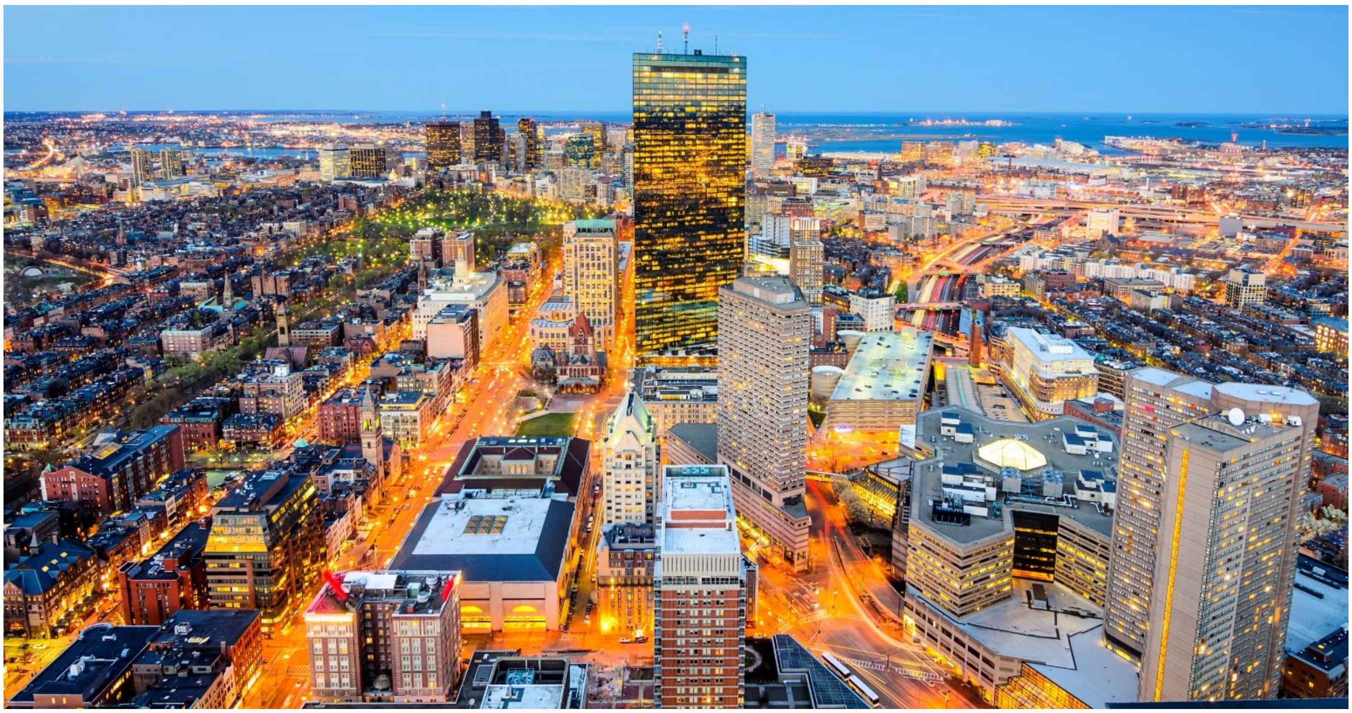
Decarbonizing Transportation

The Benefits and Costs of a Clean Transportation System in the Northeast and Mid-Atlantic Region



MJB & A

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Contents

Acknowledgements

Lead Authors: Dana Lowell, Amlan Saha, and Christopher Van Atten

This independent report, *Decarbonizing Transportation*, explores and documents the costs and benefits of a suite of abatement strategies that could be used to significantly reduce greenhouse gas emissions from on-road transportation within the Northeast and Mid-Atlantic region. This report is intended to inform and assist government officials and stakeholders within the region, as they undertake efforts to address the challenges of climate change and adaptation, while striving to further improve local air quality.

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This report reflects the analysis and judgment of the authors only and does not necessarily reflect the views of UCS or any of the reviewers.

This report is available at www.mjbradley.com.

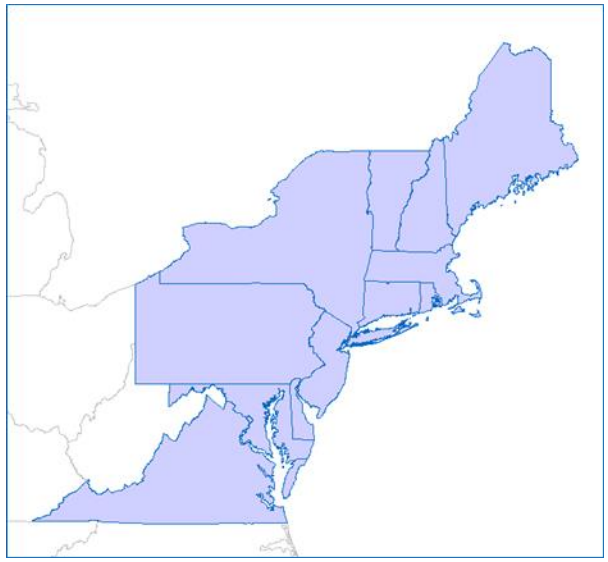
About M.J. Bradley & Associates

M.J. Bradley & Associates, LLC (MJB&A), founded in 1994, is a strategic consulting firm focused on energy and environmental issues. The firm includes a multi-disciplinary team of experts with backgrounds in economics, law, engineering, and policy. The company works with private companies, public agencies, and non-profit organizations to understand and evaluate environmental regulations and policy, facilitate multi-stakeholder initiatives, shape business strategies, and deploy clean energy technologies.

For questions or comments, please contact:

Dana Lowell
Senior Vice President
M.J. Bradley & Associates, LLC
+1 978 369 5533
dlowell@mjbradley.com

Introduction



This analysis explores the costs and benefits of abatement strategies that could be used to significantly reduce greenhouse gas (GHG) emissions from on-road transportation in the Northeast and Mid-Atlantic states. The results indicate that this 12-state region (Maine to Virginia, plus DC) could achieve a 60 – 80 percent reduction in on-road GHG emissions by 2050 using three broad strategies: (1) Increased fuel efficiency of new conventional vehicles; (2) Decarbonizing traditional liquid transportation fuels; and (3) High levels of transportation electrification combined with further efforts to decarbonize electricity production.

Achieving this level of GHG reduction within the region will require a societal investment of $12 billion - $25 billion (2015$) over the next 10 – 12 years, primarily to support vehicle electrification. However, by 2030, annual fuel cost savings will outweigh the incremental annual purchase costs for electric vehicles (EVs). By 2037, the total societal investment required to put the region on a path to achieve these GHG reductions will be paid off, and the region will start to see net financial savings. By 2050, the cumulative net financial savings for the region's residents are projected to be more than $150 billion – or at least seven times the initial societal investment.

In addition to significantly reducing GHG emissions, the modeled abatement strategies are projected to reduce net nitrogen oxide (NOx) and particulate matter ($PM_{2.5}$) emissions from vehicles. The cumulative monetized value of these emissions reductions (GHG, NOx and $PM_{2.5}$) is projected to be $144 billion – $226 billion through 2050.

Including both financial and environmental net benefits, the total cumulative societal benefits from these GHG reductions are estimated to be $311 billion – $383 billion.

Methodology

Having made significant progress in curbing air pollution from power plants, the Northeast and Mid-Atlantic states, including Washington, D.C., have begun discussing options to address emissions from the transportation sector [1]. The transportation sector, including cars, buses, trucks, and other vehicles, is the largest contributor to the region's carbon dioxide (CO_2) emissions, accounting for approximately 40 percent of emissions [2]. In the absence of meaningful progress to address transportation sector emissions, states in the region will be unable to meet their economy-wide GHG reduction targets.

This report evaluates the costs and benefits of three major strategies aimed at significantly reducing emissions from on-road vehicles, including: (1) increased fuel efficiency of new vehicles; (2) widespread vehicle electrification; and (3) decarbonizing traditional liquid transportation fuels. The geographic scope of the analysis is the coastal region from Maine to Virginia, including the District of Columbia, and the time period is through 2050.[1]

[1] Study region: Vermont, New Hampshire, Maine, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Maryland, Delaware, District of Columbia, Pennsylvania, and Virginia.

The analysis focuses on personal vehicles (cars and light trucks), medium- and heavy-duty single unit trucks, transit and school buses, and heavy-duty combination trucks (also known as tractor trailer trucks or semis). Together these vehicles accounted for more than 80 percent of the region's transportation-related carbon emissions in 2015.

Figure 1 summarizes the three abatement scenarios modeled for this project (Baseline, Mid Case, and High Case) and the assumptions included in each scenario. The Baseline is a "business as usual" case with no change to current federal new vehicle fuel efficiency and GHG standards[2], no policies designed to reduce the carbon intensity of traditional liquid fuels, and relatively low levels of vehicle electrification. The Mid and High cases include annual increases in new vehicle fuel efficiency beyond current standards, annual reductions in the carbon intensity of liquid transportation fuels, and significantly higher levels of EV penetration than in the Baseline scenario. The High Case and Mid Case scenarios have the same fuel efficiency standards for conventional vehicles. However, the Mid Case has less aggressive electric vehicle penetration, less aggressive decarbonization of the electric grid, and a later start date for annual reductions in liquid fuel carbon intensity than the High Case.

The combinations of measures modeled here is not intended to suggest an optimal mix of strategies, or a combination of specific policies designed to implement these strategies; however, it does provide a basis for analysis and a plausible mix of abatement measures that could be used to meet state GHG reduction goals.

Figure 1 Baseline and Abatement Scenario Assumptions

	Increased New Vehicle Efficiency	Vehicle electrification*	Decarbonized Fuels
Passenger cars and light trucks	**Baseline:** Current GHG emission standards through MY2025 **Mid and High Case:** 5% annual increase MY2026-2030; 2% annual increase MY2031-2050	**Baseline:** <1% EV penetration **Mid Case:** 70% by 2050 **High Case:** 90% by 2050	Lower carbon intensity for liquid fuels in the total transportation pool: **Baseline:** N/A **Mid Case:** -2% (2020); -6% (2030); -10% (2050) **High Case:** -3% (2020); -8% (2030); -16% (2050) Reductions are relative to 2010 carbon intensity
Single unit trucks	**Baseline:** Current GHG emission standards through MY2027 **Mid and High Case:** 1.5% annual increase MY2028-2050	**Baseline:** <1% EV penetration **Mid Case:** 30% by 2050 **High Case:** 70% by 2050	
Transit and school buses	**Baseline:** Current GHG emission standards through MY2027 **Mid and High Case:** 1.5% annual increase MY2028-2050	**Baseline:** <1% EV penetration **Mid Case:** 75% by 2050 (transit); 30% by 2050 (other buses) **High Case:** 95% by 2050 (transit); 70% by 2050 (other buses)	
Combination trucks	**Baseline:** Current GHG emission standards through MY2027 **Mid and High Case:** 1.5% annual increase MY2028-2050	**Baseline:** <1% EV penetration **Mid Case:** 5% by 2050 **High Case:** 30% by 2050	

* EV penetration is the percentage of all in-use vehicles that are plug-in, both battery-electric and plug-in hybrid. The grid mix assumed to satisfy incremental demand for electricity varies between the mid-case and the high-case, with a lower carbon grid mix in the High Case.

[2] In August 2018 the Department of Transportation and Environmental Protection Agency proposed flat-lining fuel efficiency and GHG emission standards at 2020 levels through 2026. As the fate of this proposal is still uncertain, for this analysis the baseline scenario includes current fuel efficiency and emission requirements through model year 2025, although these standards are likely to be less stringent than what is included in the baseline when the rule is finalized.

This analysis only addresses on-road vehicles – it excludes air travel, non-road freight transport (rail, water, and pipeline), and other non-road vehicles (e.g., construction equipment, port handing equipment). These segments of the transportation system offer further opportunities to reduce air pollution and GHG emissions but were beyond the scope of this study.

As shown in Figure 1, the modeled abatement scenarios also did not include enhancements to public transportation or other approaches designed to slow the growth of, or reduce, personal vehicle travel miles, or freight system enhancements or mode shifting to slow the growth of, or reduce, medium- and heavy-duty truck miles. Again, these strategies would offer further opportunities to reduce air pollution and GHG emissions from transportation but were beyond the scope of this study.

Based on current projections from the Energy Information Administration, this study assumes that light-duty vehicle miles traveled (VMT) will grow by 0.4 percent annually, and that medium- and heavy-duty vehicle miles will grow by 1.1 percent annually in the region (compound annual growth rate). Lower VMT growth would result in greater net GHG reductions than those summarized here, while higher VMT growth would result in lower net GHG reductions. However, due to the very high levels of vehicle electrification and low-carbon electricity in our modeled scenarios net GHG reductions in 2050 (from 1990 levels) are not very sensitive to VMT growth assumptions. Under the High scenario, a 10 percent change in 2050 light duty VMT would only produce a 0.27 percentage point change in net GHG reductions from 1990 levels. A 10 percent change in 2050 medium- and heavy duty VMT would produce a 0.58 percentage point change in net GHG reductions.

Summary of Results

M.J. Bradley & Associates used several modeling tools to evaluate the benefits and costs of the two Abatement Scenarios (Mid Case and High Case) within the study region, relative to the Baseline scenario. The methodology is discussed in more detail in Appendix A and B.

The major benefits of these abatement measures include significant reductions in gasoline and diesel fuel use and resulting reductions in net greenhouse gas (GHG) emissions, as well as reductions in net emissions of nitrogen oxides (NOx) and particulate matter ($PM_{2.5}$). The modeled reductions in gasoline and diesel use also produce significant reductions in net fuel costs, as well as higher net revenue for electric utilities, which can be used to maintain existing infrastructure and put downward pressure on future electricity rates.

The costs associated with these abatement measures include higher vehicle purchase costs compared to "baseline" vehicles without these policies, the cost of necessary electric vehicle charging infrastructure, costs required to reduce the carbon intensity of liquid transportation fuels, and costs to supply additional electricity for electric vehicles, including costs related to further reducing the carbon intensity of this electricity[3].

The costs associated with reducing the carbon intensity of traditional transportation fuels were modeled as incremental costs required to purchase the volume of renewable liquid fuels necessary to comply with the modeled carbon intensity targets. The costs associated with the accelerated adoption of electric vehicles included the incremental costs required to supply a mix of renewable and natural gas-fired electricity for vehicle charging, including the costs of battery storage technology to integrate additional renewable energy resources (wind and solar).

Figure 2 Benefits and Costs Evaluated by This Study

Monetized Benefits

- Fuel savings – reduced gasoline and diesel fuel purchases
- Vehicle maintenance costs – lower maintenance costs for electric vehicles
- Carbon abatement – climate benefits based on the social cost of carbon
- NOx and $PM_{2.5}$ reductions – value of reduced morbidity and premature mortality
- Utility net revenue – higher net revenues place downward pressure on electricity rates

Monetized Costs

- Vehicle costs – higher purchase price for more efficient and electric vehicles
- Charging infrastructure – charging equipment required to support electric vehicles
- Electricity generation and storage costs – added generation and battery storage required to supply electric vehicles with low carbon electricity
- Liquid fuels – incremental cost of renewable liquid fuels to reduce carbon intensity of liquid fuel pool

[3] Beyond current state and regional mandates for reduced carbon intensity of electricity generation.

Increased Fuel Efficiency for New Vehicles

Congress first established the Corporate Average Fuel Economy (CAFE) standards for cars in 1975, in response to the 1973 oil embargo. CAFE standards, which are set by The National Highway Traffic Safety Administration (NHTSA), part of the U.S. Department of Transportation, mandate the average new vehicle fuel economy that a manufacturer's fleet must achieve on a sales weighted basis, expressed in miles per gallon. The U.S. EPA has also established greenhouse gas emissions standards for vehicles that coordinate with the fuel economy standards. EPA's standards are expressed as grams of CO_2 per mile.

The California Air Resources Board (CARB) also has the authority to set their own GHG emission standards but has chosen to work with the federal government to harmonize the standards. The current joint fuel economy and GHG emission standards require increased fuel efficiency and reduced CO_2 emissions annually through the 2025 model year. In August 2018 the Department of Transportation and Environmental Protection Agency proposed flat-lining federal fuel efficiency and GHG emission standards at 2020 levels through 2026. CARB has indicated that they intend to maintain their standards at current levels.

Under Section 177 of the Clean Air Act, other states can adopt the CARB standards instead of EPA standards; twelve states and the District of Columbia have already done so, including Connecticut, Delaware, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Pennsylvania, Rhode Island, Vermont, and Washington.

In 2011 EPA and NHTSA also established fuel efficiency and GHG emission standards for new medium- and heavy-duty trucks, which went into effect for the 2014 model year. These standards require increased fleet average fuel efficiency and reduced CO_2 emissions for new vehicles through the 2027 model year.

