EV's from and other clean vehicles in the above pricing policies as well as **registration fees or excise taxes**. This could provide a modest incentive for households to purchase clean (e.g., electric) vehicles, but may conflict with goals to reduce vehicle ownership and usage

These policies affect travel and GHG emissions in different ways. Some primarily affect vehicle ownership decisions, others primary affect the amount or location and timing of travel, and others also encourage fuel-efficient or low-carbon vehicle use. Table 17 identifies the primary effects of each pricing mechanism and whether it is currently in use.

Table 17. Pricing Mechanisms and Their Effects

	Implementation			Primary Effects				
Pricing Policy	City	State	Currently used in MA?	Reduce Vehicle Trips	Reduce VMT	Change Time and/or Location of Travel	Reduce Vehicle Ownership	Encourage Carbon-Efficient Vehicle Ownership
Parking fees	✓		✓	✓				
Excise taxes	✓		✓				✓	✓
Registration fees		✓	✓				✓	✓
Cordon price	✓	✓		✓		✓	✓	
Tolls on specific roads	✓	✓	✓		✓	✓		
Motor fuel taxes		✓	✓		✓			✓
Carbon price		✓			✓			✓
Per-mile (VMT) fee		✓			✓			
Congestion pricing		✓			✓	✓		

Of the mechanisms listed in the above table, the City currently has the most influence over parking fees and excise taxes. The City (in cooperation with Federal and state agencies) could also potentially implement a cordon price for vehicles traveling into the City or tolls on specific roads. Tolls on limited-access highways, motor fuel taxes, registration fees, carbon pricing, and congestion pricing are all policies that could be implemented by the state (tolls or pricing in Interstate highways will also need federal approval).

8.7.2 Modeling Approach

In the sketch model, pricing was tested by applying elasticities of travel demand (VMT) and fuel efficiency to changes in the cost of travel. An elasticity represents a percent change in one variable (e.g., VMT) with respect to a percent change in another (e.g., cost per mile). Elasticities were derived from the 2018 AEO by comparing VMT and fuel consumption in the High Oil Price scenario with the Reference Case scenario, in 2030 and 2050.

This essentially represents how the National Energy Modeling System (NEMS) used to develop the AEO reflects cumulative changes in fuel price between now and 2030 or 2050. For light-duty vehicles the computed elasticity of VMT with respect to fuel price was -0.18 in 2030 and -0.34 in 2050, and the computed elasticity of fuel efficiency with respect to fuel price was 0.02 in 2030 and 0.08 in 2050. The sketch tool allows four types of price inputs: a carbon price change, fuel cost change for gasoline and diesel, price change per vehicle trip, and price change per VMT. These are converted into an equivalent cost per mile of travel so that the elasticity can be applied.[22]

In the geographic model, price changes are considered by changing the price value in the mode choice model for specific areas or origin-destination pairs where pricing is changed. Coefficients in the mode choice model reflect the value per dollar to travelers and how it trades off against travel time. The outputs of the geographic model therefore reflect tradeoffs in the time and cost of travel by alternative modes for specific travel markets, and therefore consider pricing impacts at a much more detailed level than the sketch model. Medium and heavy duty vehicle travel are not assumed to be affected by local pricing policies. The AEO shows a much smaller VMT elasticity for medium duty trucks (-0.04 to -0.07) and no appreciable impact for heavy-duty trucks, as the cost of transport is generally a small fraction of the total cost of the goods that are carried by these trucks.

8.7.3 VMT and GHG Benefits

Table 18 shows the impacts of representative pricing policies using both models. Note that the VMT and carbon prices are applied to all travel associated with trips starting and/or ending in the City of Boston. The models represent price effects in an approximately linear way so a higher increase in price would result in a proportionately higher impact on VMT and GHG.

Table 18. Effects of Pricing Mechanisms

Pricing Mechanism	Level	LDV VMT Change	GHG Change (% of Inventory)
Sketch Model (2030)			
Carbon price ($/tonne)	$30	-1.6%	-1.5%
Fuel cost change ($/gallon)	$0.20	-1.1%	-1.1%
Price change per vehicle-trip	$0.20	-10.0%	-8.7%
Price change per VMT	$0.05	-9.5%	-8.3%
Geographic Model (2050)			
Price change per VMT	$0.05	-0.7%	-0.6%
Price change per VMT	$0.20	-3.0%	-2.3%
Parking charge per auto trip	$2	-3.4%	-2.4%
Parking charge per auto trip	$5	-7.1%	-5.6%
Charge for entering central Boston – core area[a]	$10-15/day	-2.7%	-2.0%
Charge for entering central Boston – expanded area[a]	$10-15/day	-3.8%	-3.0%

[a]Cordon charge was modeled as $5 per trip, which equates to about $10-15 per day assuming 2 to 3 trips per day starting or ending within the cordon. "Core area" includes Downtown, West End, North End, Beacon Hill, Leather District, Chinatown, Bay Village, Back Bay, and South Boston Waterfront. "Expanded area" also includes Fenway, Longwood Medical Area, and Mission Hill.

[22] Using an average round-trip length of 3.8 miles and baseline fuel efficiency assumptions. The average trip length is computed from geographic model data as trip length = 10,184,000 VMT per day / (8,024,000 trips per day * 66% auto mode share) = 1.9 miles per one-way trip, doubled to 3.8 miles to assume that the cost is paid only at the destination end of the trip.

It is apparent that the geographic model shows a much lower impact of pricing policies than the elasticities used in the sketch model. (Only 2030 results are shown; results using the 2050 elasticity in the sketch model would be even higher.) [23] Pricing has been evaluated in other recent GHG studies. For example, a 2015 study for MassDOT using the Federal EERPAT tool, which simulates choices of individual households, estimated that a mileage-based fee of 0.6 cents per mile would reduce statewide GHG emissions by 0.2 percent [45]. Assuming a linear scaling, a fee of 5 cents per mile would reduce GHG by 1.4 percent – more than the geographic model predicts, but considerably less than the AEO-derived elasticity. The geographic model does not consider longer-term structural changes such as changes in location and activity patterns or auto ownership that could result from pricing policies, but rather primarily reflects short-term mode choice effects. This was dealt with in combined policy scenario 5 by also estimating an auto ownership impact as a result of the pricing and investment strategies, and considering the impact of this reduced auto ownership on mode choice. While the geographic model estimates appear conservative, applying the AEO-derived elasticities to the higher levels of pricing would lead to highly unrealistic values in the other direction (in the range of 50 to 100 percent VMT reduction).

Applying a price change per vehicle-trip (such as a parking or cordon charge) also appears to have a much greater impact than a VMT fee, fuel tax, or carbon price. To understand why this is so, it is helpful to compare the different mechanisms:

$0.20 per gallon gasoline ~ $26 per ton carbon ~ $0.01/VMT ~ $0.04/trip

So a $2 parking charge per trip is actually a very high cost compared with the example levels of fuel or carbon pricing, which add only a few cents to the cost of a trip. The charge for entering central Boston has a high local impact, decreasing VMT into Downtown Boston by 10 percent, but only a fraction (less than one-third) of all the trips into and out of the city are affected. Applying larger carbon prices, gas prices, or VMT fees (e.g., $100/ton, $1/gallon, $0.25/mile) would have a correspondingly larger impact.

The effects of pricing on auto ownership have not been as widely studied, and were not explicitly modeled here. However, some evidence in the literature exists on the impact of transportation prices on auto ownership. For example, based on a major review of studies Goodwin, Dargay and Hanly [63] conclude that a 10 percent real (inflation adjusted) fuel price increase will cause total vehicle ownership to fall less than 1 percent in the short run and 2.5 percent in the longer run.[24] On the other hand, if real income increases 10 percent, vehicle ownership and fuel consumption will increase nearly 4 percent within a year, and over 10 percent in the longer run. While this is based on a review of international studies (not just the U.S.), it does highlight the importance of considering future income levels when forecasting auto ownership. Recent surveys finding shifts in consumer preferences away from auto may mitigate these increases [64].

8.7.4 Other Benefits

Pricing provides benefits associated with reduced VMT, including reduced air pollutant emissions and motor vehicle crash costs. It also encourages a shift to active modes, which reduces health care costs. The $10-15 daily cordon price is estimated to increase walking and biking by nearly 11 percent within the City of Boston.

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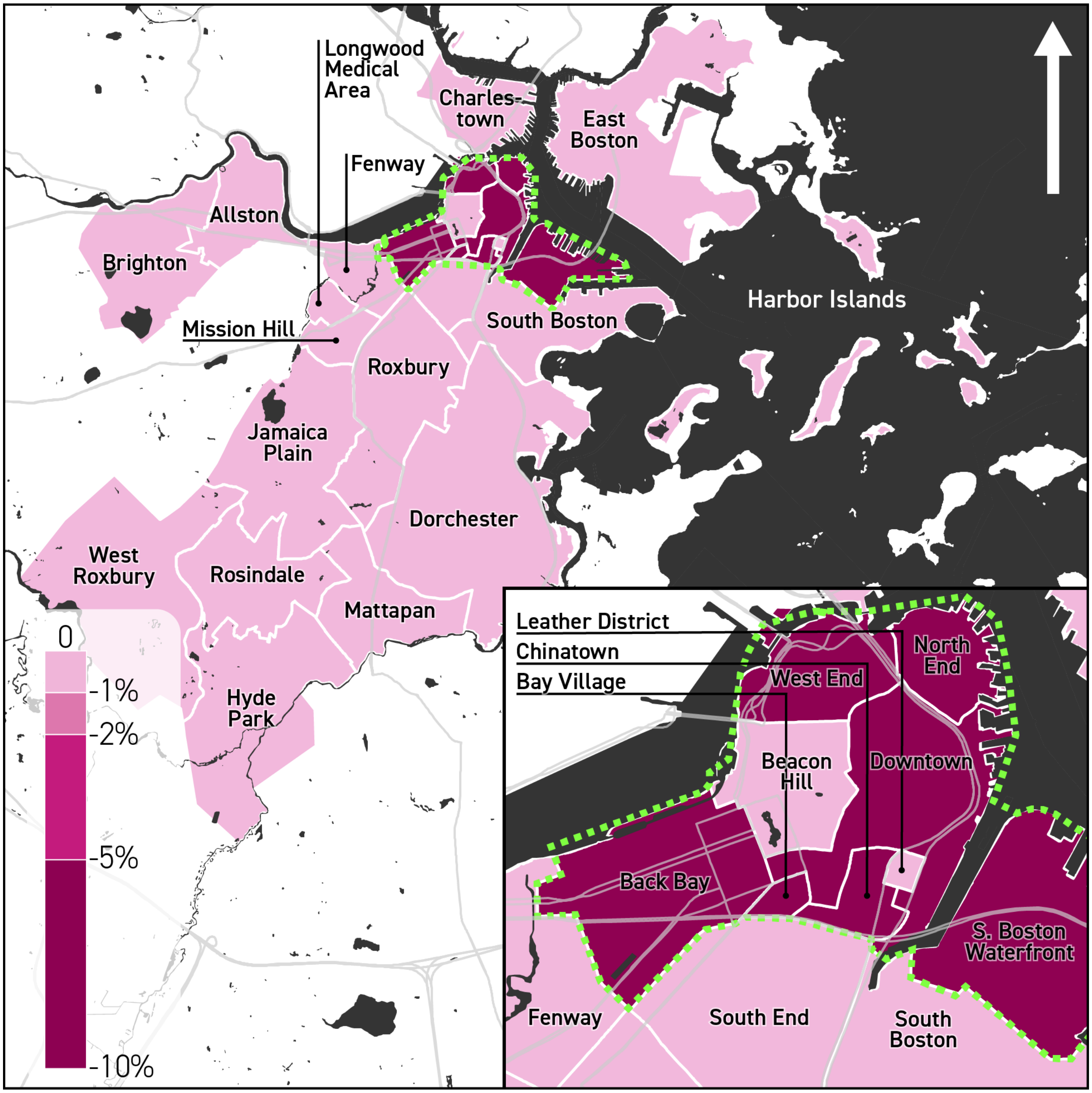
[23] Reasons for this difference are not entirely clear; the NEMS model underlying the AEO forecasts is not thoroughly documented. NEMS is likely to account for longer-term effects such as changes in auto ownership and trip lengths, but at a very aggregate level not considering Boston-specific conditions. The geographic model considers Boston-specific travel options but only evaluates short-term travel mode choices, assuming the same total amount of travel.

[24] A 10 percent increase on $3/gallon is equivalent to $100/year for a household driving 10,000 miles in a 30 mpg car.

The benefits of safety, air pollution, and health from the central area charge are expected to be valued at over $17 million in 2030.

Figure 32 shows the VMT change by neighborhood (VMT produced and attracted) for the central area charge (applied to the core area only). As might be expected, the central area neighborhoods subject to the price show the greatest change (a reduction of 5 to 10 percent) while other neighborhoods show a much smaller change (less than 1 percent). Note that the model does not account for any redistribution of trip destinations that might take place as a result of a central area charge. The other pricing policies have VMT impacts that are somewhat more evenly distributed across neighborhoods.

Figure 32. VMT Change by Neighborhood for Cordon Pricing Strategy



8.7.5 Equity Implications

Pricing has equity impacts that may need to be managed. In particular, lower-income travelers who do not have good alternatives to driving will be the most negatively impacted by pricing policies, especially when implemented at levels high enough to significantly impact travel behavior. One way to mitigate the impacts of pricing is to reinvest the revenues in improving the transportation system, and especially to improve services to low-income neighborhoods. Pricing revenues can also be directly redistributed in the form of tax credits or other progressively applied changes to tax policy that reduce the tax burden on low-income households. Congestion pricing could also benefit lower-income commuters by reducing peak-period congestion and making bus or shared-ride service faster and more reliable.

8.7.6 Policy Discussion

Various other studies have concluded that pricing is one of the most effective demand management strategies if applied at higher levels (e.g., Cambridge Systematics, Inc. [65]) and also creates revenue that can be reinvested in clean transportation improvements. However, it also is one of the most politically challenging strategies, especially at levels that will move the needle on travel behavior. Charges per mile, per gallon of fuel, or per ton or carbon on the order of what has been discussed in most forums will likely only affect demand by 1 to 2 percent. More significant changes, for example, a few dollars per trip, would have a more substantial impact, depending on the geographic extent of their application. The mechanisms directly under the City's control are also limited, and some pricing policies would need to be implemented at the state level.

Pricing policies affecting the cost of vehicle ownership (e.g., registration fees or residential parking charges) were not explicitly modeled in this study. However, the magnitude of these costs can be compared with the magnitude of other pricing approaches. For example, a price of $0.01 per VMT would result in a total cost of $100 a year for a household driving 10,000 miles (assuming all VMT is priced, not just that occurring in the city). This is relatively modest compared with other fixed costs of vehicle ownership including vehicle purchase, maintenance, and insurance. It is therefore likely that an additional registration or parking fee would have a modest impact on vehicle ownership and use unless it were set at a relatively high level (e.g., hundreds of dollars).

8.8 TRAVEL DEMAND MANAGEMENT

Travel demand management programs require or encourage employers and commercial and residential property managers to provide travel options for their employees and/or residents. TDM programs generally provide modest GHG reductions but also at modest cost compared to more capital-intensive infrastructure investments. They also support mobility options for commuters and can improve worker retention.

While employer-focused TDM programs are already active in Boston's major employment centers, the City could expand the reach of these programs as well as expand requirements for TDM options and incentives at new commercial and residential buildings as part of the permitting/development review process. These actions are estimated to reduce Boston-generated VMT and GHG emissions by about 0.5 percent. Expanded requirements for TDM programs at all worksites with at least 50 employees could reduce GHG emissions by 1.3 percent.

8.8.1 Policy Overview

Travel demand management programs have typically focused on commuter travel by reaching workers through employers and property managers. However, TDM also has been implemented for residential properties and at a neighborhood level. The state's Rideshare Regulation requires large business and educational institutions to develop plans and set goals for reducing employee and student drive-alone trips. The MassRIDES program assists employers with the implementation of programs to achieve these goals and provides resources to commuters. In addition, there are 15 Transportation Management Associations (TMAs) in Massachusetts working with 375 businesses, medical facilities, property managers, and higher learning institutions in 48 municipalities (including Boston) to create transportation solutions for commuters. About 150,000 workers in Boston (roughly one-quarter of the workforce, primarily at large companies and institutions) are currently served by four TMAs. Boston may currently choose to require a Transportation Access Plan Agreement (TAPA) for projects subject to Large Project Review (typically those with at least 50,000 square feet gross floor area) that includes implementation of TDM measures.

For this analysis, it is assumed that the City of Boston works to expand TDM activities by:

- Hiring additional staff to conduct outreach to employers and residential property managers to provide travel information and incentives to workers and residents, assisting TMAs in their activities and broadening their reach; and
- Requiring TDM options and incentives at new commercial and residential buildings through expanded use of TAPAs as part of the permitting/development review process.

8.8.2 Modeling Approach

The sketch model allows the user to enter the assumed increase in the percent of workers at Boston employment sites reached by workplace TDM programs, according to the size of the employer (<50 workers, 50-100 workers, >100 workers). TDM programs are typically more efficient at working through large employers since programs affecting more people can be implemented through a single point of contact. It was assumed that workers paying $100 a month for transit would receive a benefit of a reduced-cost transit pass valued at $30 (e.g., by receiving pre-tax transit benefits). An elasticity from the literature of transit ridership with respect to cost of -0.24 was then applied to determine the change in commute mode shares [66]. Of the new transit riders, 48 percent were assumed to have previously driven, based on the 2017 MBTA rider survey. It was also assumed that the drive-alone percentage would be reduced by 3.5 percent (in addition to the transit benefit impact), which is a typical VMT reduction obtained by running the Trip Reduction Impacts of Mobility Management Strategies (TRIMMS) TDM evaluation model for multiple strategies [45]. The percent of workers assumed to be affected is shown in Table 19

Table 19. TDM Worksite Data and Sample Scenarios

Employer size	(A) % of jobs by employer size	(B) Current workers at workplace w/TDM program	(C) Current workers receiving transit benefit	(D) New % workers at workplace w/TDM program	(E) New % workers receiving transit benefit
<50 workers	37%	10%	2%	25%	17%
50-100 workers	8%	25%	6%	40%	21%
>100 workers	37%	40%	9%	55%	24%
All sizes	82%	25%	6%	40%	21%

Notes: (A) is from CTPS 2014 employment data for eastern Massachusetts; excludes industries considered unsuitable for TDM, which is why total is less than 100 percent. (B) is based on 2014 MassCommute data from employers in Boston TMAs showing 25 percent overall participation, with an assumed breakdown by firm size. (C) is based on MassRIDES data showing that 23 percent of participating firms provide a transit subsidy or pretax deduction. (D) and (E) are policy assumptions. See Cambridge Systematics, Inc. [45] for additional references to data sources.

For the residential TDM policy, it was assumed that of the new population growth in the city (57,000 new residents by 2030 and 139,000 new residents by 2050), 70 percent would be in buildings subject to expanded residential TDM program requirements by the City (such as bike parking, manager-provided information, transit discounts, carshare and bikeshare options, and/or telework centers). A five percent reduction in drive alone mode share was assumed for affected new residents, based on evidence from the literature on typical ranges of trip reduction from TDM programs.

The assumptions in the geographic model were similar – reducing transit fares to represent worksite TDM, and reducing drive alone trip generation by new residents.

8.8.3 VMT and GHG Benefits

The modeled levels of TDM program implementation are estimated to reduce VMT by about 0.5 percent, resulting in a similar decrease in GHG emissions. More aggressive requirements (e.g., through a TDM mandate affecting all worksites of at least 50 employees) could reduce GHG emissions by 15,000 t CO_2e or 1.3 percent in 2050. Workplace-based TDM has the benefit of reaching commuters who travel from outside of Boston, in some cases for long distances. However, commute trips are less than one-quarter or all trips and are responsible for less than 30 percent of total VMT.[25] TDM requirements for new residential development can expand its reach, but will not reach the many residents of existing buildings.

8.8.4 Other Benefits

TDM can provide mobility benefits to commuters and residents, by providing people with more information on their commute options, programs to support alternative commuting (such as guaranteed ride home), and financial benefits in the form of reduced transit or other travel costs. Many private business and property managers offer commute benefits to their employees and tenants as an amenity that can support employee attraction and retention.

[25] Analysis of 2009 National Household Travel Survey data.

8.8.5 Equity Implications

When TDM programs include incentives that reduce travel costs (such as pre-tax or subsidized transit benefits), they can especially benefit lower to moderate income commuters in a location like Boston where traffic congestion and parking costs can be high.

8.8.6 Policy Discussion

While the overall travel and GHG impacts are modest, TDM programs can leverage travel changes and mobility improvements at relatively modest cost. Incorporating TDM requirements in new development could be relatively easy to implement through zoning code changes and/or provisions in the design review process. The City has already taken some steps in this direction, for example, by setting requirements for bicycle parking and including TDM requirements as part of TAPAs for some large projects. Expanding outreach to businesses and property managers would require additional staff resources (or funding for staff at existing TMAs).

9 PATHWAYS TO ZERO CARBON: COMBINED SCENARIO IMPACTS

Five illustrative paths to a zero-carbon 2050 future are provided. All pathways require a transition to decarbonized electricity for both private and public transport. Pathways 1 and 2 rely primarily on technology. Pathways 3 and 4 introduce additional investments to manage demand while improving mobility, with the objective of providing significant co-benefits that go beyond GHG reduction. Pathway 5 includes maximum levels of pricing policies as well as investment and demand reduction, to assess what it might take to achieve significant reductions in vehicle-travel to reduce congestion and improve neighborhood quality of life. This aggressive pathway was designed to demonstrate assess the measures necessary for ambitious demand reduction (20-30 percent decline in VMT) that has been proposed in other cities' Climate Action Plans (e.g., New York City 80x50; TransformTO; Draft New Paris Climate, Air and Energy Plan).

Pathway 1 – Clean private vehicles. On this pathway, the City's management of transportation infrastructure continues largely unchanged, as does the predominance of private vehicle ownership. Public policy focuses on a clean energy grid and electric vehicle incentives, leading to widespread electrification. While there is some growth in shared mobility services, most people still prefer to "drive alone" in their own vehicle. Automated vehicles gain significant market share over the long term, making travel more efficient and safer but also increasing VMT which offsets the GHG benefits of increased efficiency. The electricity grid will not only need to be decarbonized, but also grow its capacity substantially to serve the needs of the transportation sector.

Pathway 2 – Clean shared vehicles. On this pathway, GHG benefits are still largely driven by technology, but economic forces and City policy steer travelers toward clean shared mobility. Most automated vehicles are in managed fleets rather than privately owned. Economics, abetted by public sector fee structures, direct the fleet operators towards maximizing vehicle occupancy. Both vehicle ownership and VMT decline.

Pathway 3 – Clean vehicles and low-cost mobility investment. On this pathway, additional mobility investments and policies reduce the new demand for transportation energy while improving equitable mobility. Bike and pedestrian improvements encourage more active travel, improving public health and reducing health care costs. With supportive infrastructure and policies in place, electric bikes and scooters broaden the appeal of "micro-mobility" modes. Transit speed and reliability improvements stabilize ridership and efficiently serve the most dense travel markets. Lower-density markets are served by more flexible ride-hailing and microtransit, and city pricing and regulatory policies are implemented to encourage high-occupancy shared mobility trips. Land use policies encourage growth in transportation-efficient locations.