Vehicle Electrification

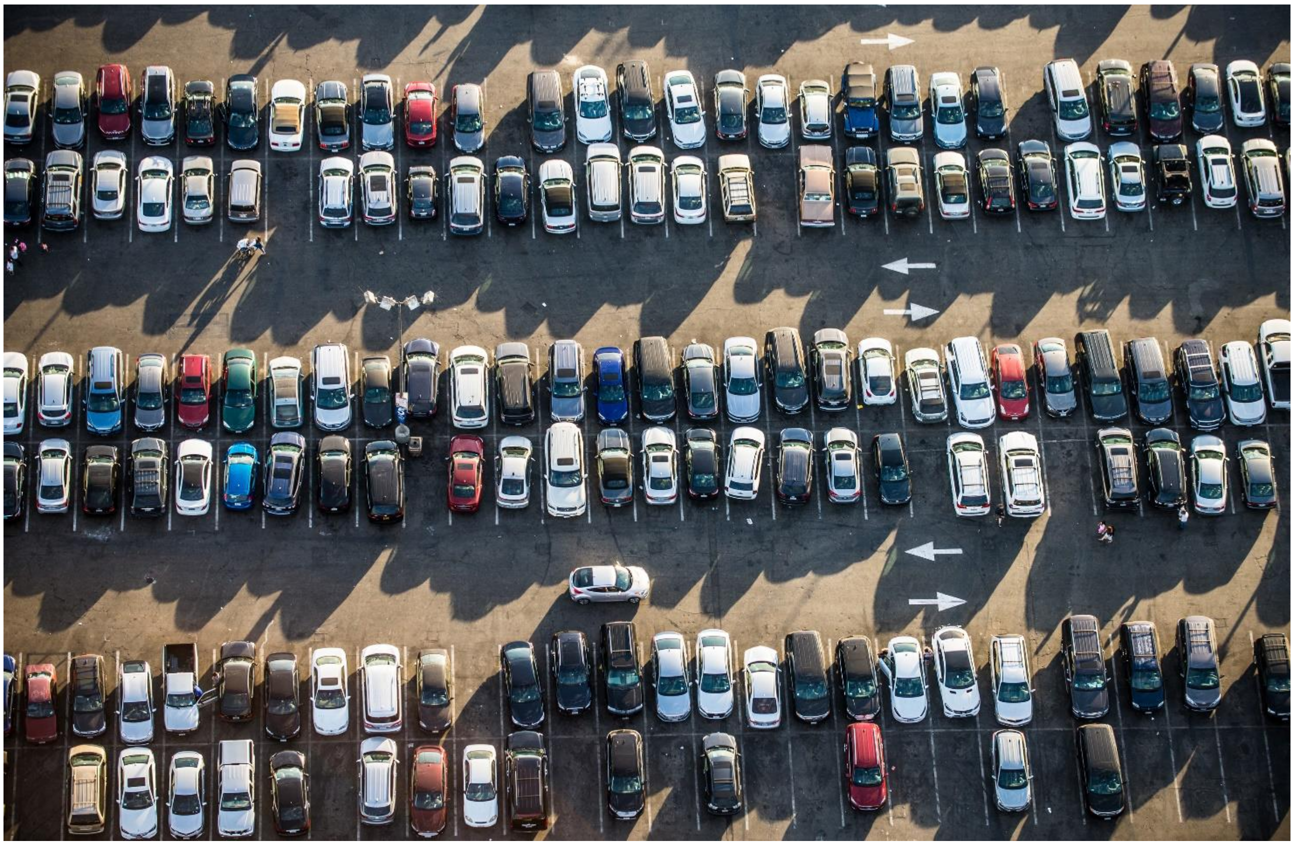
Electric vehicles have been gaining momentum in the U.S. market with a growing number of vehicle offerings and an expanding network of public charging stations. There were approximately 280,000 electric cars sold in the U.S. in 2017, making it the second largest market after China; recent estimates indicate there could be 10 – 20 million EVs on US roads by 2030. Interest in electric vehicle technology extends beyond passenger cars. Transit agencies and school districts have been piloting electric buses, cities are deploying electric garbage trucks, and several large companies have been testing electric delivery trucks.

Low Carbon Fuels

Decarbonizing transportation fuels involves substituting lower carbon fuels for the petroleum-based fuels – gasoline and diesel fuel – used by most vehicles today. Options include blending low carbon bio-fuels into conventional gasoline or diesel or replacing conventional vehicles with electric vehicles or other alternative fuel vehicles that operate on low carbon fuels.

Bio-fuel options include ethanol and bio-diesel, which can be blended with gasoline and diesel, respectively, up to limited thresholds; and drop in bio-fuels including hydrogenation-derived renewable diesel and biomethane, which can entirely substitute for their fossil fuel counterparts. On a life-cycle basis these bio-fuels have lower GHG emissions than gasoline and diesel refined from petroleum.

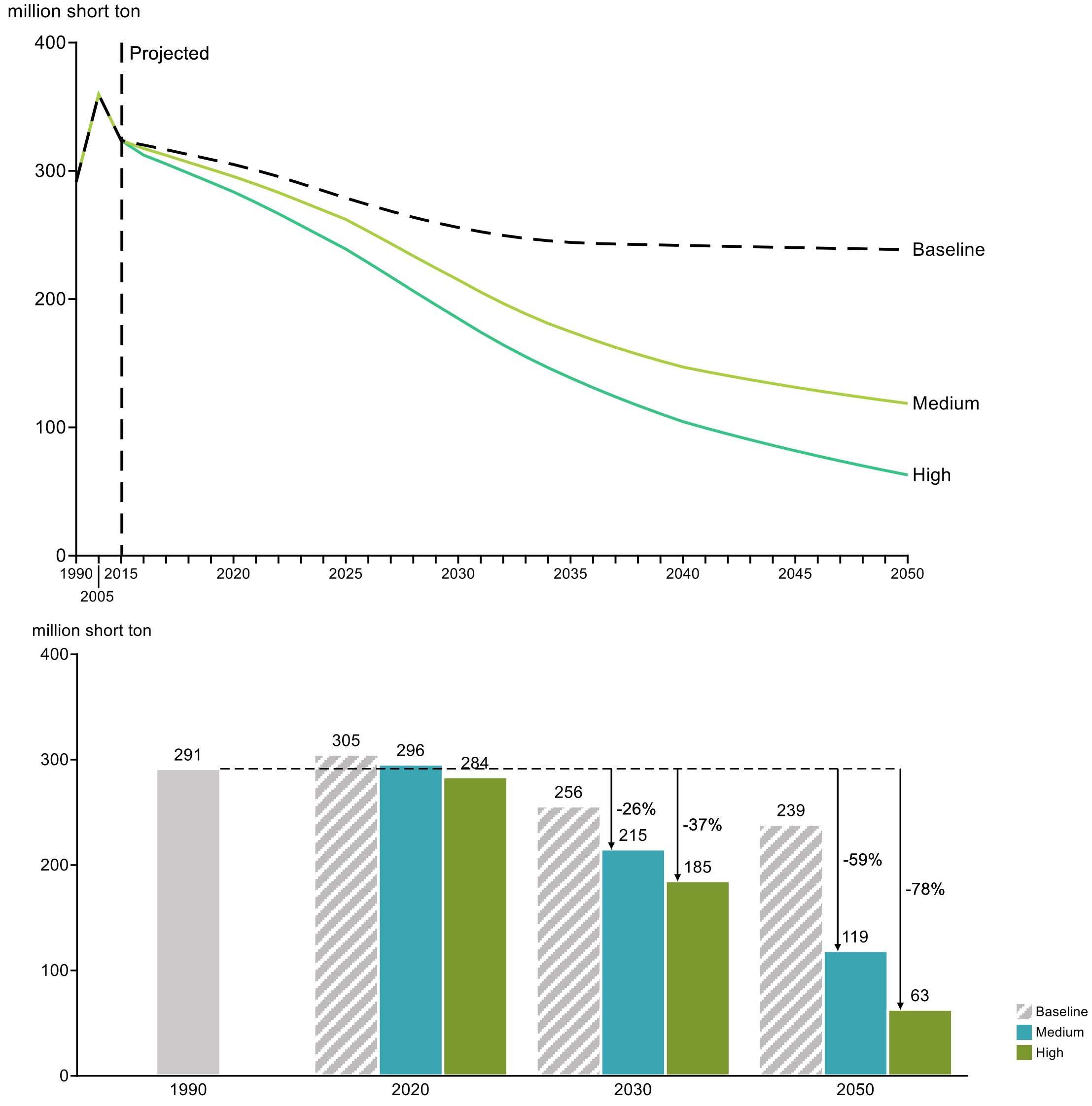
Figure 2 summarizes the monetized benefits and costs considered within the modeling framework. This study only quantifies the direct financial and environmental costs and benefits associated with the modeled abatement strategies. The study does not attempt to quantify indirect financial benefits, or security benefits, from associated macroeconomic changes (i.e., reduced imports of petroleum, more of consumers money kept in the local economy, reductions in diesel and gasoline prices due to reduced demand for these fuels). As such, the results of this study are likely conservative with respect to the magnitude of total net societal benefits resulting from GHG abatement.



Overall Carbon Abatement

The two modeled Abatement Scenarios produce significant reductions in carbon emissions from the on-road transportation sector. The High Case, which includes a combination of enhanced fuel efficiency and GHG emission standards for both light-duty and medium- and heavy-duty vehicles, high rates of electrification (powered by renewable energy sources) and increasing use of bio-fuels[4], reduces on-road transportation sector emissions by almost 80 percent below 1990 levels in 2050[5]. The Mid Case achieves a 60 percent reduction by 2050. The Baseline Scenario projects a modest decline in emissions due to the existing federal fuel efficiency and GHG emission standards.

Figure 3 Projected On-road Transportation Sector CO_2 Emissions



Direct transportation sector emissions + electrification related emissions from electric sector.
Excludes aviation fuel and residual fuel oil.

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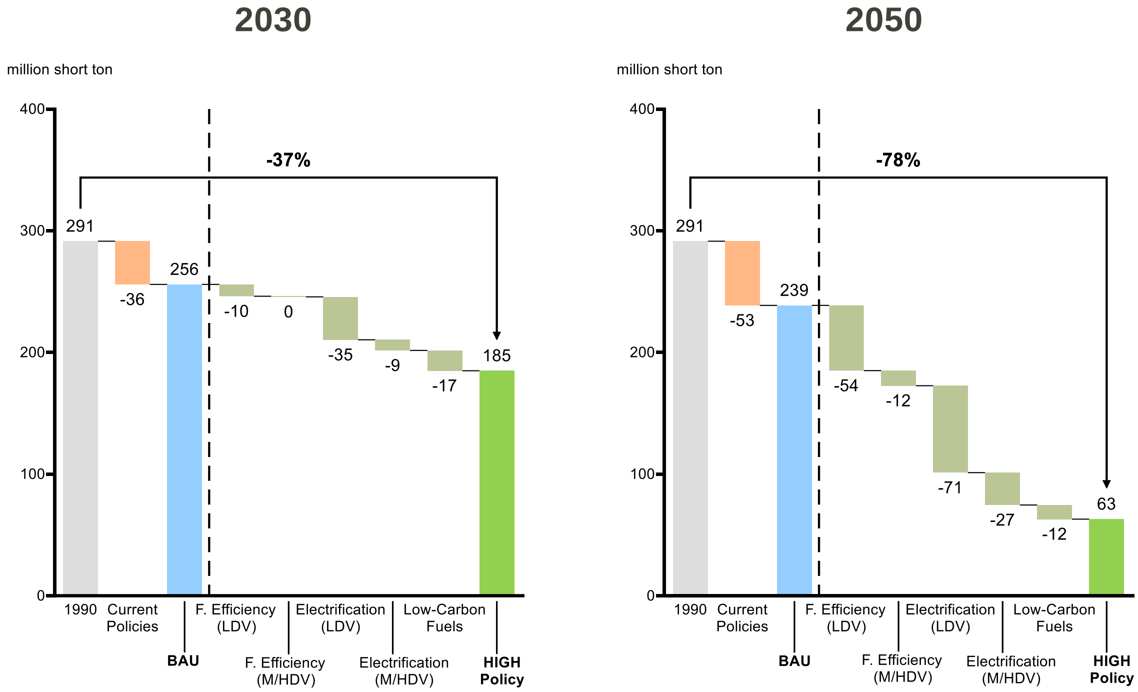
[4] To comply with targets for reduced carbon intensity of transportation fuels.
[5] This chart only includes emissions from on-road vehicles. To achieve an 80% reduction in emissions from the entire transportation sector, other strategies would need to be employed to reduce emissions from non-road equipment.

Carbon Abatement by Policy or Abatement Strategy

No single policy or abatement strategy can achieve an 80 percent reduction in transportation GHG emissions. Figure 4 illustrates the carbon emissions reductions by abatement strategy under the High Case. Light-duty vehicle electrification contributes 40 percent of the emissions abatement by 2050. Increased fuel efficiency for new light-duty vehicles contribute 31 percent, and medium- and heavy-duty vehicle electrification contributes 15 percent of the emissions abatement. Medium- and heavy-duty fuel efficiency improvements and reduced carbon intensity of liquid fuels each contribute 7 percent of the modeled emissions abatement.

Figure 4 CO_2 Reductions by Policy or Measure – High Case

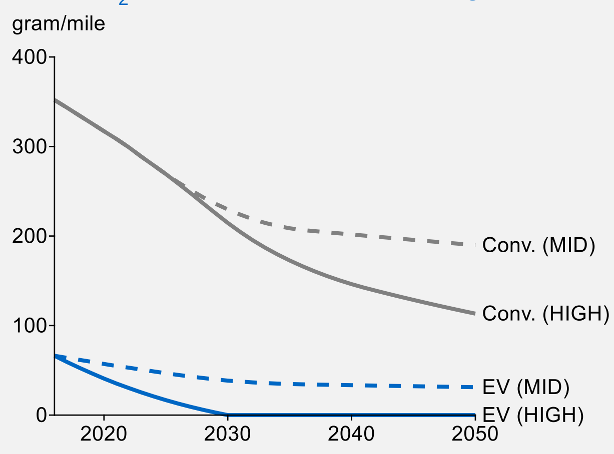


How EVs Reduce Carbon Emissions

Electric vehicles reduce carbon emissions by substituting motor gasoline and diesel fuel with lower carbon electricity. Electric vehicles are also typically more efficient than conventional vehicles. For example, with the current electric mix in New England, electric passenger car's CO_2 emissions are equivalent to a gasoline car that gets 89 miles per gallon.

In this analysis, the two abatement scenarios assume that the incremental demand for electricity from EVs is satisfied with varying combinations of natural gas and renewable energy resources—with a lower carbon resource mix in the High Scenario. (See adjacent chart for implied CO_2 emission rates of passenger cars under the two scenarios.)

CO_2 Emission Rate of Passenger Cars



Air Quality Benefits

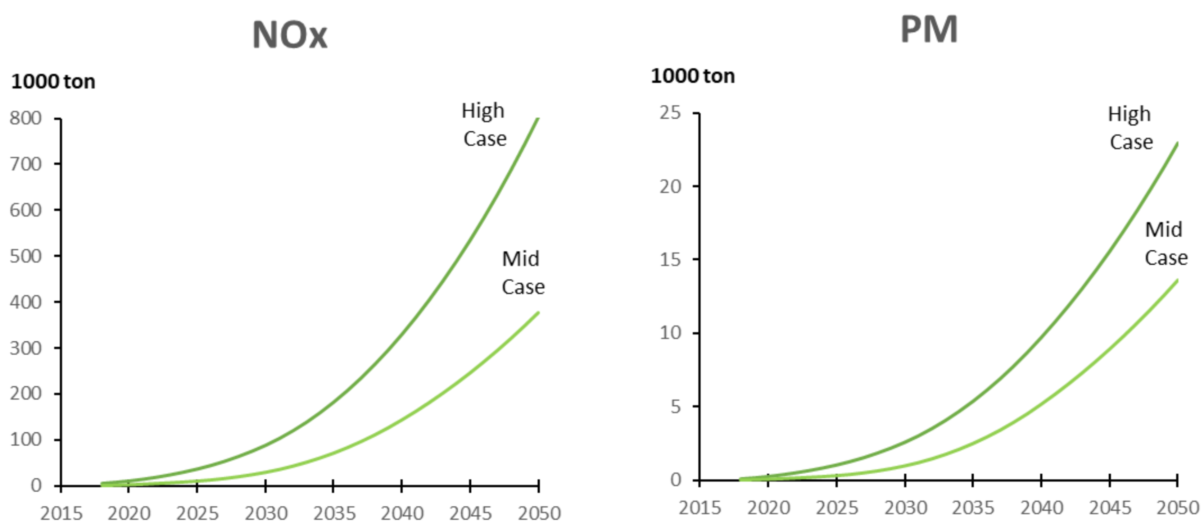
In addition to significant CO_2 reductions, the modeled abatement strategies also reduce net nitrogen oxide (NOx) and particulate matter ($PM_{2.5}$) emissions from the transportation sector due to substitution of electric vehicles for conventional vehicles with internal combustion engines. Electric vehicles are not necessarily zero emission vehicles – depending on the marginal grid mix, both NOx and $PM_{2.5}$ will be emitted when generating the electricity required to charge them. However, given the existing grid mix in the study region electric vehicle emissions (grams per mile) are already significantly lower than emissions from new gasoline and diesel vehicles. The difference is projected to increase in future years, as zero-emission renewable generation (wind, solar) makes up a greater percentage of the new capacity required to meet rising electricity demand.

By 2030 annual emissions of NOx are projected to fall by 4,400 tons in the study area under the Mid Case abatement scenario and by 12,900 tons under the High Case abatement scenario[6]. Annual emissions of $PM_{2.5}$ are projected to fall by 187 tons under the Mid Case abatement scenario and by 386 tons under the High Case abatement scenario.

By 2050 annual NOx and $PM_{2.5}$ emissions will fall by 28,400 tons and 1,014 tons, respectively, under the Mid Case abatement scenario, and by 59,000 tons and 1,600 tons, respectively, under the high Case abatement scenario.

As shown in Figure 5, by 2050 cumulative net NOx reductions are projected to total 376,000 tons under the Mid Case abatement scenario and 803,000 tons under the High Case abatement scenario. By 2050 cumulative net $PM_{2.5}$ reductions are projected to total 13,600 tons under the Mid Case abatement scenario and 23,00 tons under the High Case abatement scenario.

Figure 5 Cumulative NOx and $PM_{2.5}$ Reductions Relative to Base Case



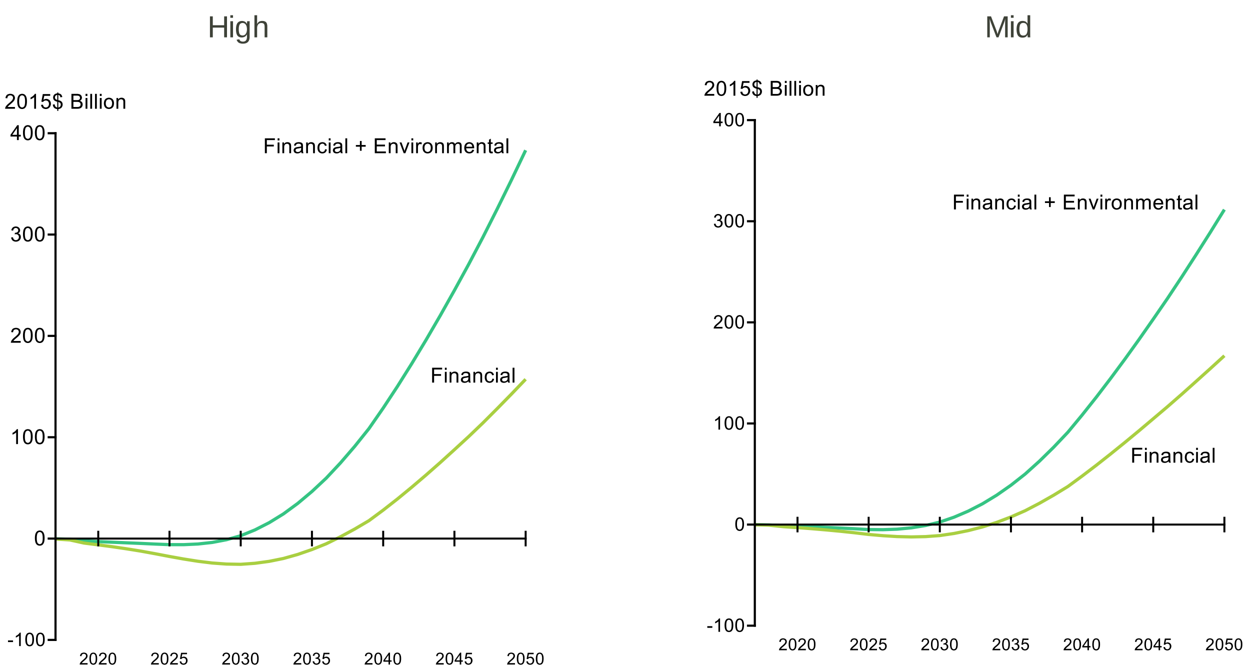
[6] Net of emissions from electricity generation for electric vehicle charging.

Net Benefits of Abatement Scenarios

The estimated cumulative net benefits (benefits minus costs) from each modeled abatement scenario, compared to the baseline scenario, are shown in Figure 6. Tabular results showing the various elements of cost and benefit each year are also included in Appendix B. State-level estimates of cumulative costs and benefits are included at Appendix F (separate document).

In Figure 6, cumulative financial benefits are the direct net financial benefits to consumers within the region that result from the modeled abatement strategies. These net financial benefits are primarily net fuel cost savings, after subtracting the costs of more expensive vehicles, and charging infrastructure for EVs. The cumulative environmental benefits shown are the monetized value of reduced GHG, NOx, and $PM_{2.5}$ emissions resulting from more efficient conventional vehicles and EVs.

Figure 6 Cumulative Net Benefits of Abatement Scenarios



With respect to estimated total net societal benefits from the modeled abatement strategies, the results of this analysis are likely conservative, because they do not assess indirect benefits from resulting macroeconomic changes, and don't account for potential reductions in the cost of traditional fuels due to over-supply resulting from reduced demand (due to high levels of transportation electrification).[7]

[7] This study only quantifies the direct financial and environmental costs and benefits associated with the modeled abatement strategies. The study does not attempt to quantify indirect financial benefits, or security benefits, from associated macroeconomic changes (i.e. reduced imports of petroleum, more of consumers money kept in the local economy, gasoline and diesel price reductions due to oversupply with reduced demand).

As shown in Figure 6, for both abatement scenarios cumulative financial "benefits" are negative in the short term – i.e. through approximately 2030 incremental annual vehicle and charging infrastructure costs are higher than annual net fuel costs savings. This is primarily due to the investment required for electric vehicle charging infrastructure, and the higher purchase price of electric vehicles compared to conventional vehicles[8]. However, over time the incremental cost of EVs is expected to fall and annual financial net benefits turn positive and expand dramatically as the region benefits from net fuel cost savings and downward pressure on electricity rates due to net revenue from electricity used to charge EVs.

Under the Mid Case scenario, the cumulative net societal "investment" required to implement the modeled abatement strategies is estimated to be $12.2 billion (2015$) through 2028. This amounts to an average of $160 per person over the next ten years ($16/person/year)[9]. Starting in 2029 annual net financial benefits (annual net fuel cost savings, not including environmental benefits) turn positive – rising to $5.4 billion in 2035, $10.3 billion in 2040, and $12.8 billion in 2050 (2015$). By 2034 the total societal investment will be paid back via net fuel cost savings, and positive cumulative financial benefits will start to accrue rapidly. By 2050 cumulative financial net benefits will reach $167 billion (2015$), over 15 times the initial investment; this equates to almost a 9 percent annual financial return to society.

Under the High Case scenario, the cumulative net societal investment required to implement the modeled abatement strategies is estimated to be $25.4 billion (2015$) through 2030. This amounts to an average of $333 per person over the next twelve years ($28/person/year). Starting in 2031 annual net financial benefits turn positive – rising to $4.9 billion in 2035, $10.4 billion in 2040, and $14.7 billion in 2050 (2015$). By 2037, the total societal investment will be paid back via net fuel cost savings, and positive cumulative financial benefits will start to accrue rapidly. By 2050 cumulative financial net benefits will reach $157 billion (2015$), over 7 times the initial investment; this equates to more than a 6 percent annual financial return to society.

While the direct *financial* return is lower from the High Case scenario than the Mid Case scenario, the environmental benefits are much greater. Under the Mid Case scenario, the cumulative value of environmental benefits reaches $144 billion (2015$) in 2050, while it reaches $226 billion under the High Case scenario.

Total cumulative societal benefits (financial + environmental) are estimated to be $311 billion through 2050 under the Mid Case scenario and $383 billion under the High Case scenario. While the High Case scenario requires a greater investment than the Mid-Case scenario it also provides a greater return on that investment when both financial and environmental benefits are included.

[8] The analysis indicates that the net benefits of more stringent fuel efficiency standards for conventional vehicles are positive every year, even in the near term; i.e. the annual fuel cost savings from more efficient vehicles are greater than the annual incremental vehicle costs to buy more efficient vehicles.

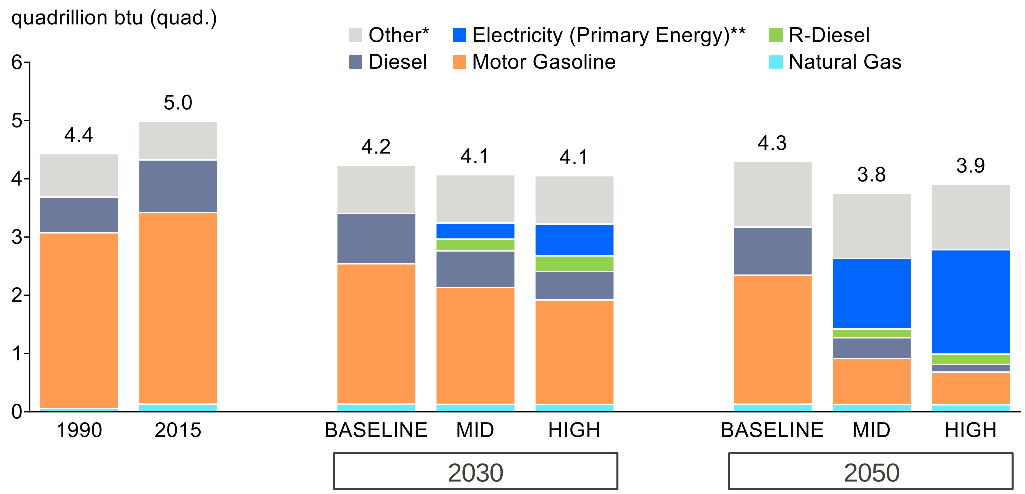
[9] According to the U.S. Census bureau the population of the 12-state study region was 72.4 million people in 2015.

Changes in Energy Use

Both Abatement Scenarios (Mid Case and High Case), imply a significant shift from reliance on motor gasoline and diesel fuel produced from petroleum to electricity, and liquid bio-fuels produced from renewable sources.[10] By 2050, the High Case increases demand for electricity within the region by 34 percent above 2018 levels. The Mid Case increases electricity demand by 25 percent above 2018 levels.[11]

Annual net increases in total consumption of renewable liquid fuels peak in 2030 at 1.4 billion gallons in the High Case and at about 1.1 billion gallons in the Mid Case. In 2050, however, under both the High and Mid cases total annual consumption of renewable liquid fuels are lower than in the Baseline case by over 100 million gallons. This is due to significant electrification in the LDV segment, and resulting reductions in total gasoline use, including reductions in the ethanol blending component of gasoline.

Figure 7 Energy Consumption by Fuel Type in 2030 and 2050



*includes aviation fuel, residual fuel oil used in marine sector, etc.
**Note that virtually all of the incremental electrical energy consumed in the High case and majority in the Mid case are assumed to come from zero-emitting sources. Consequently, the electrical energy amounts shown on this chart are illustrative estimates of primary energy consumption if conventional thermal generation sources were used instead. They do not indicate estimates of conversion efficiencies of the respective zero-emitting technologies. Delivered to primary electrical energy conversion, for the purposes of this chart, assumes an average heat rate of 9,271 btu/KWh (following EIA convention as outlined in its AEO assumptions) and a further 5% upward adjustment to account for transmission line loss.

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[10] For simplicity and conservatism this analysis modeled the use of hydrogenation-derived renewable diesel (HDRD) in lieu of petroleum diesel, and advanced lower-carbon ethanol as a replacement for the ethanol currently blended into gasoline, to comply with the modeled fuel decarbonization targets. Due to concerns about the effects of very high ethanol blend levels on older engines we assumed no increase in the percentage of ethanol in gasoline. In reality, compliance would likely be based on a mix of lower-carbon liquid fuels including HDRD, bio-diesel, advanced ethanol, and renewable gasoline. Ethanol blend levels could also potentially rise at some time in the future after most older conventional vehicles have been retired. Conversion of gasoline and diesel vehicles to operate on natural gas or bio-methane could also be used as a compliance strategy.

[11] For simplicity this analysis assumes that all "electric" vehicles will be battery electric or plug-in hybrid vehicles. Hydrogen fuel cell vehicles could also be used to "electrify" transportation, if the hydrogen is produced from water using electricity.

To put this in perspective, in 2017 the U.S. imported 583 million gallons of biomass-based and renewable diesel fuel, produced 1.6 billion gallons of bio-diesel[12], and produced 15.9 billion gallons of ethanol for blending with gasoline. [3]

Low Carbon Fuel Standards

To help reduce transportation sector GHG emissions, both California and Oregon have already implemented low carbon fuel standards – market-based policies that require transportation fuel providers to gradually reduce the average carbon intensity of transportation fuels. Fuel providers can meet the standards by blending low carbon bio-fuels into the gasoline or diesel they sell, or they can buy credits from other companies that sell alternative lower carbon fuels, such as bio-fuels, electricity, bio-methane, or hydrogen fuel. The carbon intensity of the various fuels is expressed in terms of grams of CO_2-equivalent per megajoule of energy, measured on a life-cycle basis. The standard that all fuel suppliers must meet is then expressed as a percentage reduction in average carbon intensity of the fuel they sell.

For this analysis we modeled both high levels of vehicle electrification and reduced carbon intensity of the remaining liquid transportation fuels, using bio-fuels. Both the electricity used to charge electric vehicles, and the bio-fuels used in conventional vehicles, could earn credits toward compliance with a low carbon fuel standard. For this project the implied targets for reduced carbon intensity of transportation fuels – including electric vehicles – are approximately 6% and 17% reduction by 2030 and 2050, respectively, under the MID case, and 10% and 32% reduction by 2030 and 2050, respectively, under the HIGH case.

[12] Bio-diesel and renewable diesel are produced from the same feedstocks (vegetable oils, tallow) but use a different production method, and the resulting fuels have different chemical properties.

APPENDIX A – STate Emission Pathways Tool (STEP Tool)

Background

In 2017, MJB&A designed and developed the STate Emission Pathways Tool (STEP Tool) for policymakers to carry out fast assessments of a single- or multi-state region's pathways to economy-wide future clean energy and greenhouse gas (GHG) reduction targets. It grew out of efforts to expand MJB&A's earlier electric sector-only Clean Power Plan Compliance Tool (CPP Compliance Tool) to include other sectors of the economy. The STEP Tool employs a similar analytical framework and retains the same intuitive user interface as the CPP Compliance Tool. [4]

The main purpose of the STEP Tool is to provide a simplified and transparent data-driven framework for federal and state regulators, lawmakers, and stakeholders to engage in clean energy related policy design.

Description of the STEP Tool Model

The STEP Tool is a spreadsheet-based multi-sector model that allows users to analyze state and regional energy use and their CO_2 emission trajectories under a range of economy-wide policy scenarios. It lets users build detailed custom policy scenarios by selecting from various policy options in each sector of the economy—electric, transportation, residential, commercial, and industrial—while tracking in real-time associated overall electricity generation, portfolio mix, total energy use by fuel type, vehicle miles traveled by type, CO_2 emissions, etc. The inclusion of multiple sectors of the economy allows users of the STEP Tool to examine certain energy-use interactions among the different sectors of the economy (e.g.: the impact of electric vehicles on both the electric and transportation sectors, etc.)

To produce scenario projections quickly and efficiently, the STEP Tool uses a non-optimization approach to solve for and calculate future energy use and CO_2 emissions. It does not try to reach any equilibrium condition or optimize the system for any variables. Instead, it records each user selection to construct one or more policy scenarios and then calculates their impacts in terms of changes to existing patterns of energy use. It makes use of heuristics and simplifying assumptions to produce projections at an indicative level.

The STEP Tool relies, for the most part, on several publicly available datasets from federal and state-level government agencies to build up relatively detailed characterizations of historic energy use patterns for each sector of the economy—electric, transportation, residential, commercial, and industrial. For example, for the transportation sector, the focus of this report, the STEP Tool uses the U.S. Department of Transportation Federal Highway Administration's "Highway Statistics" publication as the starting point for the development of state-by-state statistics on vehicle miles traveled, size of current vehicle stocks, etc. Various sections of the Energy Information Administration's Annual Energy Outlook and State Energy Data System datasets are used to both add further detail to the final representation of the sectors in the STEP Tool and provide a way to crosscheck against a second calculation of overall energy use and associated emissions in the sector.

By design, the current version of the STEP Tool does not provide any cost estimates. The cost-benefit determination part of this project is carried out in a separate module. See Appendix B for a detailed description of the cost-benefit methodology developed specifically for that part of the analysis.

GHG Emission Scope of STEP Tool

The STEP Tool's scope is limited to energy-related CO_2 emissions only, which accounted for about 80 percent of all U.S. GHG emissions in 2016. Non-CO_2 GHG gases—CH4, N2O, PFCs, SF6, and NF3—are not included in the STEP Tool. Also excluded are non-energy related CO_2 emissions (i.e., process related) from the industrial sector.

APPENDIX A – STate Emission Pathways Tool (STEP Tool)

Use of STEP Tool in This Report

The STEP Tool is used in this report to generate, for each year through 2050, overall transportation sector CO_2 emissions including those related to electrification of vehicles, vehicle fleet changes, and total energy use (by fuel type) associated with each modeled abatement scenario (Baseline, Mid-case, High-case). These annual projections are then used as inputs to the cost-benefit analysis module (see Appendix B) to estimate total costs and benefits associated with each policy scenario.

APPENDIX B – Cost-Benefit Methodology

OVERVIEW

This project evaluated the costs and benefits of three major abatement strategies that together can achieve significant reductions in on-road transportation GHG emissions within the 12-state study region (Maine to Virginia, plus the District of Columbia) through 2050. These abatement strategies include: more efficient new conventional vehicles, vehicle electrification in combination with efforts to further reduce the carbon intensity of electricity generation, and reductions in the carbon intensity of traditional liquid transportation fuels. This analysis assumes that both light-duty and medium/heavy duty annual vehicle miles traveled will continue to grow as projected by the Energy Information Administration, as the regional economy and population continue to grow. The modeled scenarios did not include enhancements to public transportation or other approaches designed to slow the growth or, or reduce, light-duty vehicle miles, or freight system enhancements or mode shifting to slow the growth of, or reduce, medium- and heavy-duty truck miles.

The major benefits of the modeled abatement strategies include significant reductions in gasoline and diesel fuel use and resulting reductions in net greenhouse gas (GHG) emissions, as well as reductions in net vehicle emission of nitrogen oxides (NOx) and particulate matter ($PM_{2.5}$)[13]. The modeled reductions in gasoline and diesel use also produce significant reductions in net fuel costs[14], as well as net revenue for electric utilities which can be used to maintain existing infrastructure and put downward pressure on future electricity rates.