Pathway 4 – Clean vehicles with pricing and reinvestment. On this pathway, in addition to the measures in Pathways 2 and 3, pricing is implemented to achieve greater reductions in travel demand and further reduce the additional load on the electric grid as EVs become more widespread. Pricing revenues are reinvested in world-class transportation infrastructure, including extended rail and rapid bus lines, separated bike paths, and citywide walking improvements, as well as subsidies for low-income travelers. The list of policies modeled in Pathway 4 includes:

- Smart mobility - $1/mile cost increase for ride-alone, $1/mile cost decrease for shared-ride
- AVs and shared mobility services are all electric vehicles
- Citywide separated/protected bike lane network
- Citywide walking improvements
- Citywide transit operational improvements (5 percent reduction in in-vehicle travel time)
- Go Boston transit investments
- $2/trip pricing
- Auto ownership reduction estimated to be 20 percent
- Policies to achieve light duty, medium duty, and transit vehicle electrification at levels ranging up to 100 percent in 2050

Pathway 5 – Maximum policies. On this pathway, in addition to the measures in Pathway 4, pricing is implemented at higher levels to achieve even greater reductions in travel demand and electricity load. The pricing measures include:

- VMT fee of 20 cents per mile (regionwide)
- Cordon price of $10-15 per day for expanded central area of Boston
- Parking fee of $5 applied to all trips ending at non-home locations in Boston

Pricing revenues are reinvested in free or reduced-cost transit fares in addition to transportation infrastructure improvements as described in Pathway 4. This pathway also includes land use measures to direct growth into centrally-located, transit-rich neighborhoods. Shared mobility options, improved transit and nonmotorized infrastructure, and higher costs for driving are all estimated to substantially reduce automobile ownership.[26] This pathway stretches pricing levels beyond those observed in historical data from

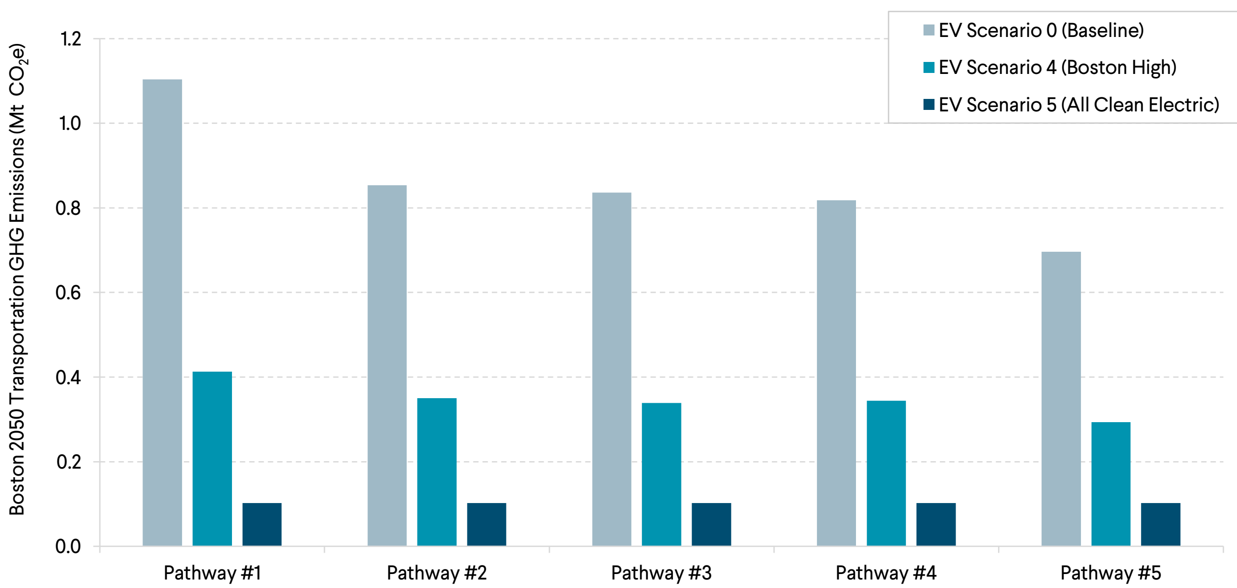
[26] The net auto ownership reduction is estimated to be 45 percent for Boston residents and 30 percent elsewhere. The auto ownership change based on pricing alone is estimated to be 30 percent in Boston and 15 percent elsewhere. The price-based ownership effect is applied multiplicatively to the estimated auto ownership reduction of 20 percent for managed shared mobility as assumed in Pathways 3 and 4 to reach the 45/30 percent reduction estimates. Key assumptions: auto ownership elasticity from the literature of -0.06 with respect to "other taxes [67], applied on a base fuel cost of $1,500/year (8,872 miles/year, 35 mpg, $6.00 per gallon to be more consistent with European conditions on which the elasticity is largely based – applying the elasticity to a base cost of U.S. fuel prices would give extremely large change values).The following additional annual costs are incurred: VMT fee - $1,774 (8,872 miles at $0.20/mile); cordon fee - $3,750 ($12.50/day at 300 days/year); parking price - $1,950 (average of 1.3 trips per vehicle per day with paid parking with additional $5 fee). The lower reduction is based on VMT fee + parking fees; the higher reduction for Boston residents is based on VMT + parking + cordon fees. The auto ownership elasticity of -0.06 is less than the elasticity

the U.S., which may introduce more uncertainty than normal into the analysis, since the models being used to evaluate these policies are being extended beyond the range of observed data. Furthermore, there may be deeper system feedbacks as a result of high pricing policies such as increased demand for transit oriented housing and employment that is not reflected in this modeling approach.

Figure 33 shows the projected 2050 GHG emissions for each pathway, under different EV market penetration scenarios (0 - Baseline, 4 – High Impact, and 5 – All Electric; applied to all households making trips into and out of Boston, not just Boston households). Only a high-EV scenario such as 4 or 5 is consistent with the objective of getting close to zero carbon emissions. However, the baseline EV scenario is also provided to show what could happen under alternative demand scenarios, if electrification technology is not advanced substantially. The emissions for EV Scenario 5 (about 100,000 t CO_2e) are the same under each pathway and reflect only the residual emissions from the heavy-duty vehicle sectors not affected by policies, since other affected sectors will have zero emissions. EV Scenario 4 reduces emissions from a 2050 baseline of nearly 1.2 Mt CO_2e to just over 400,000 t for Pathway 1 (private mobility), or as little as 340,000 t CO_2e under the greater demand reduction of Pathway 4 (shared mobility, transit/walk/bike investment, and pricing).

Figure 33. Boston 2050 Transportation GHG Emissions by Pathway

Note: EV Scenarios 0 and 4 assume electric grid GHG emissions consistent with the Massachusetts Clean Energy Standard projected through 2050. EV Scenario 5 assumes a carbon-free electricity supply, which reduces electricity GHG emissions to 0 in 2050.



Addressing the remaining 100,000 t CO_2e of emissions from heavy-duty vehicles (mostly heavy trucks, subject to federal and perhaps State policies) will require some combination of electrification and low-carbon renewable fuels. The City may have more influence over MBTA ferries and intercity buses operating out of South Station and Logan Airport, which make up a small portion of the heavy duty sector. These are candidates for requirements or incentives for electrification and/or renewable fuel applications, contingent upon advancement of these technologies to meet operating needs. Offsets may be needed to make up any remaining difference.

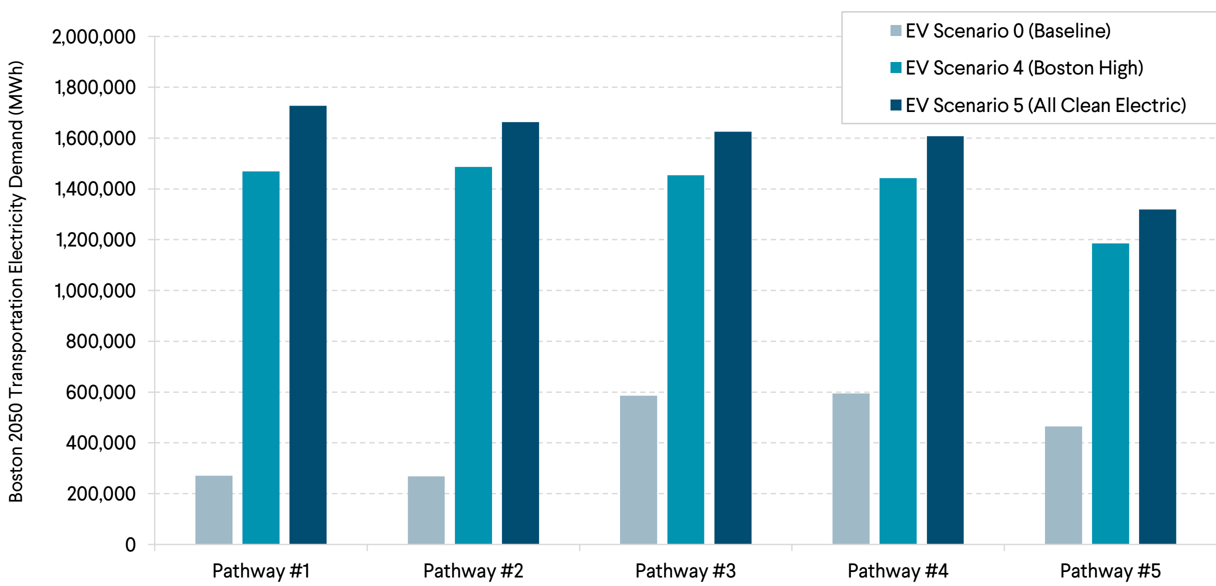
with respect to fuel price of -0.1 to -0.25 quoted in Goodwin, Dargay, and Hanly [63] and is therefore considered conservative. See http://www.vtpi.org/elasticities.pdf for a summary of auto ownership elasticity research.

Figure 34 shows the projected total vehicle electricity demand[27] under each pathway and EV scenario. Pathways 2 – 4 with baseline EV technology for private vehicles increase electricity demand from about 270,000 MWh to about 600,000 MWh, mainly because shared mobility vehicles are required to be electric. The higher EV market penetration scenarios increase electricity demand by up to 1.4 to 1.7 million MWh. The greatest increase comes with Pathway 1, unfettered private mobility. The demand management strategies under Pathways 2 – 4 reduce demand to around 1.6 million MWh. Most of this effect is due to widespread shared mobility options that reduce auto ownership, but investments in transit, walk, and bike infrastructure and pricing provide additional incremental benefits. Under Pathway 5, the more aggressive demand management strategies further reduce the additional transportation electricity use, to around 1.3 million MWh even with complete electrification.

Figure 35 shows the contribution to GHG reduction in 2050 (compared to 2016 levels) from each major type of strategy for Pathway 5. Figure 36 shows how GHG reduction will evolve over time to meet the 2050 levels. With no additional policy action, GHG emissions will decline from 1.99 Mt CO_2e in 2016 to 898,000 t CO_2e in 2050. However, unmanaged smart mobility could increase that by 51,000 t CO_2e. Combined transportation infrastructure investment strategies will reduce 54,000 t CO_2e, and pricing an additional 184,000 t CO_2e. The largest gain will be from electrification, with the efficiency benefits of EVs contributing 330,000 t CO_2e (assuming the 2016 electricity grid), an additional 334,000 t CO_2e with the MA Clean Energy Standard grid, and an additional 108,000 t CO_2e with a zero-carbon grid. The remaining 102,000 t CO_2e is due to heavy-duty vehicle emissions (largely outside the City's control) that will need to be reduced by electrification or renewable fuels, or offset.

Table 20, Table 21, and Table 22 show the GHG, electricity demand, and air pollution impacts for a variety of individual strategies as well as for the combined pathways, for EV scenarios 0, 4, and 5, respectively.

Figure 34. Boston 2050 Transportation Electricity Demand by Pathway



[27] This value represents electricity demand for all trips that have a start or end point in Boston. This value is likely to be significantly different from the in-city charging demand.