The costs associated with these policies and approaches include incremental vehicle purchase costs compared to "baseline" vehicles without these policies, the cost of necessary electric vehicle charging infrastructure, and costs required to reduce the carbon intensity of liquid transportation fuels. The costs to reduce the carbon intensity of liquid transportation fuels were modeled as incremental costs required to purchase the volume of renewable liquid fuels necessary to comply with the modeled carbon intensity targets. The costs associated with further decarbonization of electricity production were modeled as incremental costs required to purchase electricity from renewable sources, including necessary storage, rather than from combined cycle natural gas plants.

While it is likely that achieving the level of electric vehicle penetration modeled will require government subsidies in the short term, to subsidize purchase of electric vehicles and/or charging infrastructure, this project did not explicitly attempt to estimate the level or magnitude of subsidies required, because subsidies will have no effect on the magnitude of estimated net benefits. Any government subsidy would represent a "cost" to the government (and by extension to tax payers) but would provide an equal "benefit" to the subsidy recipient; when calculating net societal benefits these equivalent costs and benefits would net to zero.

All costs and monetized benefits were estimated in constant, 2015 dollars. The resulting net benefits in constant dollars were then escalated to nominal dollars using inflation projections from the Energy Information Administration (EIA) [5]. These annual nominal net benefits were also discounted using a 3 percent discount rate to determine the net present value (NPV) of these net benefits.

The methods used to estimate these costs and benefits from the modeled scenarios, and the sources of major assumptions, are discussed below. Appendix C contains tabular and graphical details of many of the major assumptions used.

All dollar values noted below are in 2015 dollars.

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[13] Net of GHG, NOx, and $PM_{2.5}$ emissions from generation of electricity used to charge electric vehicles.
[14] Net of incremental costs for electricity used to charge electric vehicles.

APPENDIX B – Cost-Benefit Methodology

BENEFITS

NET FUEL COSTS

Net incremental fuel costs for each modeled scenario were calculated for each year using estimated changes in total motor gasoline, diesel fuel, and electricity calculated by the STEP Tool (see appendix B), and projected annual regional energy prices from EIA [6]. For each fuel a weighted average price was used, which reflects the estimated percentage of total fuel use within the study region which will be used in the New England (22 percent), Middle Atlantic (53 percent) and South Atlantic (25 percent) regions defined by EIA.

For electricity costs, the weighted average residential electricity price was used for the portion of total electricity used to charge light-duty vehicles, reflecting the assumption that most light-duty vehicle charging will take place at the owners' home. For the portion of total electricity used to charge medium- and heavy-duty vehicles 110 percent of the weighted average commercial electricity price was used. This reflects the assumption that the majority of these vehicles would be charged at commercial facilities that pay commercial electric rates. The 10 percent premium on commercial rates is based on a charging model developed by MJB&A which was used to estimate the total daily load for medium and heavy-duty vehicle charging and resulting electricity costs. See below discussion under "Charging Infrastructure Costs".

See appendix D for fuel cost values used.

MONETIZED VALUE OF CO_2 REDUCTIONS

Annual reductions in carbon dioxide (CO_2) emissions compared to the baseline (million metric tons) were estimated by the STEP Tool for each modeled scenario. To calculate the monetized value of these CO_2 reductions this study used values for the "Social Cost of CO_2" ($/MT) which were developed by the U.S. government's Interagency Working Group on Social Cost of Greenhouse Gases [7].

The Interagency Working Group published social cost estimates based on average modeling results using 2.5 percent, 3 percent and 5 percent discount rates, as well as 95th percentile results using a 3 percent discount rate. For this study the authors used the average values resulting from a 3 percent discount rate, which is in the middle of the range of estimated values. Total monetized CO_2 reduction benefits would be approximately 68 percent lower if using average values resulting from a 5 percent discount rate, 46 percent higher if using average values resulting from a 2.5 percent discount rate, and three times greater if using 95th percentile values resulting from a 3 percent discount rate.

The social value of CO_2 reductions represents potential societal cost savings from avoiding the negative effects of climate change, if GHG emissions are reduced enough to keep long term warming below two degrees Celsius from pre-industrial levels.

See appendix D for the social cost of CO_2 values used.

NOx and $PM_{2.5}$ REDUCTIONS

To estimate net NOx and $PM_{2.5}$ reductions from vehicle electrification, this study estimated the reduction in emissions due to reducing miles driven by conventional vehicles, then subtracted the emissions resulting from generation of the electricity required to charge the electric vehicles that replaced them. For each modeled scenario the number of electric miles driven each year by light-duty and medium/heavy duty vehicles, and the electricity required to power them, was taken from the STEP Tool.

It is possible that the more efficient conventional vehicles assumed by the modeled abatement strategies will also have lower NOx and $PM_{2.5}$ emissions than the less efficient vehicles in the baseline scenario. However, given the way that EPA regulates light-duty vehicle emissions, and the technologies used to achieve low emissions from modern vehicles, it is not clear that an increase in fuel economy will automatically lead to an equivalent reduction in emissions. For this analysis we assumed that the remaining conventional vehicles in the fleet would have the same emissions under all scenarios. This is a conservative assumption; it is likely that actual NOx and $PM_{2.5}$ emission reductions from more efficient conventional vehicle will be non-zero. As such the estimated total emission reductions from the modeled abatement strategies will likely be higher than the values presented here.

To calculate the reduction in emissions from conventional vehicles, for each year in the analysis the authors used emission factors (grams/mile) for new conventional vehicles purchased in that year. These emission factors were derived from EPA's MOtor VEhicle Emissions Simulator (MOVES) model [8]. To calculate total avoided emissions these g/mi emission factors were multiplied by the projected number of electric miles driven by each type of vehicle and summed. See appendix C for the vehicle emission factors used.

To calculate annual emissions from electricity generation the total electricity required to charge electric vehicles each year was multiplied by generation emission factors (g/kWh). For each year in the analysis weighted average emissions factors were calculated based on the percentage of total charging electricity produced from renewable sources (solar and wind), and the percentage generated by natural gas combined cycle (NGCC) plants. NOx and $PM_{2.5}$ from renewable sources are assumed to be zero. NOx emissions from NGCC plants are assumed to be 0.0313 g/kWh and $PM_{2.5}$ emissions are assumed to be 0.0005 g/kWh. The NGCC NOx emissions factor came from EPA's IPM power sector modeling platform [9]. The IPM model does not estimate $PM_{2.5}$ emissions from electricity generation. The NGCC $PM_{2.5}$ emissions factor came from an emission factor spreadsheet provided by EPA to state planners for developing emission inventories [10].

The monetized value of the estimated NOx and $PM_{2.5}$ reductions was calculated using avoided emission damage estimates ($/MT) developed by EPA [11]. These avoided emission damage estimates represent the value of avoided human health impacts when emissions of NOx and $PM_{2.5}$ are reduced, including the value of reduced morbidity and reduced premature mortality[15]. EPA developed avoided NOx and $PM_{2.5}$ damage estimates for 17 different economic sectors, including "Electricity Generating Units" and "On-road Mobile Sources". The EPA values indicate that damages ($/MT) from on-road mobile sources are higher than damages from electricity generating units, due to differences in the location of emissions and resulting differences in population exposure. Directly emitted $PM_{2.5}$ from on-road mobile sources is 2.7 times more damaging than $PM_{2.5}$ from electricity generating units. Directly emitted NOx from on-road mobile sources is 1.4 times more damaging than NOx from electricity generating units.

EPA developed a range of estimates for NOx and $PM_{2.5}$ damages ($/MT), based on two different calculation methodologies from the scientific literature, as well as the use of two different discount rates (3 percent and 7 percent). For this study the authors used the average of the values developed by EPA. If using the highest values developed by EPA, the net monetized NOx and $PM_{2.5}$ benefits would be approximately 44 percent greater than shown here; if using the lowest values developed by EPA, the net monetized NOx and $PM_{2.5}$ benefits would be approximately 44 percent lower than shown here. See appendix D for the NOx and $PM_{2.5}$ emission damage values used.

Using these damage estimates the value of reduced emissions from conventional vehicles (on-road mobile sources) and the increased damage from electricity generation were calculated separately; the net monetized value was then calculated as the reduction from on-road mobile sources minus the increase from electricity generation.

[15] EPA's analysis only accounts for NOx damages from its role as a $PM_{2.5}$ precursor and does not include damages related to the role of NOx as an ozone precursor. There may be additional health benefits related to reductions in ground level ozone, beyond those quantified here.

APPENDIX B – Cost-Benefit Methodology

ELECTRIC UTILITY NET REVENUE

This study estimated the economic benefits that would accrue to all electric utility customers in the study region due to increased utility net revenue (revenue minus costs) from electric vehicle charging. This revenue could be used to support operation and maintenance of the electrical grid, thus reducing the need for future electricity rate increases. In general, a utility's costs to maintain their distribution infrastructure increase each year with inflation, and these costs are passed on to utility customers in accordance with rules established by the state's Public Utilities Commission (PUC), via periodic increases in residential and commercial electric rates. However, under PUC rules and procedures the majority of projected utility net revenue from increased electricity sales for electric vehicle charging would in fact be passed on to utility customers, not retained by the utility companies. In effect this net revenue would put downward pressure on future rates, delaying or reducing future rate increases, thereby reducing customer bills.

Utility net revenue was estimated using a state-level modeling framework developed by MJB&A. [12] The Authors used this framework to develop a detailed estimate of utility net revenue for the states of Connecticut, Massachusetts, Maryland, New Jersey, New York, and Pennsylvania; these states represent 80 percent of the population of the 12-state study area, and 76 percent of vehicle miles traveled. The results for these states was extrapolated to the entire study area based on total study area VMT relative to VMT in these states.

The costs of serving electric vehicle load include the cost of electricity generation, the cost of transmission, incremental peak generation capacity costs for the additional peak load resulting from EV charging, and annual infrastructure upgrade costs for increasing the capacity of the transmission and secondary distribution systems to handle the additional load.

MJB&A's state modeling framework calculates average system-wide electricity generation and transmission costs based on projections by the Energy Information Administration; across the study area baseline weighted average costs for generation and transmission are estimated to be 68 percent of revenue in 2015, falling to 62 percent of revenue in 2030 and later years. [13]

The model estimates incremental EV charging load (MW) based on assumed EV penetration each year (number of vehicles) and two different charging models, one for light-duty vehicles and one for medium- and heavy-duty vehicles.

The light-duty EV charging model accounts for where electric vehicles will charge (at the owners' home or at work/public chargers), average charging rate (kW), and when vehicles start to charge. On a typical day 80 percent of light-duty EVs are assumed to charge at home and 20 percent are assumed to charge both at home and at work (or at a public charger).

Light-duty EV charge start times are based on at-work and at-home arrival times noted in the Department of Transportation's 2009 Annual Household Travel Survey for residents of the state [14]. Workplace/public charging is assumed to start as soon as EV owners arrive at work. For home charging the authors assumed a managed off-peak charging scenario in which 80 percent of light-duty EV owners that arrive home between noon and 11 PM delay the start of home charging until the off-peak period, in response to a price signal or other incentive. Home charging is further assumed to be "managed", with various vehicles starting to charge between 11 PM and 4 AM, to avoid a large secondary peak at the beginning of the off-peak period. Based on annual mileage accumulation, the average daily charge time for most EVs will be less than three hours; as such there will be sufficient time to fully charge vehicles for the next day's travel even with significantly delayed charge start times.

Compared to starting to charge as soon as one arrives home from work, managed off-peak charging shifts charging load away from the late afternoon/early evening peak load period to the early morning hours when the grid is currently under-utilized. As such it reduces incremental afternoon peak load for EV charging and reduces utility's incremental cost to serve that load.

The M/HDV EV charging model also accounts for where and when vehicles will charge (overnight at the facility where they park, or at publicly accessible chargers during the day), the average charge rate per vehicle, and assumed charge start times. However, all three of these factors vary by M/HD vehicle type depending on how they are typically used.

Transit buses typically stay in service for twelve to eighteen hours, and can accumulate 160 miles or more, per day. Based on this duty cycle fifty percent of electric transit buses are assumed to charge over-night at their depot, while the remaining 50 percent are assumed to use in-route "opportunity charging" throughout the day, to overcome current electric bus range restrictions.

Most other medium- and heavy-duty trucks (other than tractor-trailers) remain in service for only 8 – 12 hours per day, return to the same location virtually every night, and accumulate much less mileage – on average only about 12,000 miles per year, or 50 – 60 miles per day. As such, 80 percent of these vehicles, if electric, are assumed to charge overnight at their parking locations, while only 20 percent are assumed to charge during the day at publicly accessible chargers. By contrast tractor-trailers (combination trucks) on average accumulate over 60,000 miles per year (200+ miles per day) and are often used on long-haul routes, so do not return to the same location every might. As such, only 20 percent of these vehicles, if electric, are assumed to charge over-night at a regular parking location and 80 percent are assumed to charge at publicly accessible chargers.

The charging model calculates average charge rate for the different M/HDV vehicle types based on average daily energy use and available charge time. With an average of at least eight hours per night available for charging, transit buses and combination trucks are assumed to require 100 kW over-night chargers while other M/HDV trucks are assumed to require, on average, only 19 kW over-night chargers. Based on average day-time charge time of 1-2 hours per day per vehicle, transit buses and combination trucks are assumed to require 300 kW public chargers for day-time charging, while other M/HDV trucks are assumed to require, on average, only 100 kW public chargers.

Similar to the light-duty vehicle charging model, the M/HDV charging model assumes that overnight charging for M/HDVs will be managed off-peak charging, with charge start times staggered between 10 PM and 2 AM to minimize peak load impacts. Public charging is assumed to be evenly spread across the entire day (24 hours) for combination trucks but concentrated between 6 AM and 5 PM for other M/HDV trucks, consistent with their typical daily usage patterns.

To calculate the generation capacity costs associated with adding the estimated EV charging load (both LDV and M/HDV), this analysis uses peak capacity rates ($/kW-year) that are based on modeling conducted by MJB&A in 2016 using EPA's Integrated Planning Module (IPM) [15]. This modeling was conducted to evaluate the effect of EPA's proposed Clean Power Plan on regional electricity markets. These rates were multiplied by the projected total incremental afternoon EV charging load (kW) to calculate incremental generation capacity costs resulting from electric vehicles.

This analysis assumes that the primary transmission system in the 12 target states has sufficient capacity to handle the incremental load from EV charging, but that the secondary distribution system (i.e. neighborhood transformers) may not. High levels of EV penetration may require some transformers to be upgraded to a larger size when replaced at their normal end of life, to account for the growth in daily peak load due to EV penetration. This is consistent with modeling and analysis for other states. [16]

To estimate the annual cost to utilities of these transformer upgrades, this analysis uses a value of $15.84/kW for the average annual amortized cost of secondary transformers in 2030, rising to $23.99/kW in 2050 due to inflation. These values are based on an installed cost of $352/kW in 2030, a target peak load of 90 percent of rated capacity, and an average life of 20 years. [17]

These values were multiplied by the projected total incremental afternoon EV charging load (kW) to calculate incremental infrastructure upgrade costs resulting from electric vehicles.

Utility net revenue each year is calculated as total utility revenue minus average generation and transmission costs, minus incremental generation capacity costs, minus infrastructure upgrade costs.

See appendix D for values of major assumptions used in the M/HDV charging model and utility net revenue analysis.

COSTS

INCREMENTAL VEHICLE COSTS

Two of the abatement strategies modeled here that will result in significant GHG and fuel cost reductions will also result in increased vehicle purchase costs relative to "baseline" vehicles without those policies; these include more stringent fuel efficiency and GHG emission standards for light-duty and medium- and heavy-duty vehicles, and high levels of vehicle electrification for light-duty and medium- and heavy-duty vehicles.

For both strategies the authors used a similar approach to estimate the incremental annual costs to vehicle owners in the study area that would result from these increased vehicle purchase costs. For each year in the analysis period, the authors estimated the fleet-average incremental purchase cost ($/vehicle) for applicable new vehicles – either electric vehicles, or vehicles meeting the required level of increased fuel economy that year. This incremental purchase cost was converted to an incremental cost per-mile over the life of the vehicle, based on typical new vehicle financing arrangements[16], and expected life-time mileage accumulation, per EPA's MOVES model [18]. Incremental insurance costs of 1.8 percent ($/mi) were added, and in the case of light-duty EVs per-mile maintenance cost savings were subtracted[17], to calculate a net incremental operating cost ($/mi) for newly purchased vehicles that year, relative to baseline vehicles. Based on EPA assumptions about how vehicles accumulate mileage over time[18] and assumed fleet turn-over (% new vehicles added each year, and % old vehicles retired) and fleet growth the authors then calculated an annual fleet average incremental cost ($/mi) applicable to all vehicles in operation each year (encompassing "new" vehicles from multiple years). This fleet average cost was then applied to outputs from the STEP Tool (total EV miles, total more fuel-efficient vehicle miles) to calculate total annual incremental costs in each year.