Figure 35. Contributions to 2050 Transportation GHG Reductions

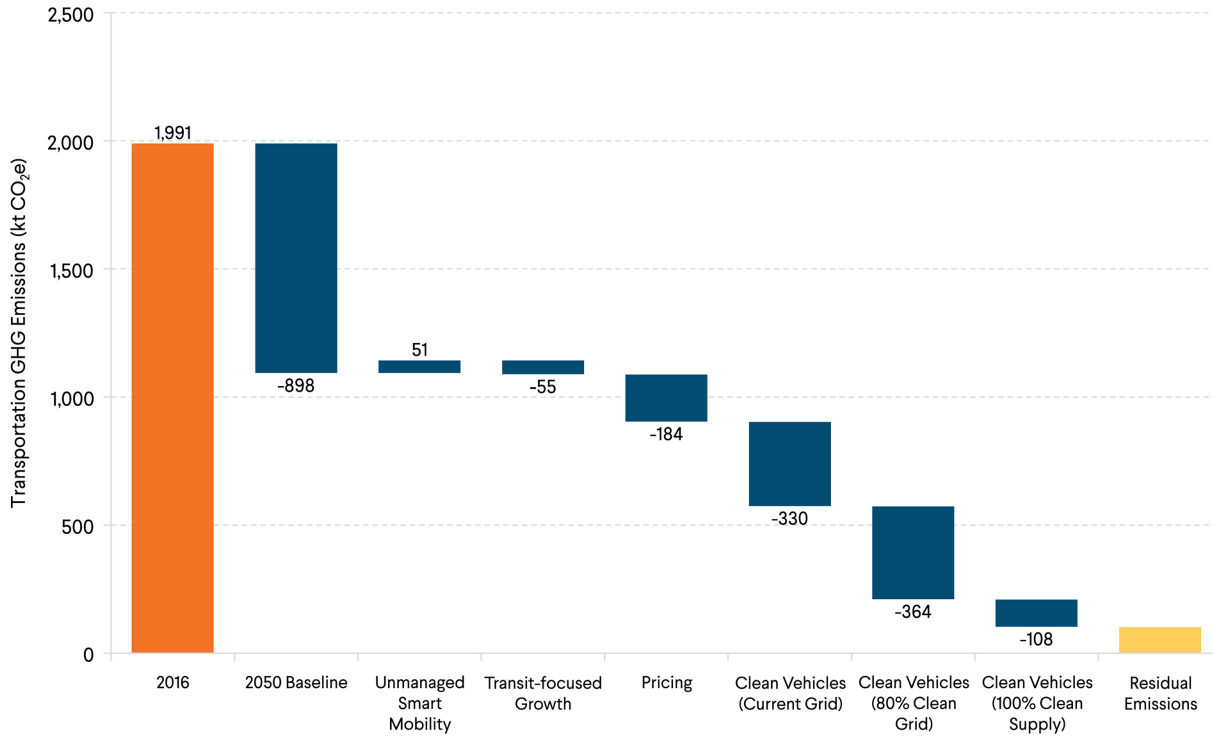


Figure 36. Trajectory towards 2050 GHG Levels

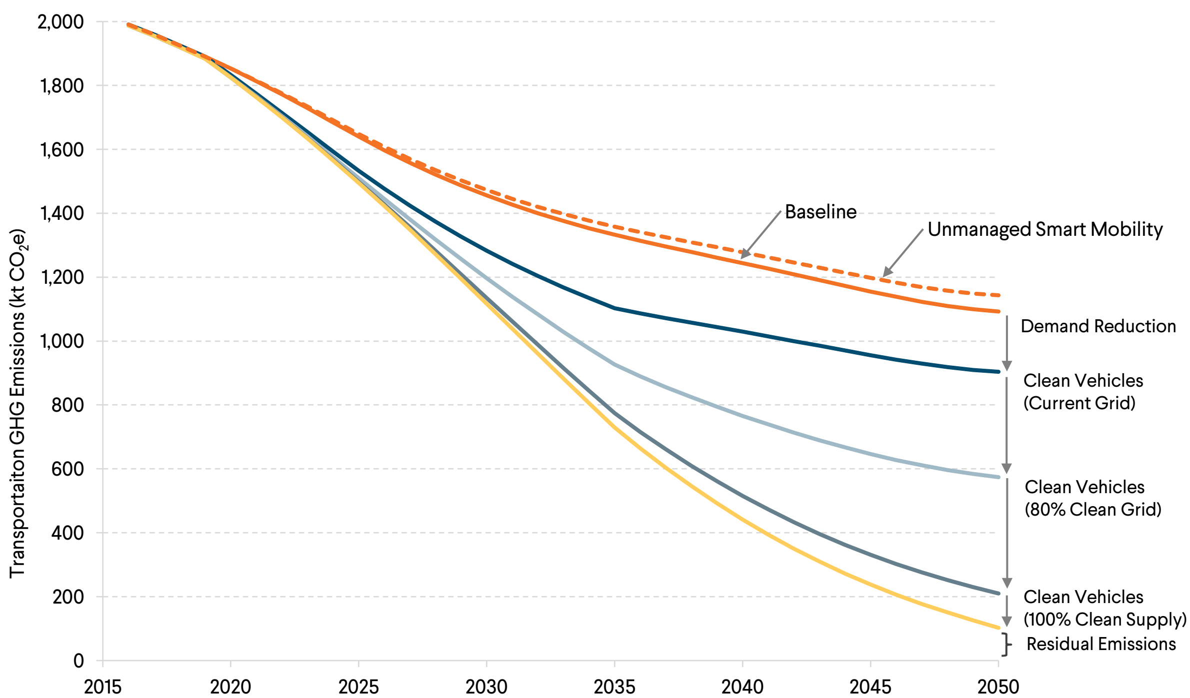


Table 20. GHG, Electricity, and Air Pollution Impacts, EV Scenario 0 (Baseline)

Scenario	Description	2050 GHG Emissions (t CO_2e)	Δ vs. 2050 Baseline (t CO_2e)	% Δ GHG vs. 2050 baseline	% Δ GHG vs. 2016 baseline	Electricity Demand (TWh)	Δ Elect vs. 2016 base (TWh)	% Δ Elect vs. 2016 baseline[a]
2016 Baseline		1,990,658						
2050 Travel Baseline w/EV Scenario		1,092,445			-45.1%	0.27	0.13	2.1%
Travel Pricing - cordon	$5 cordon charge for central area	1,070,875	(21,571)	-2.0%	-46.2%	0.27	0.13	2.0%
Travel Pricing - expanded cordon	$5/trip cordon charge for expanded central area	1,059,718	(32,727)	-3.0%	-46.8%	0.26	0.12	2.0%
Travel Pricing - VMT	$0.05 charge per VMT or ~$100/ton carbon	1,086,400	(6,046)	-0.6%	-45.4%	0.27	0.13	2.1%
Travel Pricing - VMT max	$0.20 charge per VMT	1,067,001	(25,444)	-2.3%	-46.4%	0.26	0.13	2.0%
Travel Pricing - trip	$2 per vehicle trip	1,065,895	(26,550)	-2.4%	-46.5%	0.26	0.13	2.0%
Travel Pricing - parking	$5 parking in Boston (all non-home trips)	1,031,390	(61,055)	-5.6%	-48.2%	0.26	0.12	1.9%
Travel Pricing - combined	$5 parking, $0.20/mi VMT, $5/trip cordon, free/reduced transit	934,697	(157,749)	-14.4%	-53.0%	0.24	0.10	1.6%
Active Transportation	Go Boston bike investments + citywide ped improvements	1,085,551	(6,895)	-0.6%	-45.5%	0.27	0.13	2.1%
Transit	Go Boston transit projects + key route operational improvements	1,090,366	(2,079)	-0.2%	-45.2%	0.30	0.16	2.5%
Transit fare reductions	Free bus/subway, 1/2 cost commuter rail/ferry	1,062,827	(29,619)	-2.7%	-46.6%	0.26	0.13	2.0%
TDM	Workplace and residential TDM	1,090,605	(1,841)	-0.2%	-45.2%	0.27	0.13	2.1%
Land Use	Go Boston growth focus areas	1,100,214	7,769	0.7%	-44.7%	0.27	0.13	2.1%
Land Use Pathway 5	Focus in central neighborhoods	1,068,207	(24,238)	-2.2%	-46.3%	0.26	0.13	2.0%
Low-Cost Mobility	Citywide bike, ped, and transit operational improvements	1,066,663	(25,782)	-2.4%	-46.4%	0.26	0.13	2.0%

Scenario	Description	2050 GHG Emissions (t CO_2e)	Δ vs. 2050 Baseline (t CO_2e)	% Δ GHG vs. 2050 baseline	% Δ GHG vs. 2016 baseline	Electricity Demand (TWh)	Δ Elect vs. 2016 base (TWh)	% Δ Elect vs. 2016 baseline[a]
Pathway #1	**50% CAV market share, not managed**	**1,103,787**	**11,342**	**1.0%**	**-44.6%**	**0.27**	**0.13**	**2.1%**
CAV (Private) - Managed	50% CAV market share, pricing to restrain travel increase	1,059,497	(32,989)	-3.0%	-46.8%	0.26	0.12	2.0%
SM - Incremental, Not Managed	+6% market share	1,129,534	37,088	3.4%	-43.3%	0.28	0.14	2.2%
SM - Incremental, Managed	+6% market share, cross-subsidy of shared ride, all EV	1,070,846	(21,600)	-2.0%	-46.2%	0.35	0.22	3.5%
SM - Full, Not Managed	+28% SM market share, no cross-subsidy, all EV	880,985	(211,460)	-19.4%	-55.7%	0.60	0.47	7.5%
Pathway #2	**+28% SM market share, cross-subsidy of shared ride, all EV**	**853,532**	**(238,913)**	**-21.9%**	**-57.1%**	**0.60**	**0.46**	**7.4%**
Pathway #3	**Pathway #2 + Low-Cost Mobility**	**836,069**	**(256,377)**	**-23.5%**	**-58.0%**	**0.59**	**0.45**	**7.2%**
Pathway #4	**Pathway #3 + $2/vehicle trip charge**	**817,936**	**(274,509)**	**-25.1%**	**-58.9%**	**0.59**	**0.46**	**7.4%**
Pathway #5	**Combined max pricing, infrastructure, LU, TDM**	**696,445**	**(396,000)**	**-36.2%**	**-65.0%**	**0.46**	**0.33**	**5.3%**

[a] Change in regional electricity consumption as a percentage of City of Boston baseline electricity use.

Table 21. GHG, Electricity, and Air Pollution Impacts, EV Scenario 4 (High Impact)

Scenario	Description	2050 GHG Emissions (t CO_2e)	Δ vs. 2050 Baseline (t CO_2e)	% Δ GHG vs. 2050 baseline	% Δ GHG vs. 2016 baseline	Electricity Demand (TWh)	Δ Elect vs. 2016 base (TWh)	% Δ Elect vs. 2016 baseline[a]
2016 Baseline		1,990,658				0.14		
2050 Travel Baseline w/EV Scenario		409,463	-	-	-79.4%	1.45	1.32	21.2%
Travel Pricing - cordon	$5 cordon charge for central area	402,371	(7,092)	-1.7%	-79.8%	1.43	1.29	20.8%
Travel Pricing - expanded cordon	$5/trip cordon charge for expanded central area	398,703	(10,760)	-2.6%	-80.0%	1.41	1.27	20.5%
Travel Pricing - VMT	$0.05 charge per VMT or ~$100/ton carbon	407,475	(1,988)	-0.5%	-79.5%	1.45	1.31	21.1%
Travel Pricing - VMT max	$0.20 charge per VMT	401,097	(8,366)	-2.0%	-79.9%	1.42	1.28	20.7%
Travel Pricing - trip	$2 per vehicle trip	400,733	(8,730)	-2.1%	-79.9%	1.42	1.28	20.7%
Travel Pricing - parking	$5 parking in Boston (all non-home trips)	389,388	(20,074)	-4.9%	-80.4%	1.38	1.24	19.9%
Travel Pricing - combined	$5 parking, $0.20/mi VMT, $5/trip cordon, free/reduced transit	357,596	(51,867)	-12.7%	-82.0%	1.25	1.11	17.9%
Active Transportation	Go Boston bike investments + citywide ped improvements	407,196	(2,267)	-0.6%	-79.5%	1.45	1.31	21.1%
Transit	Go Boston transit projects + key route operational improvements	410,153	690	0.2%	-79.4%	1.48	1.34	21.6%
Transit fare reductions	Free bus/subway, 1/2 cost commuter rail/ferry	399,724	(9,738)	-2.4%	-79.9%	1.42	1.28	20.6%
TDM	Workplace and residential TDM	408,858	(605)	-0.1%	-79.5%	1.45	1.31	21.2%
Land Use	Go Boston growth focus areas	412,017	2,554	0.6%	-79.3%	1.46	1.33	21.4%
Land Use Pathway 5	Focus in central neighborhoods	401,494	(7,969)	-1.9%	-79.8%	1.42	1.28	20.7%
Low-Cost Mobility	Citywide bike, ped, and transit operational improvements	400,986	(8,477)	-2.1%	-79.9%	1.42	1.28	20.7%

Scenario	Description	2050 GHG Emissions (t CO_2e)	Δ vs. 2050 Baseline (t CO_2e)	% Δ GHG vs. 2050 baseline	% Δ GHG vs. 2016 baseline	Electricity Demand (TWh)	Δ Elect vs. 2016 base (TWh)	% Δ Elect vs. 2016 baseline[a]
Pathway #1	**50% CAV market share, not managed**	**413,192**	**3,729**	**0.9%**	**-79.2%**	**1.47**	**1.33**	**21.5%**
CAV (Private) - Managed	50% CAV market share, pricing to restrain travel increase	398,617	(10,846)	-2.6%	-80.0%	1.41	1.27	20.5%
SM - Incremental, Not Managed	+6% market share	421,657	12,194	3.0%	-78.8%	1.50	1.36	22.0%
SM - Incremental, Managed	+6% market share, cross-subsidy of shared ride, all EV	406,984	(2,479)	-0.6%	-79.6%	1.51	1.37	22.1%
SM - Full, Not Managed	+28% SM market share, no cross-subsidy, all EV	359,246	(50,217)	-12.3%	-82.0%	1.52	1.38	22.3%
Pathway #2	**+28% SM market share, cross-subsidy of shared ride, all EV**	**350,243**	**(59,220)**	**-14.5%**	**-82.4%**	**1.49**	**1.35**	**21.7%**
Pathway #3	**Pathway #2 + Low-Cost Mobility**	**343,885**	**(65,578)**	**-16.0%**	**-82.7%**	**1.45**	**1.31**	**21.2%**
Pathway #4	**Pathway #3 + $2/vehicle trip charge**	**338,585**	**(70,878)**	**-17.3%**	**-83.0%**	**1.44**	**1.30**	**21.0%**
Pathway #5	**Combined max pricing, infrastructure, LU, TDM**	**293,460**	**(116,003)**	**-28.3%**	**-85.3%**	**1.19**	**1.05**	**16.9%**

[a] Change in regional electricity consumption as a percentage of City of Boston baseline electricity use.