In the case of more efficient new vehicles, which are assumed to keep getting more efficient each year, new vehicle purchase costs and fleet average annual costs ($/mi) start out low in the early years of the analysis period and continually increase over time, as new vehicles get more efficient and therefore relatively more expensive. Electric vehicle costs are the opposite – electric vehicles are assumed to have high incremental costs (relative to conventional vehicles) in the near term, with this incremental cost falling overt time as the

[16] 72-month new vehicle loan at 4.25 percent interest; financed incremental cost assumed to include 5 percent sales tax.
[17] Maintenance costs savings are based on manufacturer-recommended scheduled maintenance for current Ford electric and conventional vehicles.
[18] All vehicles are assumed to accumulate the most annual miles when brand new, with annual mileage accumulation decreasing each year until the vehicle is retired from the fleet.

technology matures and battery costs fall. This means that the fleet average incremental cost of EVs ($/mi) is high in the near term but falls over time.

Incremental vehicle purchase cost assumptions ($/vehicle) for both light-duty and medium-heavy-duty vehicles required to meet more stringent fuel economy standards were developed by MJB&A based on prior work conducted by the International Council on Clean Transportation (ICCT) [19] [20]. The prior ICCT work evaluated costs associated with specific technology packages that could significantly increase fuel efficiency of light-duty vehicles and heavy-duty combination trucks. Based on this prior work MJB&A developed "cost curves" which identify the incremental cost associated with a specific reduction in GHG emissions (%) relative to a baseline starting year. Based on the required fuel economy targets modeled in the STEP Tool for each year, these curves were used to estimate the fleet average incremental new vehicle cost associated with compliance with those targets.

Fleet average incremental purchase costs for new light-duty EVs were developed by MJB&A using data from a literature review of current and projected EV costs conducted by ICCT in 2016. [21] ICCT's estimated incremental costs, for electric cars with various battery sizes, were adjusted downward based on more recent estimates of future battery costs ($/kWh), which indicate that pack costs will fall below $100/kWh by 2030. [22] [23] MJB&A also used these estimates to develop new estimates for the average cost of electric light trucks, based on slightly larger batteries (due to greater energy use per mile) and larger, more expensive drive systems (based on relative ICE engine size for current light trucks relative to cars). Finally, MJB&A used assumptions for the relative number of new light trucks versus new cars purchased each year, as well as assumptions about the evolution of EV battery size over time, to estimate the fleet average incremental cost for new light-duty EVs each year in the analysis period. With respect to battery size, this analysis assumes that between now and 2035 EVs will on average become more capable, with larger batteries and longer range. After 2035 the analysis assumes that 35 percent of all new EVs sold will have 150-mile advertised range, 55 percent will have 200-mile range, and 10 percent will have 300-mile range.[19]

For medium- and heavy-duty vehicles, MJB&A estimated future incremental electric vehicle purchase costs based on current costs for a limited number of electric models [24] and assumed future reductions in electric drive train costs and battery costs. This analysis assumes that current incremental electric drivetrain costs of more than 100 percent (relative to conventional vehicles) will fall by 10 percent every five model years as the technology matures and production volumes increase. Currently, batteries for electric M/HDVs are about 50 percent more expensive ($/kWh) than light-duty EV batteries. As with light-duty battery costs, this analysis assumes that M/HDV battery costs will fall significantly over time, and that the cost difference between M/HDV and LDV batteries will narrow to only 15 percent by 2050.

See appendix D for the incremental vehicle purchase costs ($/vehicle) used in the analysis.

ELECTRIC VEHICLE CHARGING INFRASTRUCTURE COSTS

This analysis assumes that most charging of light-duty electric vehicles will be done at the vehicle owner's home, so that most EV owners will choose to purchase a dedicated home charger when they purchase their vehicle. The exceptions are individuals who live in multiple-unit dwellings[20], who may not have a dedicated parking space and therefore may not be able to install a dedicated home charger. For this analysis the authors assume that only 50 percent of individuals living in multiple-unit dwellings will have access to a dedicated home charger; given the housing characteristics within the 12-state study area 85 percent of all

[19] By comparison, most EV models available today have 80 – 125 mile advertised range. Only four models are available with greater than 200-mile range.
[20] For this study multiple unit dwellings are any dwellings other than a single-family or a two-family unit.

EV's are therefore assumed to have access to a home charger[21]. This analysis further assumes that owners of battery electric vehicles (BEV) will install a Level 2 home charger and that owners of plug-in hybrid vehicles (PHEV) will install a Level 1 home charger[22].

While most charging will be done at home, these home chargers will need to be supplemented by publicly accessible chargers to: 1) accommodate PEV owners in multiple-unit dwellings, 2) allow for long-distance travel in battery electric vehicles, and 3) allow PHEV owners to maximize electric miles. Necessary publicly accessible chargers will include Level 2 chargers at workplaces, Level 2 chargers at other locations where vehicles spend time (i.e. shopping centers), and higher-power direct current fast chargers (DCFC)[23], likely concentrated along highway corridors and/or in dense urban areas with a large percentage of the population living in multiple unit dwellings.

For this analysis MJB&A used the National Renewable Energy Laboratory's Electric Vehicle Infrastructure Projection Tool (EVI-Pro) Lite, to estimate the number of publicly accessible chargers that would be required to support the levels of PEV penetration modeled. [25] EVI-Pro uses detailed data on personal vehicle travel patterns, electric vehicle attributes, and charging station characteristics in bottom-up simulations to estimate the quantity and type of charging infrastructure necessary to support regional adoption of light-duty electric vehicles. The Lite version of the tool allows one to estimate the total number of Level 2 and DCFC charge ports required in different states and cities based on various input parameters, including the total number of EVs (up to 10 percent penetration), the percentage of EVs with access to a home charger, the fleet mix (% PHEV with 20 and 50 mile electric range; % BEV with 100 and 250 mile range) and whether PHEVs will be given full support to maximize electric miles or only partial support.

MJB&A used the EVI-Pro Lite tool to estimate the number of Level 2 and DCFC charge ports required at 10 percent EV penetration, for each state in the study area. Based on these results the authors calculated a weighted average value for the number of Level 2 and DCFC public chargers required (ports per 1,000 EVs) to support light-duty EVs across the study area. These weighted average values are 6.8 DCFC charge ports per 1,000 EVs, and 47.7 – 79.4 Level 2 charge ports per 1,000 EVs[24]. The range of values for Level 2 charge ports results from EVI-Pro Lite's assessment of what would be required for partial or full PHEV support.

For medium- and heavy-duty vehicles MJB&A estimated the number of privately owned (depot based) chargers required based on the percentage of total vehicles assumed to charge over-night (noted above), and the percentage of total vehicles typically in service each day (85 percent to 95 percent depending on vehicle type). The resulting values used in the analysis are one depot-based charger for every 2.3 electric transit buses, one charger for every 1.3 electric single-unit trucks, and one for every 5.3 electric combination trucks.

We used a similar method to estimate the number of publicly accessible chargers required for M/HDVs, which also incorporates assumptions for average daily charge time per vehicle, and a conservative assumption that on average public chargers would only be used for 60 percent of the hours per day that they could potentially be available for use. The resulting values used in the analysis are one in-route charger for every 23.8 electric transit buses, one publicly accessible charger for every 23.8 electric single unit trucks, and one publicly accessible charger for every 8.3 electric combination trucks.

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[21] This varies from a low of 70 percent in the District of Columbia, to a high of 90 percent in Pennsylvania.
[22] Level 1 chargers operate at 120 volts alternating current (AC) and are limited to 1.9 kilowatts (kW) charge rate. Level 2 chargers operate at 240 volts AC and can charge at rates between 4.8 and 9.6 kW.
[23] DCFCs operate at voltages above 480 volts direct current (DC), and for light-duty vehicles generally charge at rates between 25 kW and 100 kW.
[24] Projected DCFC requirements range from a low of 5.4 ports/1000 EV in Maryland, to a high of 13.1 ports per 1000 EV in Vermont.

Level 1 home chargers are assumed to cost $500 each and Level 2 home chargers are assumed to cost $1,000 each [26]. Level 2 public/workplace chargers are assumed to cost $8,500 each [27] and DCFC are assumed to cost $1,350/kW [28].

For home chargers fleet average estimated charger costs, including financing costs[25], were amortized over the projected life of the EVs they were purchased with, to estimate the average cost of home chargers per EV mile driven ($/mi). The resulting values are $0.005/mile in 2018, rising to $0.008/mile in 2050[26].

For depot-based chargers for M/HDVs, and publicly accessible chargers for both LDVs and M/HDVs, the estimated charger costs, including financing costs, were amortized over the projected energy through-put over their life, to estimate the average cost of these chargers per unit of charging energy delivered ($/kWh).

For these chargers, significantly higher financing costs were included, compared to home chargers, to reflect the fact that most would be owned and operated by third party charging companies; for all depot-based and public chargers a 10 percent rate of return on invested capital for 10 years was included in the amortized cost. Annual maintenance costs equivalent to 1.5 percent of capital costs were also included, and costs were amortized over a 20-year charger life.

The resulting values for the amortized cost of public chargers required to support light-duty EVs in the study area are $0.024/kWh for partial PHEV support and $0.032/kWh for full PHEV support. As discussed in Appendix B, the EV penetration scenarios modeled assume significant numbers of PHEVs in the fleet in the near term but virtually no PHEVS after 2035. For this analysis the authors therefore assumed charging infrastructure that would provide full PHEV support prior to 2035 but only partial PHEV support after 2035.

The resulting values for the amortized cost of depot-based and public chargers required to support medium- and heavy-duty EVs in the study area average $0.097/kWh in 2020, falling to $0.084/kWh in 2050[27].

To calculate total annual costs for charging infrastructure in each year the above values ($/mi or $/kWh) were multiplied by the STEP tool estimate of total EV miles or charging energy (kW) to support the modeled level of EV penetration.

See appendix D for values of major assumptions used to estimate amortized charger costs.

DECARBONIZING TRADITIONAL LIQUID FUELS

Reducing the carbon intensity of the total transportation fuel pool can be achieved by substituting lower-carbon liquid fuels for traditional fuels – typically "renewable" fuels derived from bio-mass – or by substituting lower-carbon gaseous fuels (propane, natural gas) or electricity for traditional liquid fuels.

For this project we modeled very high levels of vehicle electrification (i.e. substituting electricity for traditional liquid fuels) along with decarbonization of the remaining pool of liquid fuels using bio-fuels. The modeling was done in two steps this way to ensure that benefits and costs were not double-counted. Based on this two-step modeling approach, the targets shown in Figure 1 for reduced fuel carbon intensity apply only to the remaining liquid fuel pool, after vehicle electrification. As discussed in the text box (Low Carbon Fuel

[25] It is assumed that charger costs would be financed as part of a 72-month new car loan at 4.25 percent interest; the financed cost also assumed to include 5 percent sales tax.

[26] Fleet average costs rise over time as a greater percentage of total EVs are assumed to be battery vehicles that, compared to plug-in hybrids, require more expensive Level 2 chargers.

[27] Estimated amortized charger costs are lower for transit buses and combination trucks than for single unit trucks due to higher annual miles per vehicle and higher life-time charger throughput. The reduction in average costs over time reflects the modeled EV scenario which assumes lower penetration of electric combination trucks than single unit trucks in the near and medium -term.

Standard) on page 15, the implied targets for reduced carbon intensity of the entire transportation fuel pool (including electricity) would be much higher.

For the remaining pool of liquid fuels, compliance with the targets for reduced carbon intensity shown in Figure 1 were modeled by estimating the volume of renewable liquid fuels that would need to be substituted each year to meet the relevant target. For simplicity and conservatism this analysis modeled the use of only two bio-fuels for compliance: 1) hydrogenation-derived renewable diesel (HDRD)[28] as a substitute for petroleum diesel, and 2) advanced lower-carbon ethanol as a replacement for the ethanol currently blended into gasoline, which is primarily produced from corn[29]. Due to concerns about the effects of very high ethanol blend levels on older engines the authors assumed no increase in the percentage of ethanol in gasoline as a compliance strategy (average 6.5% by energy content). The authors believe that this is a conservative approach relative to estimating costs associated with liquid fuel decarbonization.

HDRD is assumed to have about 70 percent lower life-cycle GHG emissions than petroleum diesel [29]. The carbon intensity of ethanol used for blending with gasoline is assumed to fall from 80% of the carbon intensity of gasoline (per unit of energy) in 2015, to 60% in 2030, and 20% in 2050. For each year the STEP tool calculates the volume of lower-carbon ethanol required for blending (based on total gasoline use) and the volume of HDRD required to lower the carbon intensity of the total pool of liquid fuels to the target level. To estimate the total costs associated with liquid fuel decarbonization these volumes are multiplied by the projected incremental cost of HDRD relative to petroleum diesel ($1/gallon) [30], and the incremental cost of low-carbon ethanol relative to current ethanol. There are significant uncertainties in the incremental cost of lower carbon ethanol; for conservatism it is assumed to be the same as HDRD, per unit of carbon reduction. The assumed incremental cost of low carbon ethanol increases from $0.05/gallon in 2020, to $0.32/gallon in 2040 and $0.48/gallon in 2050 as net carbon content decreases[30].

LOW CARBON GRID

The resources used to power the electric grid in the Northeast and Mid-Atlantic region have been rapidly evolving over the past decade in response to market forces and state and federal policies. In New England, for example, natural gas accounted for only 15 percent of electricity production in 2000, compared with almost 50 percent in 2017. Renewable generation (excluding hydro) in New England has increased from 8 percent to 11 percent over the same time period. Looking forward, the resource mix will continue to evolve in response to economic forces, clean energy policies, and the adjusted Regional Greenhouse Gas Initiative (RGGI) program cap.

For the purpose of this analysis, MJB&A assumed a mix of electric generating facilities would supply the incremental electricity demand from deploying a large number of plugin electric vehicles. Based on recent trends, in the Medium Scenario, MJB&A assumed that incremental demand from the transportation sector

[28] HDRD is manufactured from used or virgin vegetable oils and tallow. The bio-mass feedstock is typically hydro-treated to convert plant oils into alkanes with very similar chemical composition to petroleum-derived diesel. The authors could have modeled other diesel substitutes as well, for example bio-diesel blends. While bio-diesel is made from the same feedstock as HDRD a different manufacturing process is used and the resulting fuel, while less expensive than HDRD, must typically be used in blends with petroleum diesel below 20 percent. HDRD is approved by engine manufacturers for use neat (100 percent) with no engine modifications, making it easier to adopt for wide-spread use.

[29] Some corn ethanol producers are already lowering the carbon content of their fuel through process improvements and the use of bio-methane for process heat. Other potential ways to further lower the carbon content of ethanol include carbon capture and storage at ethanol plants, and the use of cellulosic feedstocks.

[30] Under this modeling approach the incremental cost of HDRD is used as the conservative upset value for the cost of fuel decarbonization. If the actual cost of low-carbon ethanol (per unit of carbon reduction) was higher than this cost, fuel suppliers could use additional HDRD (and less low-carbon ethanol) to meet the carbon intensity targets, while keeping costs the same as estimated here.

would be satisfied with a 50:50 combination of gas-fired electricity generation and renewable energy (wind and solar). In the High Scenario, MJB&A assumed that incremental demand would be satisfied with a 50:50 mix of natural gas and renewable generating facilities in 2016, but transition to 100 percent renewable energy by 2030 (and beyond) in response to further tightening of the RGGI program cap, or other policy actions to further decarbonize the grid. For the purpose of this analysis, the focus was not on the total resource mix of the electric grid, only the resources assumed to satisfy the incremental demand from electrification of the transportation sector. This assumed resource mix then determined the CO_2 emission rate of an electric vehicle, the total CO_2 emissions from the transportation sector through the forecast, and the energy and capacity costs of powering an increasing share of the transportation sector with low carbon electricity.

The projected electric system costs to supply energy for transportation electrification in the modeled abatement scenarios include: (1) the variable and fixed operating costs of running the existing fleet of natural gas combined cycle (NGCC) facilities in the region at a higher average capacity factor, including a projection of natural gas prices; (2) the capital costs and fixed operating costs of a 70:30 mix of wind and solar energy[31]; and (3) the costs of adding utility-scale battery storage systems to help integrate a high level of wind and solar capacity.

The cost and performance assumptions for wind, solar, and NGCC technology were obtained from the National Renewable Energy Laboratories (NREL) 2017 Annual Technology Baseline and Standard Scenarios (Mid Case). [31] Delivered natural gas prices for the region were obtained from the U.S. EIA's Annual Energy Outlook 2018 (Reference Case) [32].

In order to reflect the potential costs of integrating additional renewable energy capacity, MJB&A assumed that incremental renewable new builds would require energy storage capacity equal to 15 percent of the renewable capacity added each year. Battery price projections were derived in a three-step process. First, MJB&A obtained the current capital cost estimates provided in EIA's U.S. Battery Storage Market Trends Report (May 2018) for large-scale battery storage [33]. Second, MJB&A calculated a compound average growth rate factor (CAGR) for battery storage technology from Bloomberg New Energy Finance's projection for car battery costs (in energy terms). Finally, this CAGR is applied to the capital cost estimates from the first step to calculate a power capacity unit price trajectory through 2050. "Long duration" battery costs are used since this is likely to be the dominant battery type used for renewable integration, although some amount of "short duration" batteries may also be required for frequency/regulation support, etc. MJB&A assumed a useful life for a battery of 20 years. Other options would be available for integrating additional renewable resources; however, this approach is felt to be a reasonable and conservative proxy to calculate associated costs.

The renewable energy costs, natural gas prices, and battery storage price trajectory used are shown in Appendix D.

ANNUAL NET BENEFITS

The projected annual costs, benefits, and net benefits from the modeled abatement scenarios (relative to the baseline scenario) are shown in Table B-1 (Mid Case scenario) and Table B-2 (High Case scenario).