Table 22. GHG, Electricity, and Air Pollution Impacts, EV Scenario 5 (All Electric)

Scenario	Description	2050 GHG Emissions (t CO_2e)	Δ vs. 2050 Baseline (t CO_2e)	% Δ GHG vs. 2016 baseline	Electricity Demand (TWh)	Δ Elect vs. 2016 base (TWh)	% Δ Elect vs. 2016 baseline[b]
2016 Baseline		1,990,658			0.14		
2050 Travel Baseline w/EV Scenario					1.71	1.57	25.3%
Travel Pricing - cordon	$5 cordon charge for central area				1.67	1.54	24.8%
Travel Pricing - expanded cordon	$5/trip cordon charge for expanded central area				1.66	1.52	24.5%
Travel Pricing - VMT	$0.05 charge per VMT or ~$100/ton carbon				1.70	1.56	25.2%
Travel Pricing - VMT max	$0.20 charge per VMT				1.67	1.53	24.7%
Travel Pricing - trip	$2 per vehicle trip				1.67	1.53	24.6%
Travel Pricing - parking	$5 parking in Boston (all non-home trips)				1.61	1.47	23.8%
Travel Pricing - combined	$5 parking, $0.20/mi VMT, $5/trip cordon, free/reduced transit	102,342[a]	-	-94.9% [a]	1.46	1.32	21.3%
Active Transportation	Go Boston bike investments + citywide ped improvements				1.70	1.56	25.1%
Transit	Go Boston transit projects + key route operational improvements				1.73	1.59	25.6%
Transit fare reductions	Free bus/subway, 1/2 cost commuter rail/ferry				1.66	1.52	24.6%
TDM	Workplace and residential TDM				1.71	1.57	25.3%
Land Use	Go Boston growth focus areas				1.72	1.58	25.5%
Land Use Pathway 5	Focus in central neighborhoods				1.67	1.53	24.7%
Low-Cost Mobility	Citywide bike, ped, and transit operational improvements				1.67	1.53	24.7%

Scenario	Description	2050 GHG Emissions (t CO_2e)	Δ vs. 2050 Baseline (t CO_2e)	% Δ GHG vs. 2016 baseline	Electricity Demand (TWh)	Δ Elect vs. 2016 base (TWh)	% Δ Elect vs. 2016 baseline[b]
Pathway #1	**50% CAV market share, not managed**				**1.73**	**1.59**	**25.6%**
CAV (Private) - Managed	50% CAV market share, pricing to restrain travel increase				1.66	1.52	24.5%
SM - Incremental, Not Managed	+6% market share				1.77	1.63	26.3%
SM - Incremental, Managed	+6% market share, cross-subsidy of shared ride, all EV				1.75	1.62	26.1%
SM - Full, Not Managed	+28% SM market share, no cross-subsidy, all EV				1.71	1.57	25.3%
Pathway #2	**+28% SM market share, cross-subsidy of shared ride, all EV**				**1.66**	**1.52**	**24.6%**
Pathway #3	**Pathway #2 + Low-Cost Mobility**				**1.63**	**1.49**	**24.0%**
Pathway #4	**Pathway #3 + $2/vehicle trip charge**				**1.61**	**1.47**	**23.7%**
Pathway #5	**Combined max pricing, infrastructure, LU, TDM**				**1.32**	**1.18**	**19.0%**

[a] Because GHG emissions from all light and medium-duty vehicles are reduced to zero in this scenario through electrification and a zero-emissions grid, travel reduction measures will have no incremental impact on GHG. GHG impacts are therefore the same as the 2050 baseline impacts for all scenarios.

[b] Change in regional electricity consumption is expressed as a percentage of City of Boston baseline electricity use.

10 Other Benefits and Impacts

This section describes other benefits and impacts associated with the five illustrative pathways, including VMT, active PMT (miles walking and biking), air pollutant emissions, physical activity and health, and safety.

10.1 VMT and Active PMT Changes

Vehicle travel creates a number of negative externalities, including air pollution, congestion, decreased safety, and neighborhood livability (although these may be mitigated by clean and automated vehicle technology). Figure 37 shows changes in regional VMT under the illustrative pathways. Pathway 1 increases VMT by about 222 million miles a year or 6 percent, mainly as a result of broad market penetration of automated vehicles. Pathway 2 reduces VMT marginally, as the VMT reductions from reduced auto ownership and shared-ride smart mobility are offset by ride-alone smart mobility and deadhead (repositioning) activity. Pathways 3 and 4 add mobility improvements and pricing incentives, reducing VMT by up to 7 percent. With the maximum pricing and investment policies in Scenario 5, and considering the effects of reduced auto ownership, VMT is reduced by nearly 30 percent.

Physical activity, including activity walking and biking, is an important contributor to public health. Figure 37 also shows how person-miles of travel by active modes changes. Under Pathways 1 and 2 it decreases by 12-13 percent regionally (mostly within the City of Boston) as CAVs and smart mobility pull travelers from walking, biking, and other modes. Under Pathway 3 it increases by 17 percent (mostly for trips destined outside of Boston) due to improved biking and walking conditions. Pathway 4 increases the regional change to 23 percent as the added cost of driving further shifts people to other modes. Under Pathway 5, active travel increase by over 50 percent.

Table 23 shows VMT and active PMT travel impacts for a variety of individual policies and combined scenarios.

Figure 37. Daily Change in Travel

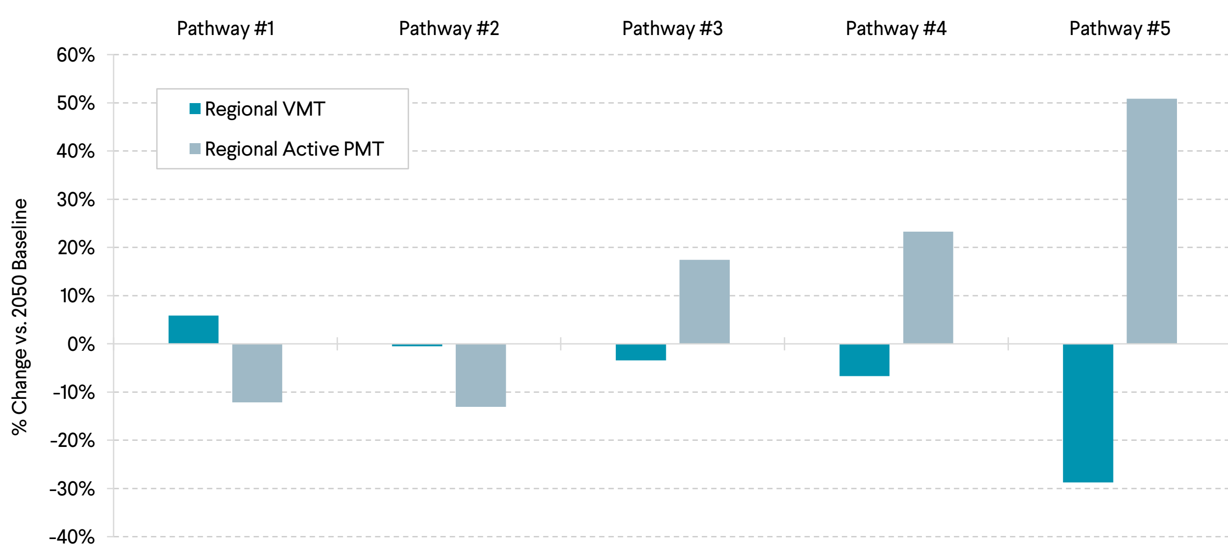


Table 23. Travel Impacts (All EV Scenarios)

Scenario	Description	2050 VMT (Change)	VMT % Δ vs 2050 Base	2050 Active PMT (Change)	Active PMT % Δ vs 2050 Base
2050 Travel Baseline		**3,774,007,986**		**482,804,579**	
Travel Pricing - cordon	$5 cordon charge for central area	(94,931,601)	-2.5%	18,521,001	3.8%
Travel Pricing - expanded cordon	$5/trip cordon charge for expanded central area	(144,029,469)	-3.8%	28,204,044	5.8%
Travel Pricing - VMT	$0.05 charge per VMT or ~$100/ton carbon	(26,606,260)	-0.7%	3,887,893	0.8%
Travel Pricing - VMT max	$0.20 charge per VMT	(111,978,226)	-3.0%	15,913,022	3.3%
Travel Pricing - trip	$2 per vehicle trip	(116,846,248)	-3.1%	35,288,002	7.3%
Travel Pricing - parking	$5 parking in Boston (all non-home trips)	(268,699,013)	-7.1%	82,197,656	17.0%
Travel Pricing - combined	$5 parking, $0.20/mi VMT, $5/trip cordon, free/reduced transit	(694,242,299)	-18.4%	102,095,203	21.1%
Active Transportation	Go Boston bike investments + citywide ped improvements	(30,343,145)	-0.8%	40,839,859	8.5%
Transit	Go Boston transit projects + key route operational improvements	(14,313,934)	-0.4%	(8,234,405)	-1.7%
Transit fare reductions	Free bus/subway, 1/2 cost commuter rail/ferry	(130,350,455)	-3.5%	(18,022,572)	-3.7%
TDM	Workplace and residential TDM	(8,101,487)	-0.2%	(1,094,305)	-0.2%
Land Use	Go Boston growth focus areas	34,189,883	0.9%	(2,306,448)	-0.5%
Land Use Pathway 5	Focus in central neighborhoods	(106,671,076)	-2.8%	7,087,682	1.5%
Low-Cost Mobility	Citywide bike, ped, and transit operational improvements	(113,466,923)	-3.0%	147,931,862	30.6%
Pathway #1	**50% CAV market share, not managed**	**221,794,470**	**5.9%**	**(58,502,829)**	**-12.1%**
CAV (Private) - Managed	50% CAV market share, pricing to restrain travel increase	17,409,477	0.5%	(9,015,769)	-1.9%
SM - Incremental, Not Managed	+6% market share	163,222,395	4.3%	(34,995,618)	-7.2%
SM - Incremental, Managed	+6% market share, cross-subsidy of shared ride, all EV	(125,373,492)	-3.3%	(32,674,435)	-6.8%
SM - Full, Not Managed	+28% SM market share, no cross-subsidy, all EV	99,353,708	2.6%	(61,273,470)	-12.7%
Pathway #2	**+28% SM market share, cross-subsidy of shared ride, all EV**	**(20,210,020)**	**-0.5%**	**(63,250,447)**	**-13.1%**
Pathway #3	**Pathway #2 + Low-Cost Mobility**	**(129,936,049)**	**-3.4%**	**84,118,517**	**17.4%**
Pathway #4	**Pathway #3 + $2/vehicle trip charge**	**(252,881,788)**	**-6.7%**	**112,280,432**	**23.3%**
Pathway #5	**Combined max pricing, infrastructure, LU, TDM**	**(1,086,273,995)**	**-28.8%**	**245,353,491**	**50.8%**

10.2 Emissions and Health

Most of the various pathways reduce air pollution, with reductions of up to 9,700 kg per year of fine particulate matter ($PM_{2.5}$) and 296,000 kg per year of oxides of nitrogen (NO_x) in 2050 for the full-electrification scenario. These represent reductions of about 80 percent for $PM_{2.5}$ and 75 percent for NO_x, compared to the transportation sector 2050 baseline. Emissions are not fully eliminated because heavy vehicles (not affected by policies here) are responsible for a significant fraction of PM and NO_x emissions. Most of the benefits come from vehicle electrification, which eliminates tailpipe emissions (powerplant emissions are not considered); electrification of medium duty trucks, buses, and rail is especially important as these vehicles have much higher emission rates per mile than light-duty vehicles, for which emissions are expected to be very small in the future due to stringent emissions standards. The monetary value of air pollution benefits (primarily from reduced mortality and morbidity) is up to $15 million in 2050.[28]

The daily increase in active PMT under Pathway 4 is equivalent to 112 million person-miles of walking and biking a year, an increase of 23 percent over 2050 projected baseline levels. Pathway 5 increases active PMT by 245 million person-miles a year, an increase of 50 percent. At a health care cost savings of $0.21 per mile (see "Active Transportation" section), the Pathway 5 increase equates to a value of $52 million in health care costs saved. At a value of lives saved of $1.50 per mile, the Pathway 5 increase equates to a value of $368 million.

10.3 Safety

Reducing VMT is likely to reduce crashes and resulting economic costs. At a crash cost of $0.14 per mile,[29] the economic impact of crashes could be reduced by as much as $259 million annually under Pathway 5. This assumes average crash rates by severity level for the United States, which may not be applicable to Boston. This also assumes that CAVs used for smart mobility applications have very few crashes; if vehicles used in smart/shared mobility applications have crash rates consistent with current levels, the crash benefit of Pathway 5 is about $154 million annually. The valuation includes quality of life effects and is therefore comparable to the physical activity benefit value of lives saved.

10.4 Summary of Co-Benefits

Table 24 shows emissions, health, and safety benefits in detail for Pathway 5. Note that crash costs and physical activity costs are the same across EV scenarios since they are based only on VMT, not vehicle fuel technology.

[28] Valued at $18/kg for NO_x and $976/kg for $PM_{2.5}$, based on research conducted by Cambridge Systematics for Federal Transit Administration for New Starts project assessment procedures (year 2035 valuation, converted from 2010 to 2016 dollars).

[29] Value used by Cambridge Systematics in analysis for Georgetown Climate Center, based on crash rates and valuation by severity level used by FTA in their New Starts evaluation procedures [68].

Table 24. Illustrative Benefits and Impacts for Pathway 5

EV Scenario:	0 – Baseline		4 – Boston High Impact		5 – All Electric	
	2030	2050	2030	2050	2030	2050
Motor vehicle crash cost change	$(141,295,346)	$(258,596,156)	$(141,295,346)	$(258,596,156)	$(141,295,346)	$(258,596,156)
$PM_{2.5}$ change, kg	(2,346)	(3,066)	(6,102)	(8,948)	(6,102)	(9,729)
NO_x change, kg	(41,928)	(34,275)	(174,706)	(281,030)	(174,706)	(295,840)
$PM_{2.5}$ change	-15%	-26%	-39%	-75%	-39%	-81%
NO_x change	-8%	-9%	-34%	-70%	-34%	-74%
Air pollution cost change	$(3,030,911)	$(3,598,260)	$(9,046,522)	$(13,704,261)	$(9,046,522)	$(14,728,624)
Phys act health care cost change	$(23,109,706)	$(51,524,233)	$(23,109,706)	$(51,524,233)	$(23,109,706)	$(51,524,233)
Veh op cost change	$(180,409,689)	$(315,509,392)	$(196,677,756)	$(336,242,757)	$(196,677,756)	$(346,226,500)

Table 25 provides a qualitative assessment of the various benefits and impacts of the GHG reduction strategies.

Table 25. Co-Benefits Assessment

	Clean Vehicles	Travel Pricing	Transit, Walking, Biking, TDM	Private CAVs	Smart Mobility
GHG	↑↑	↑	↑	↓	↑↓
Air pollution	↑↑	↑	↑	↑↓	↑↓
VMT reduction	↓	↑	↑	↓↓	↑↓
Mobility	---	↓	↑↑	↑↑	↑↑
Safety	---	↑	↑	↑↑	↑↑
Physical Activity and Health	---	↑	↑↑	↓	↓
Equity	---	↑↓	↑↑	↓	↑

↑ = positive (beneficial) impact

↓ = negative (not beneficial) impact

↑↓ = could go either way

--- = neutral/little or no impact

11 COSTS AND COST-EFFECTIVENESS

11.1 METHOD

The costs associated with the various strategies, and the cost-effectiveness in terms of tons of GHG reduced per dollar spent, were estimated for strategies for which costs could be estimated. Costs and cost savings were grouped into three categories depending upon their incidence:

- **Public sector costs** – Costs associated with government expenditures on infrastructure construction and maintenance and service provision. Examples include walk, bike, and transit investments, TDM program administration, and public EV charging infrastructure.
- **Private sector costs and savings** – Additional costs, or cost reductions, to travelers (households and businesses). Examples include higher vehicle purchase costs for EVs, fuel and maintenance cost savings, and home and workplace charging equipment.
- **Social costs and savings** – Impacts that are broadly borne by society including motor vehicle crashes, air pollution, and public health.

The cost-effectiveness analysis only measured net social costs and benefits. Transfers, such as transit fares, user fees, tolls, and vehicle purchase incentives, were not considered. These represent a transfer of money from one sector to another, rather than a net social cost or benefit. However, estimates were made of new public revenue from pricing policies to assist in determining what level of revenue might be available for reinvestment in clean transportation or redistribution to support equity objectives.

Cost-effectiveness was calculated as follows:

- Identifying an expected time-stream of costs over the 2020-2050 period associated with implementation of each strategy;
- Identifying a corresponding time-stream of benefits (e.g., vehicle operating cost savings by year);
- Converting annual values into a net present value and summing across cost components for each strategy;
- Estimating cumulative 2020-2050 GHG reductions through a linear ramp-up from 2020 (0) to 2050 levels;[30]
- Dividing cumulative net cost or benefit over the 2020-2050 period by cumulative GHG reductions.

Cost-effectiveness was not estimated for the private CAV strategies. Costs would be borne mainly by the private sector but are assumed to be offset by user benefits that support bringing these technologies to market.

The cost-effectiveness estimates for clean vehicles are based on the Scenario 5 level of EV implementation (full electrification). However, the costs and benefits are generally set up so that they scale linearly, and different levels of implementation would show similar cost-effectiveness.

[30] The analysis was focused on year 2030 and 2050 GHG reductions, so a detailed estimate of year-by-year GHG reductions over the entire period was not developed. The approximation of 2020-2050 benefits was made so that the cost-effectiveness numbers could be compared to other studies which have similarly divided cumulative costs by cumulative benefits.

Cost-effectiveness considers changes in vehicle operating costs. Cost-effectiveness for vehicle/fuel technologies will therefore be highly sensitive to energy prices, including absolute prices and the relative difference between petroleum fuels and electricity. The cost-effectiveness of demand reduction strategies shows modest sensitivity to fuel prices, since vehicle operating cost savings are considered. Cost-effectiveness is evaluated under two price scenarios: the AEO baseline price forecast (with electricity adjusted for New England rates), and an alternative forecast in which petroleum prices are doubled and electricity prices increase by a factor of 1.5.

11.2 Results

Table 25 shows cost-effectiveness estimates under the baseline and higher energy price scenarios. Light duty electrification strategies incur a modest net cost with baseline fuel savings, but a net savings at higher fuel costs. Bus electrification shows a net savings under both fuel price scenarios, while truck and commuter rail electrification are more expensive. (Commuter rail is expensive because of the high cost of catenary as well as accelerated vehicle purchase.) Medium-duty trucks do not break even under either scenario, due to higher vehicle and charging equipment costs. However, these are based on average values and some specific vocational purposes (e.g., high-VMT and/or intense stop-and-go duty cycles) could potentially look more favorable. The medium-duty truck sector is very diverse and specific vocations and vehicle characteristics need to be considered. Buses benefit from lower electricity prices, as the MBTA pays a wholesale rate that is just over half as much as the consumer rate [45]. Transit and school buses are evaluated with the same assumptions.

For the travel demand strategies, active transportation, land use, and TDM all yield net social cost savings, although active transportation and TDM require public sector investment. Road pricing and smart mobility pricing incur some public sector costs for administration and enforcement, while transit incurs higher costs per ton reduced. Pricing cost-effectiveness will depend largely on the implementation technology. We estimate a cost of $150 million for a central Boston installation based on MassDOT all-electronic tolling experience; a cheaper cordon pricing system, for example using cameras mounted on existing structures, would increase cost-effectiveness correspondingly. Also, vehicle operating cost savings are not included for the pricing policy, since drivers are "pushed" rather than "pulled" to other modes. The travel strategies do provide other mobility and social benefits (as described earlier in this report), and should be considered evaluated based on their complete benefits, not just GHG reductions.

Figure 38 illustrates the various cost and cost savings components for the electrification strategies, under the high energy price scenario. Figure 39 shows a "marginal abatement cost curve" that plots the cumulative GHG reduction from each strategy vs. the cost per ton of GHG reduced, arraying the strategies from most to least cost-effective. Note that some strategies have a "negative cost," meaning that the strategy saves money. Thus, the electrification of buses, land use, and travel demand management are money-savers and they reduce GHG emissions, albeit modestly. Investments in walking and biking have a slightly larger GHG impact and come at a very modest cost. The electrification of light-duty vehicles has the single largest impact on emissions and also has a low abatement cost (which would be negative if fuel prices rise enough). Investment in new transit has the highest cost and a relatively small potential to reduce GHG emissions.

Public transit illustrates the limits of using a single criterion such as abatement cost. Except for bus electrification, transit is a very expensive way to reduce GHG emissions. However, the cost per unit of GHG emissions is just one of many that factor into transportation planning. A city's transit system is the center of economic opportunity, and the extent to which it is equitably planned and implemented is a major determinant of life quality. Investment in transit and active modes produces modest reductions in GHGs, but they also reduce vehicle traffic. If those investments are not made, vehicle traffic in Boston will increase as the lower cost of operating EVs and the convenience of ride-hailing result in growing demand for vehicle travel. In addition, equity is not captured in the calculation of abatement cost, and socially vulnerable populations rely more on transit than the general population.

A full set of cost assumptions for all strategies is provided in Table 26.

Table 26. Costs and Cost-Effectiveness

	GHG Reduction 2020-50 (kt)	Cumulative Cost Savings, 2020 – 2050 ($millions)					$/Ton 2020-50 GHG Reduced		
		Private Sector	Public Sector	Social	Total Monetary	Total w/Social	Public Sector	Total Monetary	Total w/Social
EV Scenario 5 with baseline (AEO forecast) fuel price trends									
Light-duty vehicles	(3,895)	$73	$128	$(70)	$201	$131	$33	$52	$34
Medium-duty trucks	(388)	$201	$-	$(15)	$201	$186	$-	$518	$480
Transit & school buses	(283)	$-	$(124)	$(19)	$(124)	$(144)	net savings	net savings	net savings
Commuter rail	(383)	$-	$535	$(83)	$535	$452	$1,397	$1,397	$1,179
Combined EV	(4,949)	$274	$538	$(188)	$812	$625	$109	$164	$126
EV Scenario 5 with higher fuel prices									
Light-duty vehicles	(3,895)	$(1,374)	$128	$(70)	$(1,247)	$(1,317)	$33	net savings	net savings
Medium-duty trucks	(388)	$110	$-	$(15)	$110	$95	$-	$283	$245
Transit & school buses	(283)	$-	$(492)	$(19)	$(492)	$(511)	net savings	net savings	net savings
Commuter rail	(383)	$-	$183	$(83)	$183	$100	$479	$479	$261
Combined EV	(4,949)	$(1,265)	$(181)	$(188)	$(1,445)	$(1,633)	net savings	net savings	net savings
Travel Scenarios w/baseline fuel prices									
Active Transportation	(246)	$(71)	$-	$(9)	$(71)	$(80)	$337	$64	net savings
Land Use	(380)	$(67)	$83	$(97)	$16	$(81)	$-	net savings	net savings
Pricing	(2,299)	$-	$667	$(201)	$667	$466	$290	$203	$203
Smart Mobility	(398)	$-	$27	$(3)	$27	$23	$67	$67	$59
TDM	(64)	$(29)	$23	$(5)	$(7)	$(12)	$350	net savings	net savings
Transit	(204)	$(27)	$1,896	$(4)	$1,869	$1,865	$9,303	$9,171	$9,151
Travel Scenarios w/higher fuel prices									
Active Transportation	(246)	$(88)	$83	$(97)	$(5)	$(103)	$337	net savings	net savings
Land Use	(380)	$(88)	$-	$(9)	$(88)	$(97)	$-	net savings	net savings
Pricing	(2,299)	$-	$667	$(201)	$667	$466	$290	$203	$203
Smart Mobility	(398)	$-	$27	$(3)	$27	$23	$67	$67	$59
TDM	(64)	$(39)	$23	$(5)	$(17)	$(21)	$350	net savings	net savings
Transit	(204)	$(35)	$1,896	$(4)	$1,861	$1,857	$9,303	$9,132	$9,112