In addition, estimates of cumulative costs and benefits for each state in the region are included at Appendix F. For these state-level estimates, total projected regional costs and benefits were apportioned to each state based on the state share of regional light-duty and medium/heavy duty vehicle miles traveled.

[31] This assumption was guided by the Regional Greenhouse Gas Initiative (RGGI) IPM model results through 2030.

Table B-1 Annual Costs and Benefits Relative to Baseline – Mid Case Scenario

2015 $ billions			2018	2020	2025	2030	2035	2040	2045	2050
Incremental Vehicle Costs	Vehicle Efficiency	LDV (CAFE+)	$0.00	$0.00	$0.00	($0.85)	($2.18)	($3.25)	($4.23)	($4.70)
		M/HDV (EPA Phase 3)	$0.00	$0.00	$0.00	($0.06)	($0.35)	($0.97)	($2.01)	($3.57)
	Transportation Electrification	LDV	($0.27)	($0.55)	($1.11)	($1.95)	($2.11)	($1.76)	($1.21)	($0.42)
		M/HDV	($0.15)	($0.30)	($0.63)	($1.01)	($1.62)	($2.28)	($2.86)	($3.25)
PEV Charging Infrastructure		LDV - home chargers	($0.03)	($0.05)	($0.14)	($0.55)	($1.33)	($2.20)	($2.81)	($3.43)
		LDV - Public Chargers	($0.09)	($0.15)	($0.28)	($0.78)	($1.50)	($1.79)	($2.20)	($2.60)
		M/HDV	($0.06)	($0.10)	($0.19)	($0.36)	($0.65)	($0.93)	($1.21)	($1.44)
Incremental Electricity Cost		LDV	($0.42)	($0.76)	($1.56)	($4.54)	($8.85)	($14.27)	($17.70)	($20.97)
		M/HDV	($0.08)	($0.14)	($0.28)	($0.58)	($1.04)	($1.51)	($1.95)	($2.30)
Low Carbon Fuel Standard			($0.47)	($0.72)	($1.26)	($1.74)	($1.94)	($1.83)	($1.64)	($1.41)
Low Carbon Grid			$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Sub-total Costs			**($1.57)**	**($2.76)**	**($5.46)**	**($12.41)**	**($21.58)**	**($30.79)**	**($37.81)**	**($44.11)**
Gasoline Savings			$0.82	$1.54	$3.16	$10.87	$21.21	$31.71	$37.56	$42.44
Diesel Fuel Savings			($0.01)	($0.00)	$0.04	$0.90	$2.77	$5.08	$7.11	$8.93
Utility Net Revenue from PEV Charging			$0.14	$0.27	$0.58	$1.68	$2.97	$4.32	$5.04	$5.56
Sub-total Financial Savings			**$0.95**	**$1.81**	**$3.78**	**$13.44**	**$26.95**	**$41.11**	**$49.71**	**$56.93**
NET FINANCIAL BENEFITS			**($0.61)**	**($0.95)**	**($1.68)**	**$1.03**	**$5.38**	**$10.32**	**$11.90**	**$12.83**
Monetized GHG Benefits (3% AVG)			$0.25	$0.41	$0.80	$2.11	$3.97	$5.90	$7.23	$8.58
Monetized NOx Benefits (AVG)			$0.01	$0.01	$0.03	$0.08	$0.17	$0.28	$0.37	$0.47
Monetized $PM_{2.5}$ Benefits (AVG)			$0.01	$0.02	$0.04	$0.15	$0.31	$0.50	$0.65	$0.80
NET FINANCIAL + ENVIRONMENTAL BENEFITS			**($0.34)**	**($0.51)**	**($0.81)**	**$3.38**	**$9.83**	**$17.00**	**$20.15**	**$22.67**
CUMULATIVE NET BENEFITS		**Financial**	**($1.22)**	**($3.02)**	**($9.77)**	**($10.88)**	**$7.54**	**$47.95**	**$104.67**	**$166.97**
		Financial + Envi	**($0.68)**	**($1.68)**	**($4.93)**	**$2.45**	**$38.92**	**$108.31**	**$203.17**	**$311.51**

nom $ billions		2018	2020	2025	2030	2035	2040	2045	2050
NET ANNUAL BENEFITS	**Financial**	**($0.61)**	**($1.00)**	**($1.99)**	**$1.37**	**$7.92**	**$17.04**	**$22.11**	**$26.97**
	Financial + Envi	**($0.34)**	**($0.53)**	**($0.96)**	**$4.46**	**$14.48**	**$28.06**	**$37.43**	**$47.66**
CUMULATIVE NET BENEFITS	**Financial**	**($1.22)**	**($3.09)**	**($10.75)**	**($12.00)**	**$14.24**	**$78.34**	**$178.97**	**$303.76**
	Financial + Envi	**($0.68)**	**($1.71)**	**($5.41)**	**$4.17**	**$55.99**	**$165.99**	**$334.32**	**$551.42**

NPV $ billions 3%	discount rate	2018	2020	2025	2030	2035	2040	2045	2050
NET ANNUAL BENEFITS	**Financial**	**($0.61)**	**($0.94)**	**($1.62)**	**$0.96**	**$4.79**	**$8.89**	**$9.95**	**$10.47**
	Financial + Envi	**($0.34)**	**($0.50)**	**($0.78)**	**$3.13**	**$8.76**	**$14.64**	**$16.85**	**$18.51**
CUMULATIVE NET BENEFITS	**Financial**	**($1.22)**	**($3.01)**	**($9.57)**	**($10.66)**	**$5.96**	**$41.18**	**$89.15**	**$140.47**
	Financial + Envi	**($0.68)**	**($1.67)**	**($4.83)**	**$2.05**	**$34.96**	**$95.47**	**$175.68**	**$264.93**

Table B-2 Annual Costs and Benefits Relative to Baseline – High Case Scenario

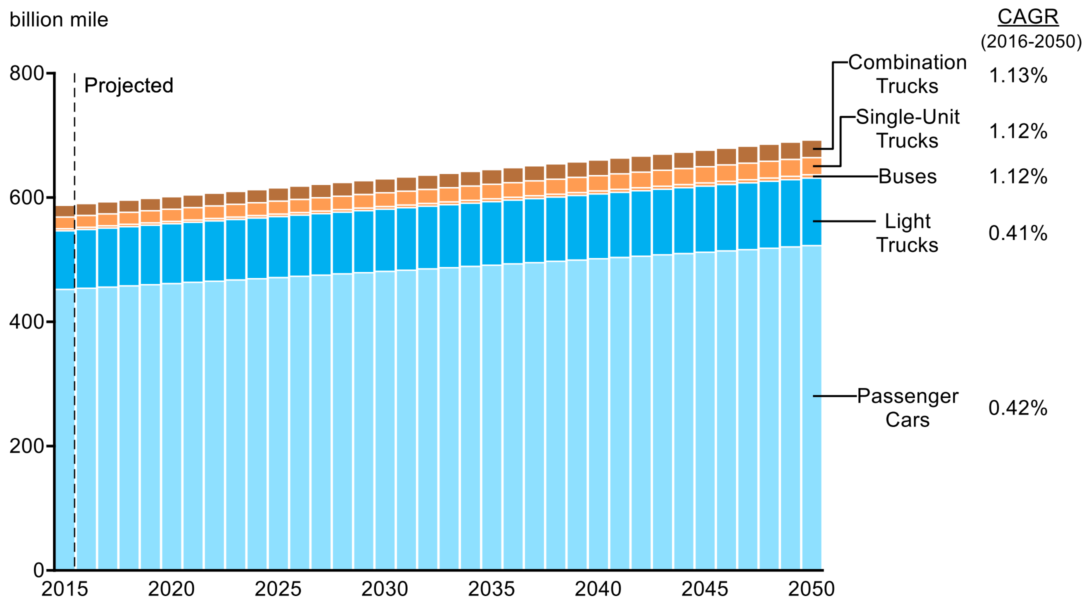
2015 $ billions			2018	2020	2025	2030	2035	2040	2045	2050
Incremental Vehicle Costs	Vehicle Efficiency	LDV (CAFE+)	$0.00	$0.00	$0.00	($0.70)	($1.67)	($2.43)	($2.85)	($2.67)
		M/HDV (EPA Phase 3)	$0.00	$0.00	$0.00	($0.05)	($0.23)	($0.59)	($1.02)	($1.50)
	Transportation Electrification	LDV	($0.84)	($1.67)	($3.31)	($4.20)	($3.56)	($2.39)	($1.29)	($0.17)
		M/HDV	($0.37)	($0.73)	($1.72)	($2.54)	($3.74)	($4.98)	($6.13)	($6.97)
PEV Charging Infrastructure		LDV - home chargers	($0.08)	($0.16)	($0.44)	($1.01)	($2.01)	($2.93)	($3.67)	($4.44)
		LDV - Public Chargers	($0.26)	($0.44)	($0.85)	($1.41)	($2.23)	($2.36)	($2.86)	($3.35)
		M/HDV	($0.14)	($0.23)	($0.59)	($0.94)	($1.61)	($2.26)	($3.01)	($3.76)
Incremental Electricity Cost		LDV	($1.23)	($2.28)	($4.76)	($8.17)	($13.13)	($18.83)	($23.00)	($26.96)
		M/HDV	($0.18)	($0.32)	($1.00)	($1.71)	($2.82)	($3.97)	($5.20)	($6.35)
Low Carbon Fuel Standard			($0.94)	($1.19)	($1.76)	($2.20)	($2.12)	($1.98)	($1.76)	($1.51)
Low Carbon Grid			($0.01)	($0.01)	$0.01	$0.13	$0.29	$0.58	$0.88	$1.35
Sub-total Costs			($4.05)	($7.03)	($14.42)	($22.78)	($32.83)	($42.15)	($49.92)	($56.33)
Gasoline Savings			$2.27	$4.24	$8.69	$16.59	$27.31	$37.67	$44.04	$49.34
Diesel Fuel Savings			$0.05	$0.22	$1.23	$2.74	$5.69	$8.88	$11.81	$14.39
Utility Net Revenue from PEV Charging			$0.41	$0.78	$1.81	$3.21	$4.68	$6.00	$6.81	$7.27
Sub-total Financial Savings			$2.72	$5.24	$11.73	$22.53	$37.69	$52.55	$62.67	$71.01
NET FINANCIAL BENEFITS			($1.33)	($1.79)	($2.70)	($0.25)	$4.86	$10.40	$12.75	$14.67
Monetized GHG Benefits (3% AVG)			$0.60	$0.93	$1.90	$3.68	$6.02	$8.54	$10.51	$12.56
Monetized NOx Benefits (AVG)			$0.03	$0.04	$0.10	$0.21	$0.37	$0.55	$0.74	$0.95
Monetized $PM_{2.5}$ Benefits (AVG)			$0.04	$0.06	$0.14	$0.30	$0.53	$0.77	$1.00	$1.24
NET FINANCIAL + ENVIRONMENTAL BENEFITS			($0.66)	($0.75)	($0.55)	$3.93	$11.78	$20.27	$25.00	$29.43
CUMULATIVE NET BENEFITS		Financial	($2.66)	($6.21)	($17.67)	($25.40)	($10.81)	$28.06	$87.72	$157.21
		Financial + Envi	($1.33)	($3.00)	($5.98)	$2.81	$46.45	$128.77	$244.93	$383.19

nom $ billions		2018	2020	2025	2030	2035	2040	2045	2050
NET ANNUAL BENEFITS	Financial	($1.33)	($1.88)	($3.19)	($0.33)	$7.16	$17.17	$23.69	$30.85
	Financial + Envi	($0.66)	($0.79)	($0.65)	$5.19	$17.36	$33.45	$46.44	$61.87
CUMULATIVE NET BENEFITS	Financial	($2.66)	($6.34)	($19.34)	($28.98)	($8.10)	$53.63	$159.52	$298.81
	Financial + Envi	($1.33)	($3.05)	($6.43)	$4.97	$66.99	$197.49	$403.70	$680.86

NPV $ billions 3%	discount rate	2018	2020	2025	2030	2035	2040	2045	2050
NET ANNUAL BENEFITS	Financial	($1.33)	($1.77)	($2.60)	($0.23)	$4.33	$8.96	$10.66	$11.98
	Financial + Envi	($0.66)	($0.74)	($0.53)	$3.64	$10.50	$17.46	$20.91	$24.03
CUMULATIVE NET BENEFITS	Financial	($2.66)	($6.18)	($17.33)	($24.65)	($11.52)	$22.36	$72.80	$130.05
	Financial + Envi	($1.33)	($2.98)	($5.89)	$2.31	$41.69	$113.48	$211.69	$325.58

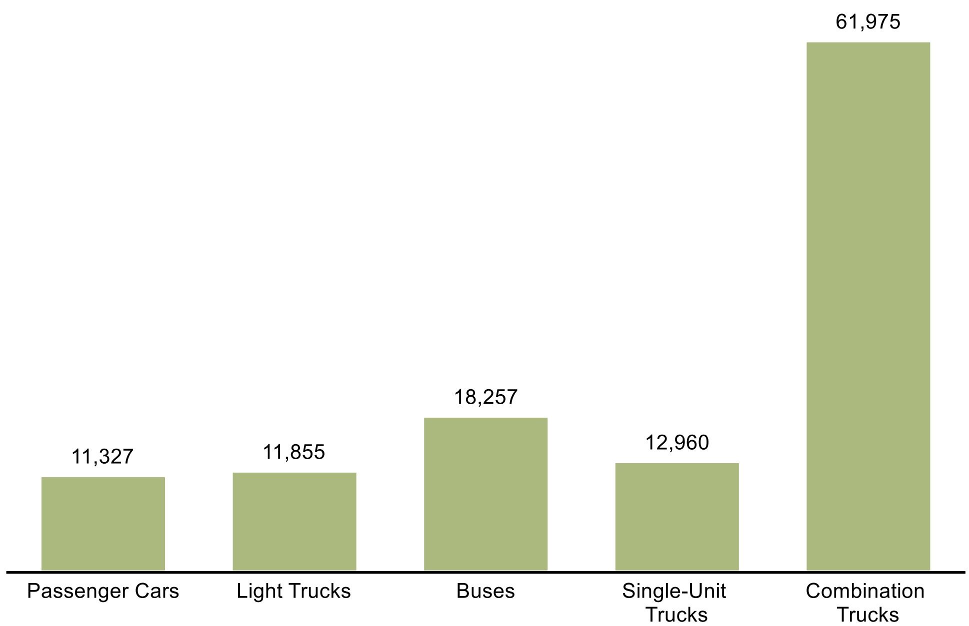
APPENDIX C – STEP Tool Modeling Inputs

Figure C-1 Vehicle Miles Traveled (billion mile)



Source: MJB&A Analysis, Federal Highway Administration 2015, Energy Information Administration, 2018 Annual Energy Outlook

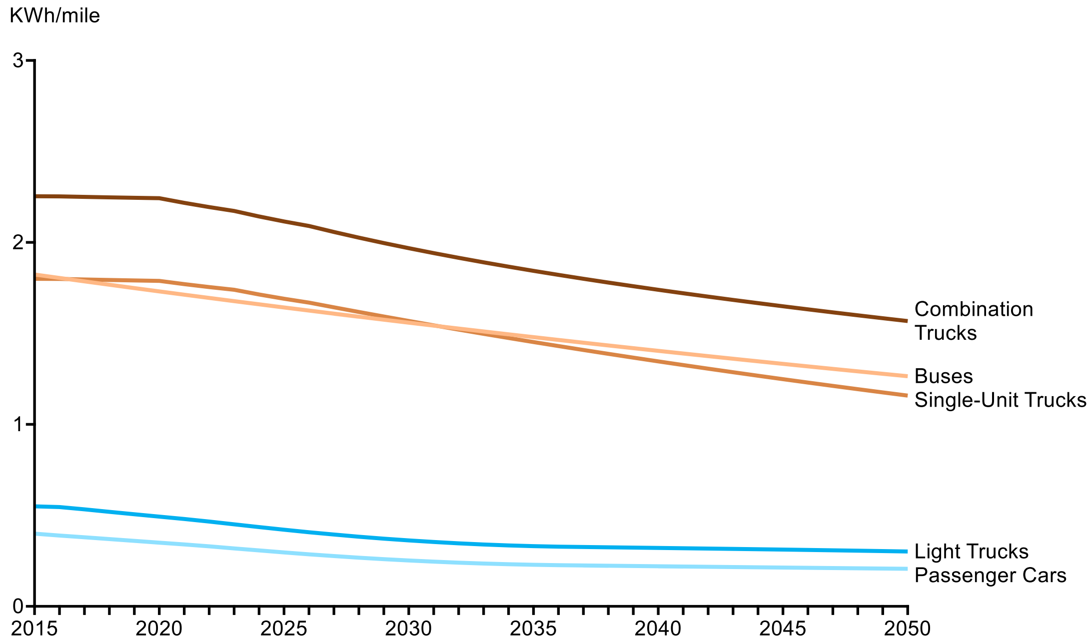
Figure C-2 Average Vehicle Miles Traveled Per Vehicle Per Year (2015; mile)



Source: MJB&A Analysis, Federal Highway Administration 2015

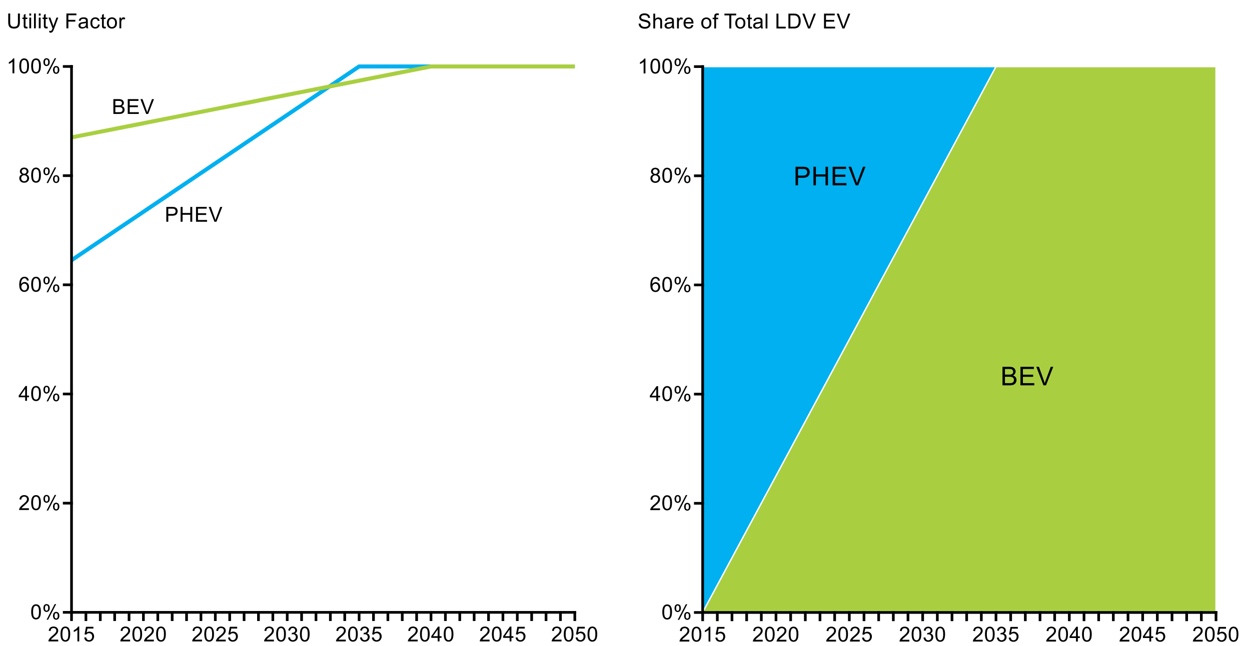
APPENDIX C – STEP Tool Modeling Inputs

Figure C-3 Electric Vehicle Efficiency (KWh/mile)



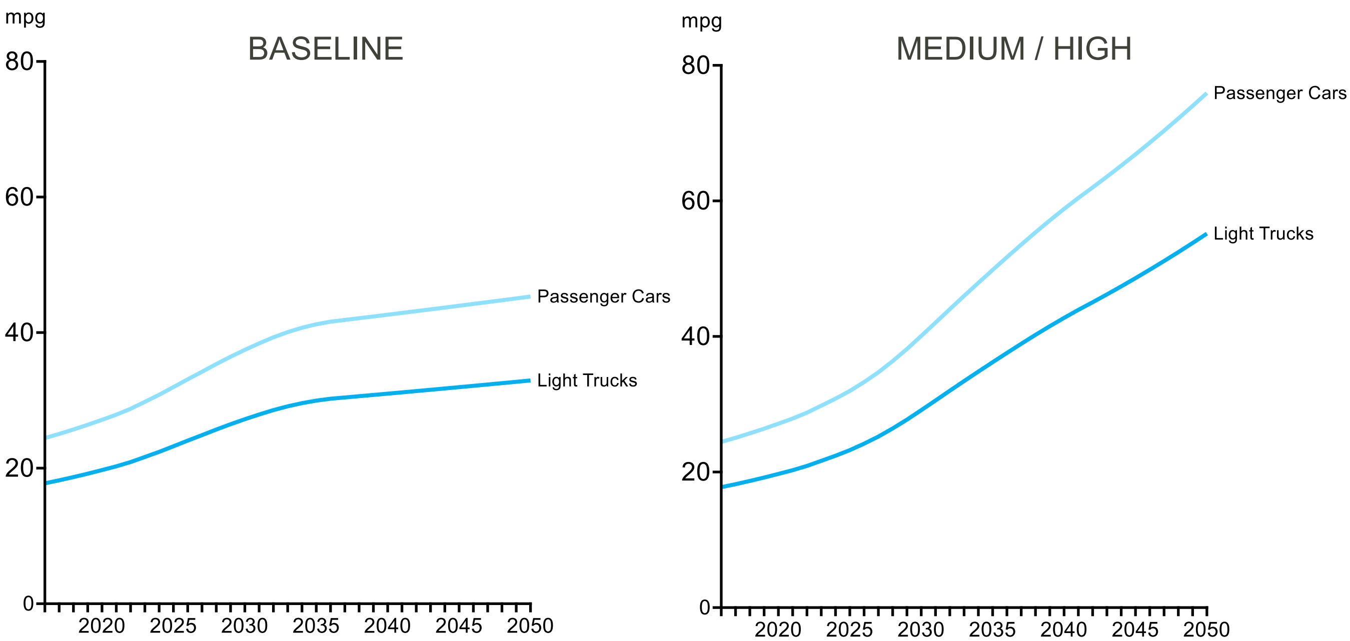
Source: MJB&A Analysis

Figure C-4 Characteristics of LDV Electric Vehicles



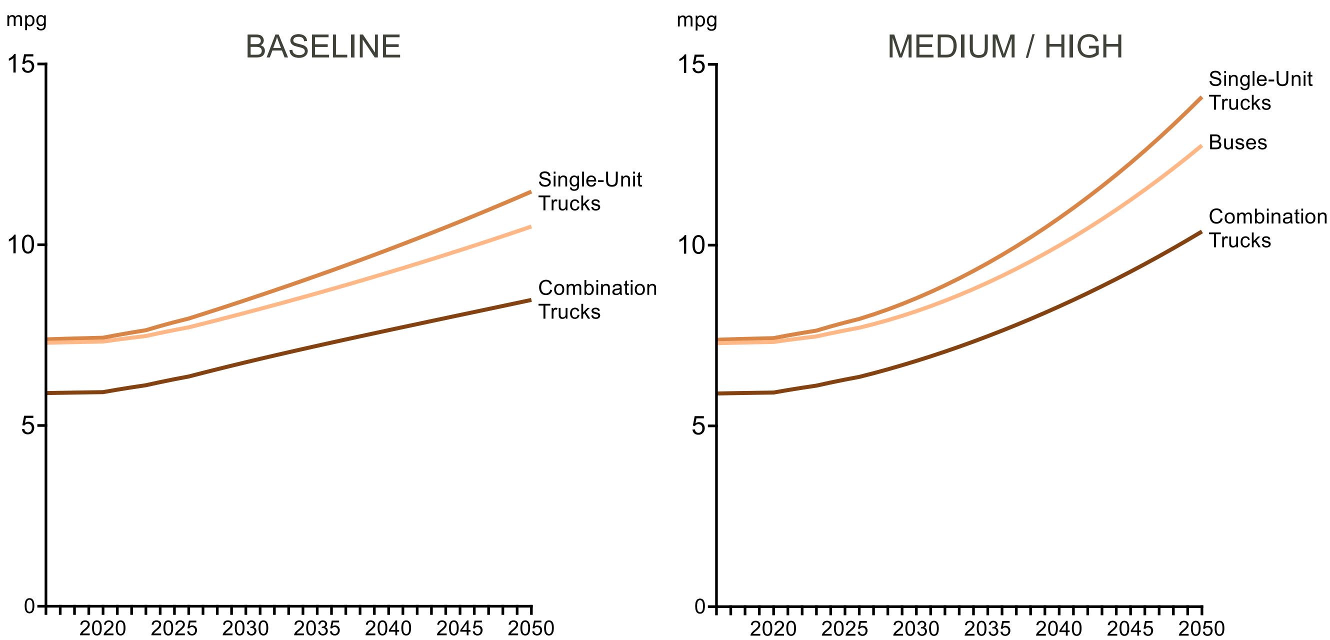
Source: MJB&A Analysis

Figure C-5 Light Duty Vehicle Efficiency (mpg)



Source: MJB&A Analysis

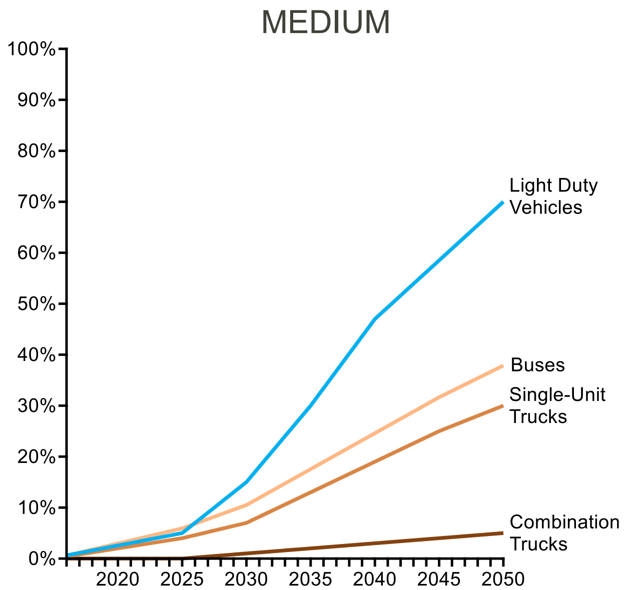
Figure C-6 Medium/Heavy Duty Vehicle Efficiency (mpg)

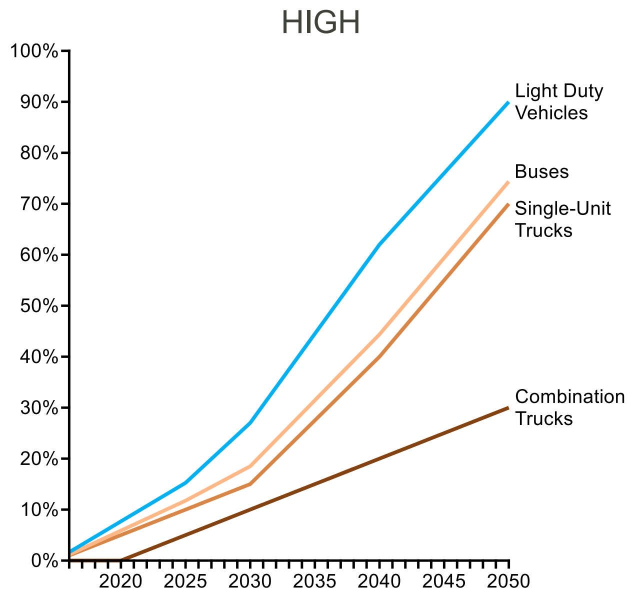


Source: MJB&A Analysis

APPENDIX C – STEP Tool Modeling Inputs

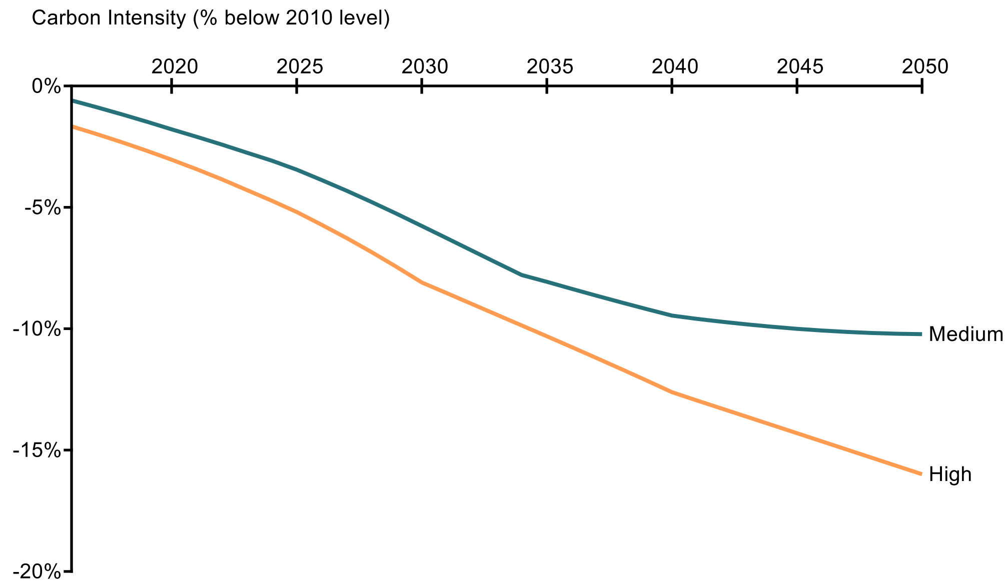
Figure C-7 Electric Vehicle Penetration (% of in-use fleet)





Source: MJB&A Analysis

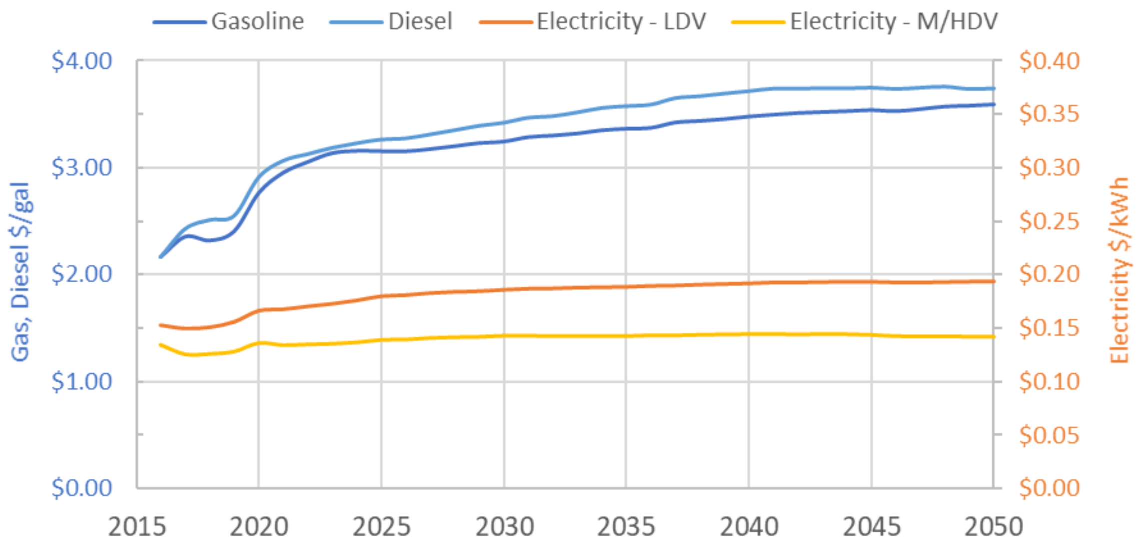
Figure C-6 Liquid Fuel Carbon Intensity Targets (% below 2010 level; not including electricity)



Source: MJB&A Analysis

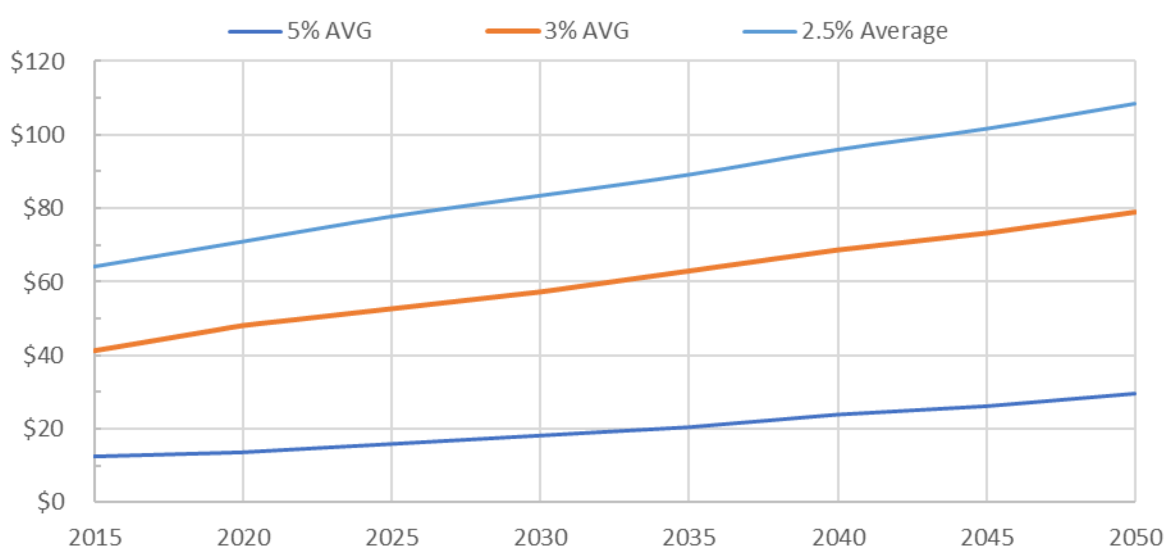
APPENDIX D – Cost Benefit Analysis Data Inputs

Figure D-1 Weighted Average Energy Prices in Study Region (2015 $)