Figure 38. Electrification Costs and Cost Savings, High Energy Prices

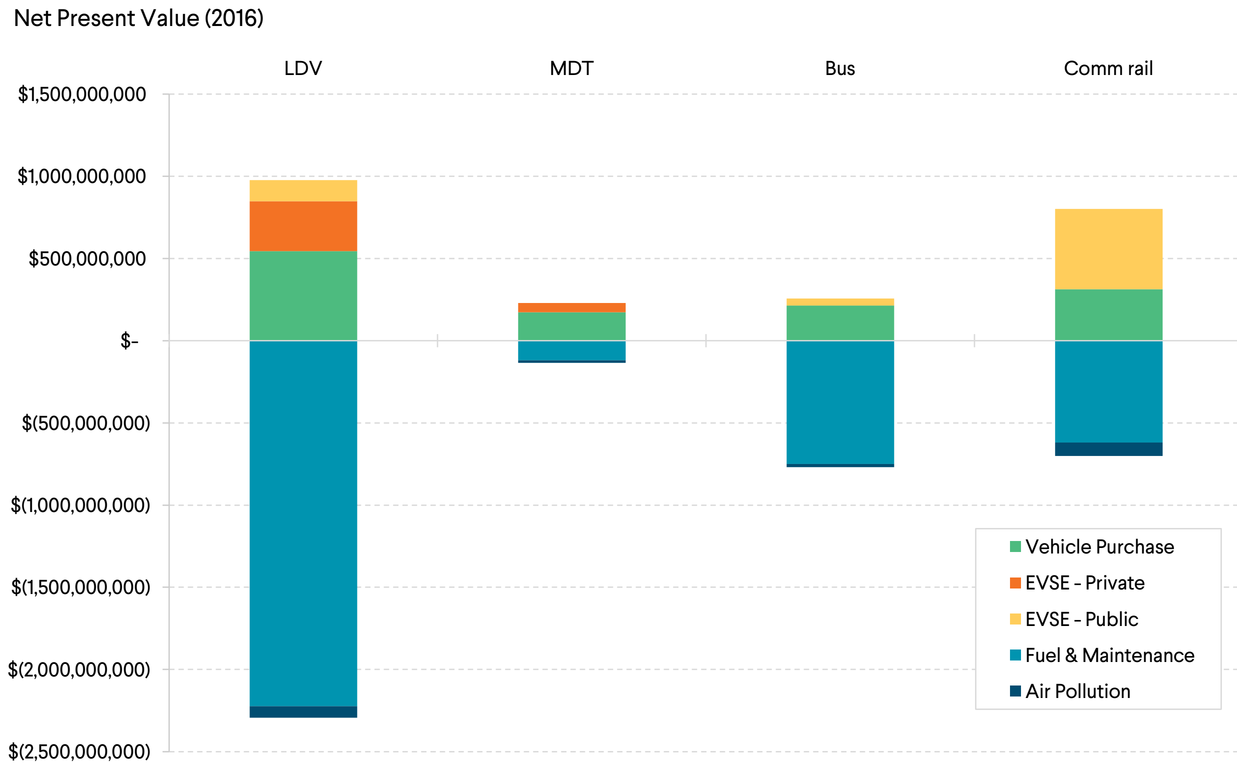


Figure 39. Marginal Abatement Cost Curve for Transportation

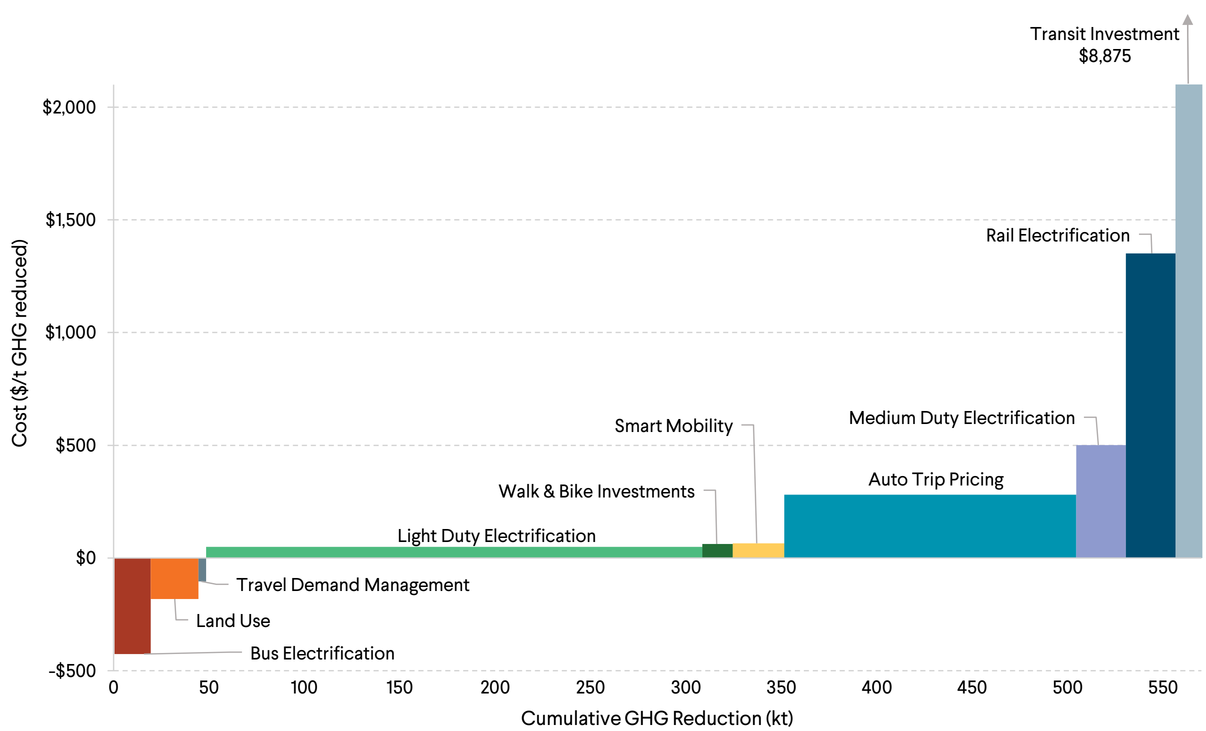


Table 27. Key Cost Assumptions

Cost Item	Units	Cost per Unit	Source
Discount rate		4%	
LDV: BEV-200 – 2020 incremental	Vehicle	$9,494	Wolfram & Lutsey [41]
LDV: BEV-200 - 2030 incremental		$3,165	"
LDV: PHEV-30 - 2020 incremental	Vehicle	$4,171	"
LDV: PHEV-30 - 2030 incremental		$2,733	"
MDV: EV - 2020 incremental	Vehicle	$90,000	Mai et al. [37], Figure 8
MDV: EV - 2030 incremental		$60,000	"
LDV: Maint cost savings/year: BEV	$/vehicle	$75	Mai et al. [37], Table 8
LDV: Maint cost savings/year: PHEV	$/vehicle	$37	"
MDT: Maint cost savings/year: BEV	$/vehicle	$531	"
Bus: Maint cost savings/year: BEV	$/vehicle	$6,947	"
Transit bus: EV - Incremental	Vehicle	$200,000	Various (EV - $800,000 vs. hybrid - $600,000)
Commuter rail: EV - Incremental	Vehicle	$1,166,667	Same price as diesel ($2.2M) but accelerated replacement
Commuter rail: electric catenary	Mile 2-way	$2,000,000	http://cs.trains.com/trn/f/111/t/189389.aspx
Miles of commuter rail	Miles 2-way	398	MBTA, Wikipedia
Charging station: home	Station	$1,500	Mai et al. [37], Cole [69]
Charging station: curbside/garage	Station	$5,000	Mai et al. [37], Cole [69]
Charging station: curbside - fast	Station	$60,000	Mai et al. [37], Cole [69]
Charging station: MDT - fast	Station	$20,000	Mai et al. [37], Table 10
Charging station: bus	Station	$40,000	Mai et al. [37], Table 10
EVSE per 1000 veh: LDT L1/L2 home/work		1,200	Mai et al. [37], Table 9
EVSE per 1000 veh: LDT L1/L2 public		15	"
EVSE per 1000 veh: Public DCFC		0.5	"
EVSE per 1000 veh: MDT		1,000	
PHEV electric travel fraction	% of miles	60%	
Scrappage of 15-year old LDV (2049)		$2,000	
Scrappage of 15-year old MDT (2049)		$5,000	
Bus ops efficiency: capital	Mile 2-way	$11,000	CS research
Bus ops efficiency: operating	Mile 2-way/yr	$1,400	"
BRT construction	Mile 2-way	$20,000,000	Sample projects
BRT vehicle (EV)	Vehicle	$800,000	Recent reports and news articles
BRT operating	$/VRH	$153	National Transit Database [31] for MBTA – Motor Bus (MB)
Urban rail construction	Mile 2-way	$50,000,000	Sample projects
Urban rail vehicle	Vehicle	$2,200,000	CS research (review of transit agency purchases)
Urban rail operating	VRH	$153	National Transit Database [31] for MBTA - LR/HR
Transit priority infrastructure	Mile 2-way	$11,000	Build-up of costs from various sources
Bike lane construction	Mile 2-way	$25,000	CS research (maintenance @ 10% of construction/yr)
SBL/BB construction	Mile 2-way	$200,000	" (used as average for all facilities per mile)
Shared-use path construction	Mile 2-way	$1,000,000	"

Cost Item	Units	Cost per Unit	Source
Bike lane/path maintenance	% of constr cost per year	10%	
Ped. intersection improvements	Intersection	$75,000	200 over 10 years = $1.5M/year
Cordon pricing - gantries & design	System	$150,000,000	MassDOT all-electronic tolling[a]
Road pricing – administrative costs	Annual, % of revenue	1%	Oregon DOT Mileage Based User Fee Study [70] estimated admin costs at <3% of revenue
Smart mobility pricing – administrative costs	$ per transaction	$0.01	
TDM - administration	Staff person	$150,000	Loaded labor cost (salary, benefits, overhead)
Vehicle op cost: non-fuel: LDV	$/VMT	$0.12	AAA [71], maint/repair + depreciation/mile
Motor veh crash cost per VMT	$/VMT	$0.14	CS research, based on FTA New Starts factors
Health benefit of walk & bike	$/PMT	$0.21	Gotschi [50]
Time savings	$/pax-hr	$14.80	USDOT BCA guidance June 2018
Valuation - $PM_{2.5}$	$/kg	$976.00	CS research for FTA
Valuation - NO_x	$/kg	$17.69	"

a Pricing costs: The MassDOT 2014-18 CIP listed $160 M to complete all-electronic tolling on the Mass Pike and harbor tunnels, including ramp reconfiguration (possibly $93 million without ramps). A MassDOT press release stated $130 M to design and build system, with 16 gantries ($8 million/gantry), plus $133 million for toll plaza removal/reconstruction. This study estimates $6 million per tolling point with 25 tolling points. Cordon pricing systems implemented in London and Stockholm required an initial investment of $400 to $500 million, or about $35 to $50 million per square mile covered; annual operating costs for the London system were noted at about $170 million or 40 percent of annual revenues. A congestion pricing system in Manhattan was projected to incur $224 million in capital cost and $229 million in annual operating costs [72]. It is likely that current technology would reduce costs for a Boston system, although annual operating costs also were not accounted for in this study. Costs would likely be lower if system were to be combined with a GPS-based tracking system potentially required for some implementation of state VMT pricing.

11.3 Revenue Generation

The road pricing strategies evaluated in this report would generate substantial revenues. After paying expenses for program administration and enforcement, the remaining revenue could potentially be reinvested in transportation improvements, modal subsidies (e.g., reduced transit or shared-ride fares), and/or redistributed to taxpayers. The revenue generated or subsidy required by each pricing strategy will depend upon the total number of trips by the priced or subsidized mode and therefore will be different under combined policy scenarios than if any particular strategy were applied by itself.

The VMT fee is estimated to generate about $440 million per year based on 6.5 million daily VMT (2050) with at least one trip-end in Boston. This is under Scenario 5 which includes combined demand reduction policies. If applied by itself, the revenue generation would be higher – over $700 million per year at 2050 baseline VMT levels of just over 10 million per day. This revenue would presumably flow into a statewide fund which would be redistributed towards transportation investment and/or tax reduction on a statewide basis (along with additional revenue generated by outside-Boston VMT).

The central area congestion charge is estimated to generate about $3 billion of revenue annually in 2050 under Scenario 5. The $5 parking fee is estimated to generate about $1.5 billion annually in 2050 under Scenario 5, based on 1.2 million daily trips driving into Boston. These revenue levels would more than double if the price levels were applied to baseline conditions with no other policies in place.

The smart mobility cross-subsidy ($1/mile fee on ride-alone, $1/mile discount on shared-ride) would require a subsidy of about $1 billion at Scenario 5 smart mobility ridership levels. That estimate is based on 453,000 daily ride-alone trips and 863,000 daily shared-ride trips in 2050.

The transit fare subsidies (free walk-access trips, half-price drive-access trips) would require a subsidy of about $1.6 billion per year under Scenario 5 conditions, based on 864,000 daily walk-access trips and 199,000 daily drive-access trips. This represents an increase in total transit trips of 56 percent compared to baseline 2050 conditions.

The net effect of all the pricing and subsidy policies, combined, would be new revenue of about $2.2 billion annually in 2050 that would be available for reinvestment and/or reductions in other taxes. This assumes that administrative and enforcement costs are about 1 percent of gross revenues and subsidies, or $76 million a year.

Table 27 shows daily person-trips and vehicle-trips produced in 2050, as well as modal shares, under baseline and Scenario 5 policy conditions. “In Boston” refers to trips starting and ending in Boston. “Region” refers to trips with one end in Boston, and one end elsewhere.

Table 28. Summary of Baseline and Scenario 5 Trips

Daily Trips Produced in 2050	in Boston	Region
Vehicle Trips		
Private Vehicle, Vehicle Trips Produced		
Baseline	1,617,101	2,659,069
Scenario 5 Change vs. Baseline	(950,981)	(1,446,629)
Scenario 5 New Total	666,119	1,212,440
% Change vs. Baseline	-59%	-54%
Shared Mobility Vehicle Trips Produced		
Baseline	69,552	90,969
Scenario 5 Change vs. Baseline	545,595	793,374
Scenario 5 New Total	615,148	884,343
% Change vs. Baseline	784%	872%
Total Auto (Private + SM) Vehicle Trips Produced		
Baseline	1,686,653	2,750,038
Scenario 5 Change vs. Baseline	(405,386)	(653,254)
Scenario 5 New Total	1,281,267	2,096,784
% Change vs. Baseline	-24%	-24%
Person Trips		
Private Vehicle, Person Trips Produced		
Baseline	2,010,145	3,250,585
Scenario 5 Change vs. Baseline	(1,156,397)	(1,827,466)
Scenario 5 New Total	853,748	1,423,120
% Change vs. Baseline	-58%	-56%
Shared Mobility Person Trips Produced		
Baseline	79,899	104,502
Scenario 5 Change vs. Baseline	804,166	1,211,342
Scenario 5 New Total	884,065	1,315,844
% Change vs. Baseline	1006%	1159%
Transit Trips Produced		
Baseline	470,680	681,282
Scenario 5 Change vs. Baseline	201,727	382,093

Daily Trips Produced in 2050	in Boston	Region
Scenario 5 New Total	672,406	1,063,374
% Change vs. Baseline	43%	56%
Walk + Bike Trips Produced		
Baseline	973,448	1,081,711
Scenario 5 Change vs. Baseline	106,315	186,430
Scenario 5 New Total	1,079,763	1,268,141
% Change vs. Baseline	11%	17%
Total Person Trips Produced		
Baseline	3,534,172	5,118,079
Scenario 5 Change vs. Baseline	(44,189)	(47,600)
Scenario 5 New Total	3,489,983	5,070,479
% Change vs. Baseline	-1%	-1%
Share of Trips by Auto		
Baseline	59%	66%
Scenario 5	50%	54%
Share of Trips by Transit, Walk, and Bike		
Baseline	41%	34%
Scenario 5	50%	46%

12 Policy Implications

Table 28 presents potential policies to support clean transportation and work towards net zero emissions. Some policies should be implemented in the short term to achieve maximum long-term benefits, especially those which are lower cost, respond to immediate needs, or affect the built environment, which changes slowly over time. Others may be considered for mid- or long-term implementation depending upon whether technology and markets are moving in a favorable or unfavorable direction with respect to GHG emissions, and to provide time to gather the necessary political and financial support. More detailed policy summary tables are included as an attachment to this report. Summarizing the emissions savings, energy savings, air pollution reductions, and costs, timing of each strategy, key modeling assumptions, key issues that may need to be considered, and potential economic development implications.

Table 29. City of Boston Policies to Work towards Carbon Neutrality

Policy	Timing	Contingencies
Requirements for clean transportation amenities in new development (EV charging infrastructure & readiness, continue/expand TDM requirements)	1-2 years	Initial limited EV charging requirements with readiness to expand later based on EV demand growth
Policies to support micro-mobility such as electric bicycles (safe and equitable service provision and operation)	1-2 years	Technologies are experimental, adapt regulations as they evolve and use is demonstrated
Testing of policies to encourage multi-occupancy shared vehicle use	1-3 years	Introduce as TNC ridesharing services are demonstrated successful When services are fully developed, stabilize policies at an optimum level
Zoning changes to increase population and jobs near transit and encourage reductions in vehicle use	1-5 years	Prioritize neighborhoods with highest demand and largest gap between current and desired zoning

Policy	Timing	Contingencies
Travel pricing options (e.g., cordon/ congestion pricing, parking fees, fees for high-emission vehicles)	2-5 years+	Start with modeling and pilot tests to explore options, develop political support, address equity
Programs to support commercial light/ medium truck EV adoption (information, incentives, partnerships)	2-5 years+	Begin with pilots for niche fleet applications, expand as technology is demonstrated
Policies to regulate the technology and use of self-driving vehicles	2-10 years	Prepare in advance, and implement as these vehicles come to market and use cases are observed
Subsidies, incentives, or direct investment in EV charging facilities serving existing multi-family and commercial buildings	5-10 years	Implement as a clear market for EVs (beyond early adopters) is demonstrated
Higher cost transit investments	5-10 years	Build political support for increased revenue stream
Restrictions on ICE vehicles	10 years+	Consider if EV technology is advanced enough to address equity and economic concerns; provide multi-year advance notice
Strategically located public charging infrastructure for EVs	Ongoing	Expand over time to support growing demand
Additional funding for investments to implement Complete Streets, bike, pedestrian, and transit improvements in street work	Ongoing	Continue as part of all street work; accelerate additional low-cost improvements; make higher-cost improvements as funding can be obtained
Curb space reprioritization to support active transportation, transit, and shared mobility	Ongoing	Initial experiments in locations/ times with high TNC use and priority bike routes; expand depending on mode shift over time and evaluation of impacts
Low-cost transit speed and reliability improvements	Ongoing	Continue pilot implementation in priority bus corridors; expand to full implementation as pilots are demonstrated successful and funding and support can be obtained
Continue/ expand EV purchases for public fleets (city fleets and transit)	Ongoing	Replace existing fleet vehicles with EVs as technologically and financially feasible for the intended application
Partnerships with neighboring communities and regional and state agencies to promote electrification and non-auto travel options	Ongoing	

13 Issues for Future Consideration/Analysis

The following are some issues that could not be fully investigated in this study and may warrant further policy development and analysis:

- **Public sector levers in EV infrastructure development**; in particular, how can EVSE be financed or incentivized in existing multifamily and commercial buildings? How can the challenges of existing buildings without off-street parking be addressed?
- Policies and market potential for **light and medium duty commercial truck electrification**. Truck registration should be examined by ownership (fleets vs. individual) and vocation, and opportunities and barriers for electrification considered. For what part of the commercial truck market does electrification make sense? How can the City influence that market?
- Further development of **coordinated land use and travel reduction policies**. How can the city focus growth to maximize transportation efficiency within land use constraints?
- **Equity mitigation strategies**, especially with respect to pricing. How can pricing policies be implemented to support clean mobility and in a way that mitigates equity concerns?
- **Pricing and economic development.** Pricing could have very beneficial effects to the region's economy by reducing congestion and funding new transit and multimodal capacity, but could also discourage businesses that are more dependent on automobile access. What is the balance of the effects? How can negative effects by mitigated and positive effects by maximized?
- **Long-term auto ownership and travel impacts of widespread smart mobility**. More locally-specific data would be very useful to examine how ownership might change under future situations where smart mobility and other travel options are widespread and reduce the need to own a car.

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PEOPLE AND ORGANIZATIONS

Technical Advisory Group for Transportation

Name	Organization
Kevin Boughan	Eversource
Kathryn Carlson	A Better City
Hong-Hanh Chu	Commomwealth of Massachusetts
Bronwyn Cooke	City of Cambridge
Sean Donaghy	Massachusetts Bay Transportation Authority
Sandeep Dudhwewala	National Grid
Marc Ebuña	Transit Matters
Peter Furth	Northeastern University
Steve Gehrke	Metropolitan Area Planning Council
Jay Gordon	Massachusetts Institute of Technology
Henry Kelly	Boston University/ University of Michigan
Jonathan Lee	Boston Planning & Development Agency
Jieping Li	Boston Region Metropolitan Planning Organization
Darlene Lombos	Community Labor United
Rafael Mares	Conservation Law Foundation
Benjamin Miller	Commomwealth of Massachusetts
Mackay Miller	National Grid
Khalida Smalls	Community Labor United
Eric Sundquist	Smart State Transportation Initiative
Josh Weiland	City of Boston
Elizabeth Weyant	Metropolitan Area Planning Council
Jules Williams	Commonwealth of Massachusetts

Conflict of Interest Disclosures

Christopher Porter, Martin Milkovits, Xiao Yun (Jane) Chang, Scott Boone, Michael Walsh, Joshua Castigliego, and Cutler Cleveland declare that they have no affiliations with or involvement in any organization or entity with any financial or non-financial interest in the subject matter or materials discussed in this report.

ABBREVIATIONS

AEO	Annual Energy Outlook
AFDC	US DOE Alternative Fuels Data Center
BEV	Battery Electric Vehicles
CAV	Connected/ Autonomous Vehicles
CNG	Compressed Natural Gas
CO_2e	Carbon Dioxide Equivalent
CTPS	Central Transportation Planning Staff
DEP	Massachusetts Department of Environmental Protection
EFS	NREL Electrification Futures Study
EV	Electric Vehicle
EVSE	Electric Vehicle Support Equipment
GHG	Greenhouse Gas
GTFS	General Transit Feed Specification
GVWR	Gross Vehicle Weight Rating
HOV	High-Occupancy Vehicle
ICE	Internal Combustion Engine
LDV	Light-Duty Vehicle
LNG	Liquefied Natural Gas
MA3T	Market Acceptance of Advanced Automotive Technologies
MAPC	Metropolitan Area Planning Council
MassDOT	Massachusetts Department of Transportation
MBTA	Massachusetts Bay Transportation Authority
MDT	Medium-Duty Truck
MDV	Medium-Duty Vehicle
MEPA	Massachusetts Environmental Policy Act
MOVES	Motor Vehicle Emissions Simulator Model
MPGGE	Miles per Gallon of Gasoline Equivalent
MPO	Boston Region Metropolitan Planning Organization
MY	Model Year
NREL	National Renewable Energy Laboratory
NTD	National Transit Database
PHEV	Plug-in Hybrid Electric Vehicles
PMT	Person-Miles of Travel
RFS2	Renewable Fuel Standard
SM	Shared Mobility
t CO_2e	Tonnes (Metric ton) of CO_2e
TAZ	Traffic Analysis Zone
TDM	Travel Demand Management
TIP	MPO's Transportation Improvement Program
TRIMMS	Trip Reduction Impacts of Mobility Management Strategies
VHT	Vehicle-Hours of Travel
VMT	Vehicle-Miles of Travel
W	Watt
Wh	Watt-hour
ZEV	Zero Emission Vehicle

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