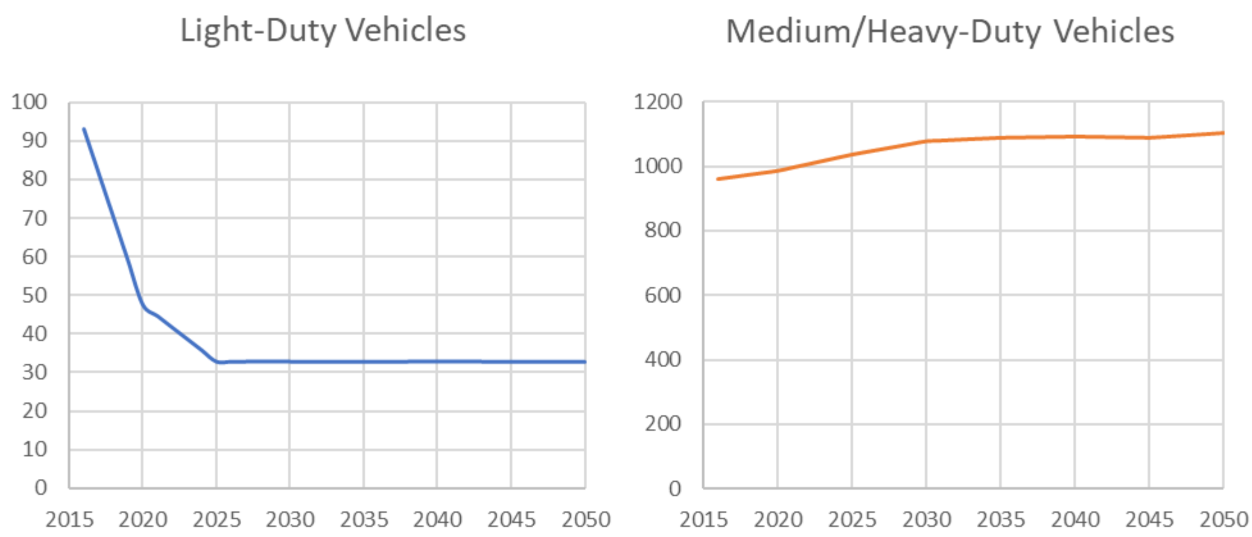
Source: Energy Information Administration, 2018 Annual Energy Outlook

Figure D-2 Social Cost of CO_2 (2015 $/MT)



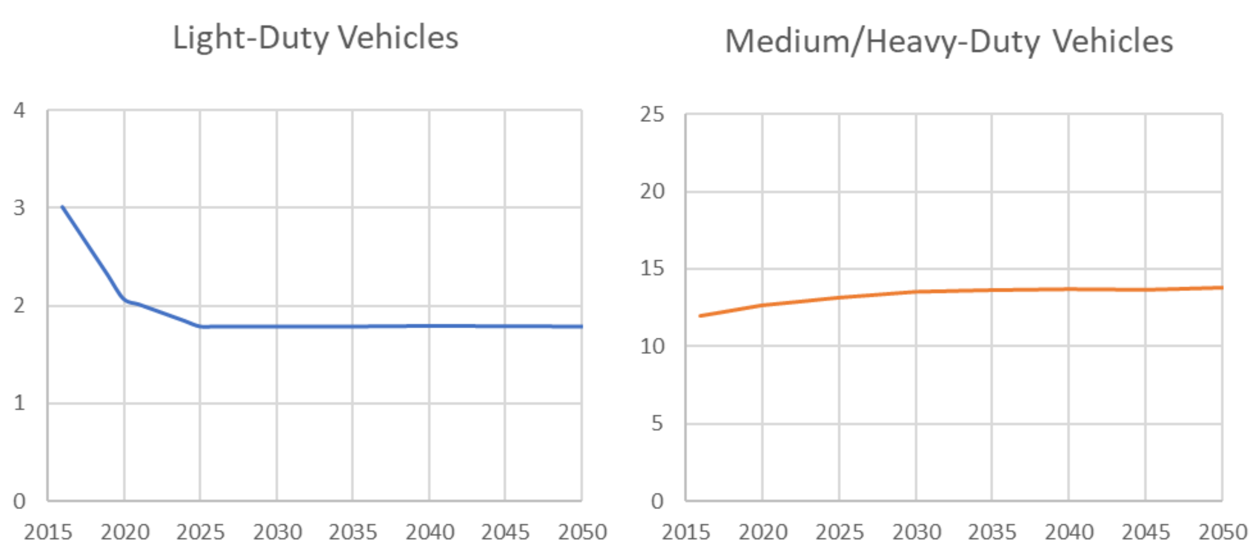
Source: Interagency Working Group on the Social Cost of Greenhouse Gases, July 2015

Figure D-3 New Conventional Vehicle NOx Emissions (mg/mi)



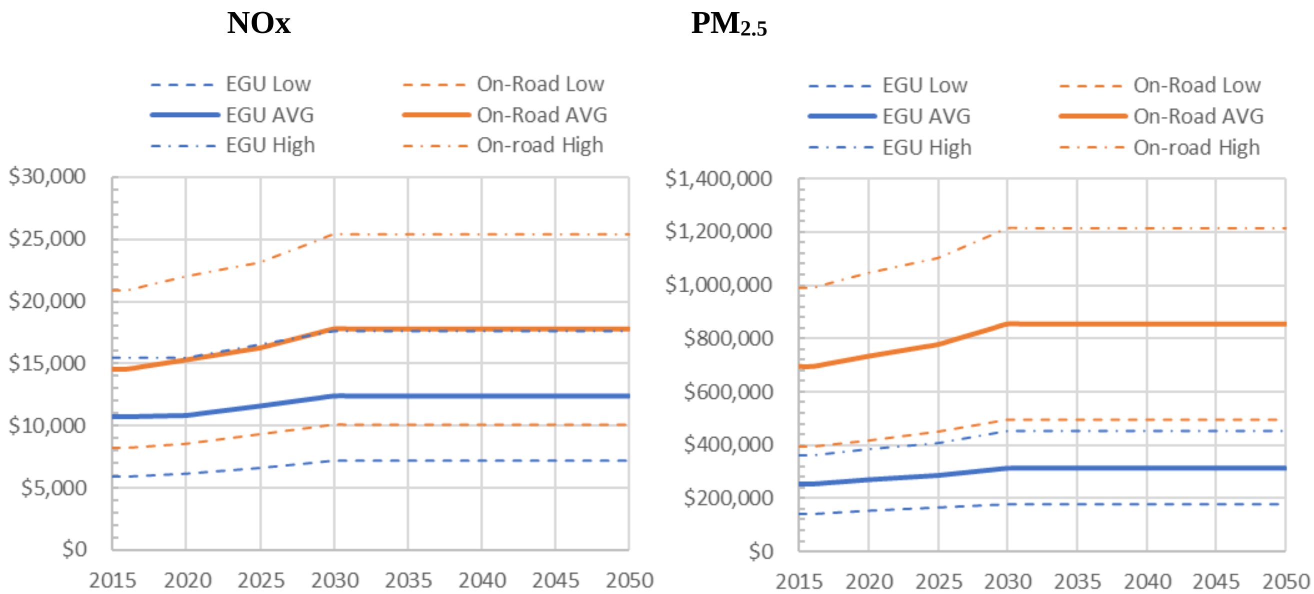
Source: Environmental Protection Agency, MOVES Model

Figure D-4 New Conventional Vehicle $PM_{2.5}$ Emissions (mg/mi)



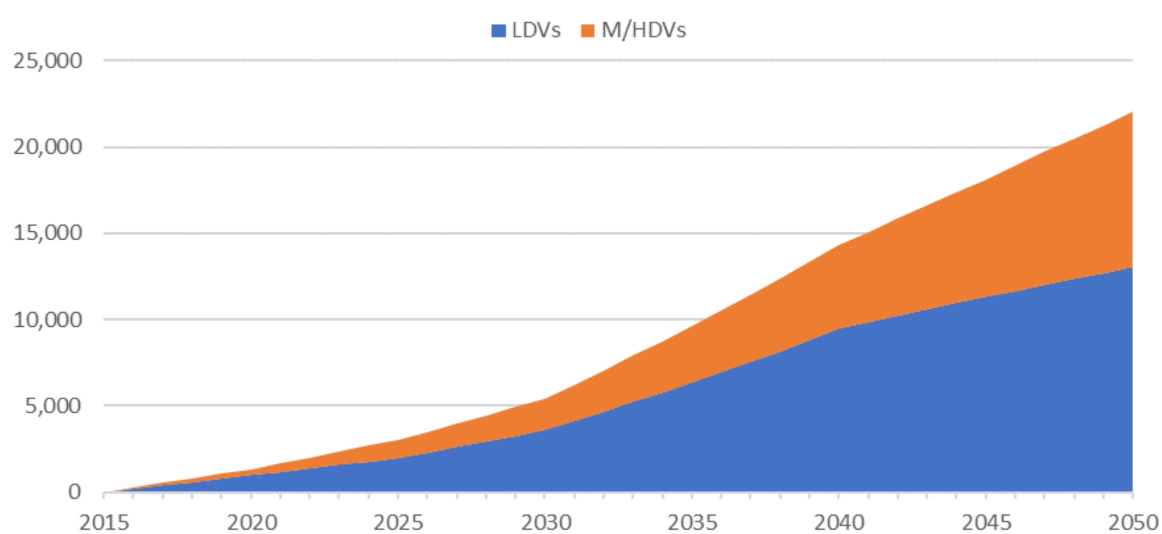
Source: Environmental Protection Agency, MOVES Model

Figure D-5 NOx and $PM_{2.5}$ Emission Damage Estimates (2015 $/MT)



Source: Environmental Protection Agency, 17 Sector Study

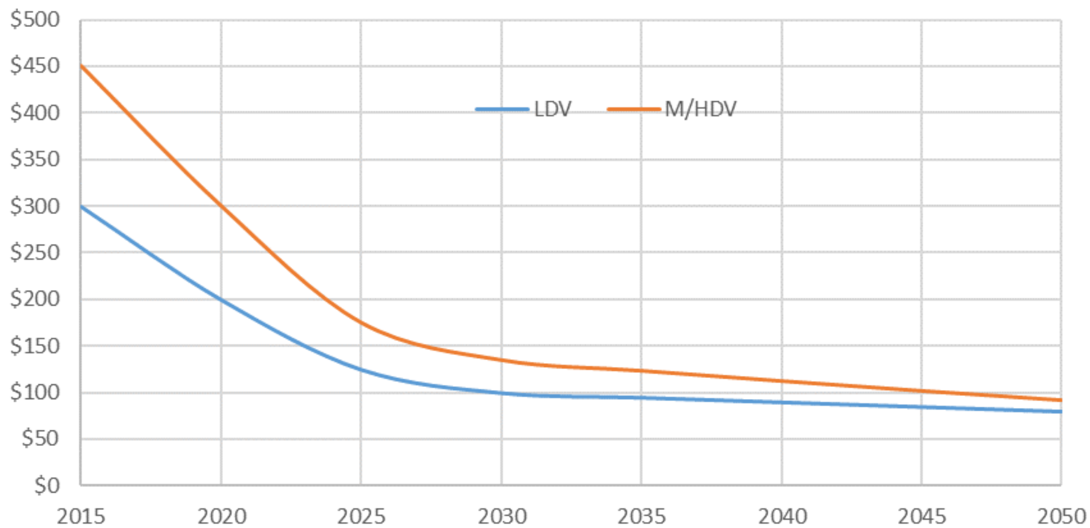
Figure D-6 Projected Incremental EV Charging Load (MW) During Afternoon Peak Load Period (High)



Source: MJB&A Analysis

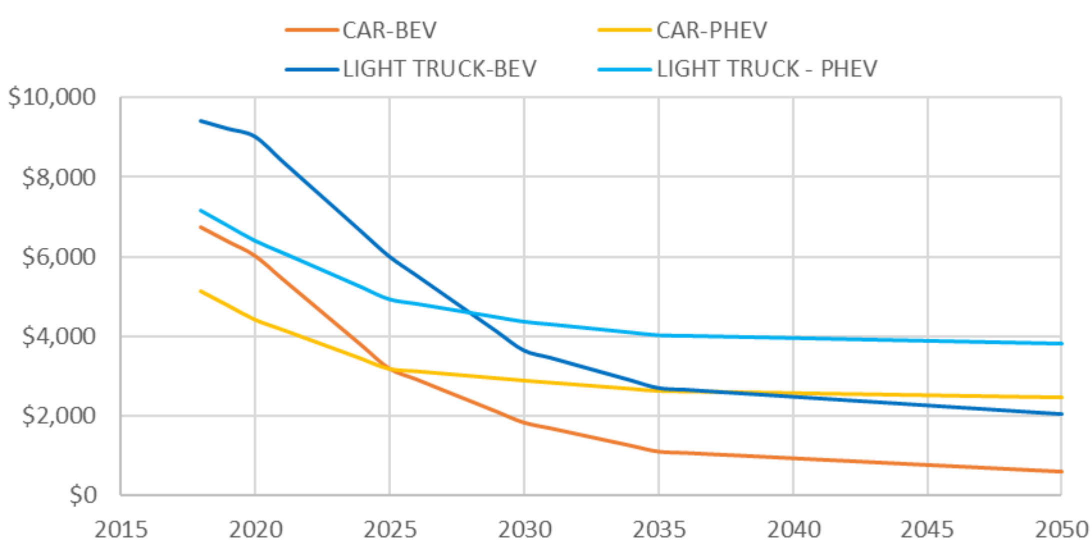
APPENDIX D – Cost Benefit Analysis Data Inputs

Figure D-7 Electric Vehicle Battery Pack Cost (2015 $/kWh)



Source: Various sources; MJB&A analysis

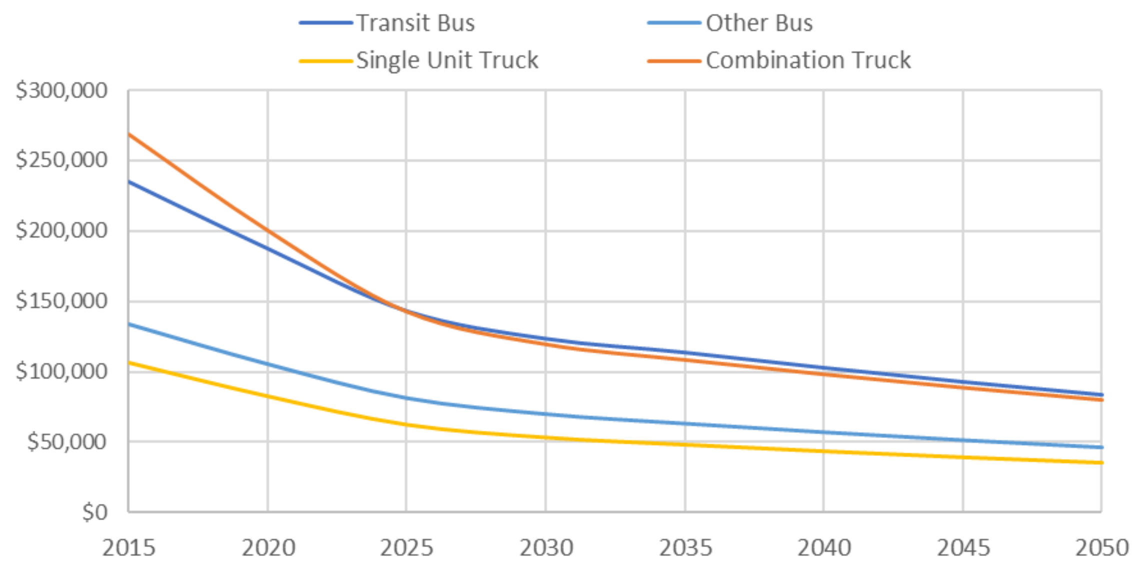
Figure D-8 Fleet Average Incremental Cost of New Electric Light-Duty Vehicles (2015



Source: ICCT; MJB&A Analysis

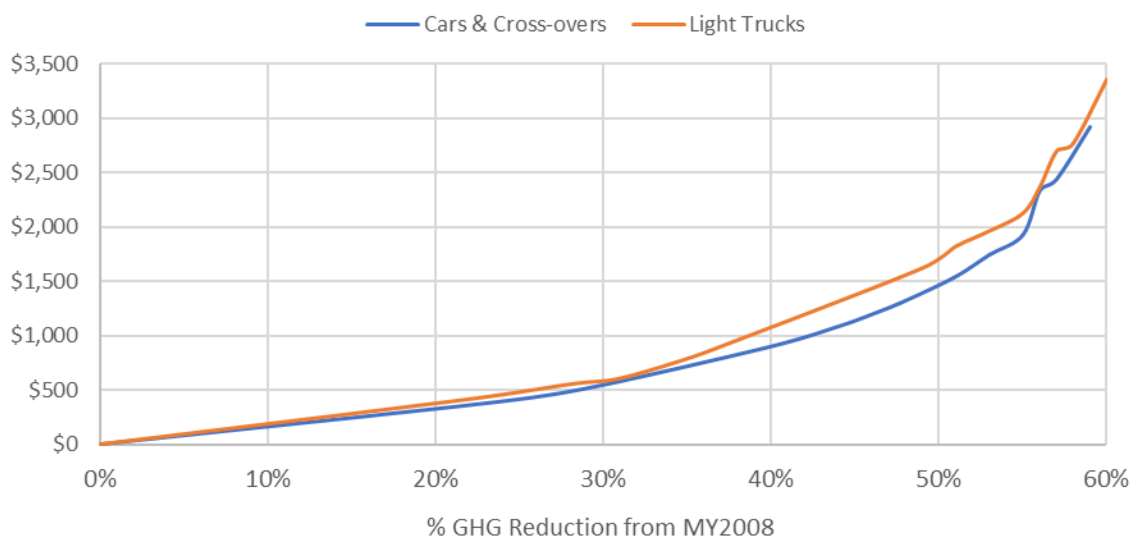
APPENDIX D – Cost Benefit Analysis Data Inputs

Figure D-9 Incremental Cost of New Medium- and Heavy-duty Electric Vehicles (2015 $)



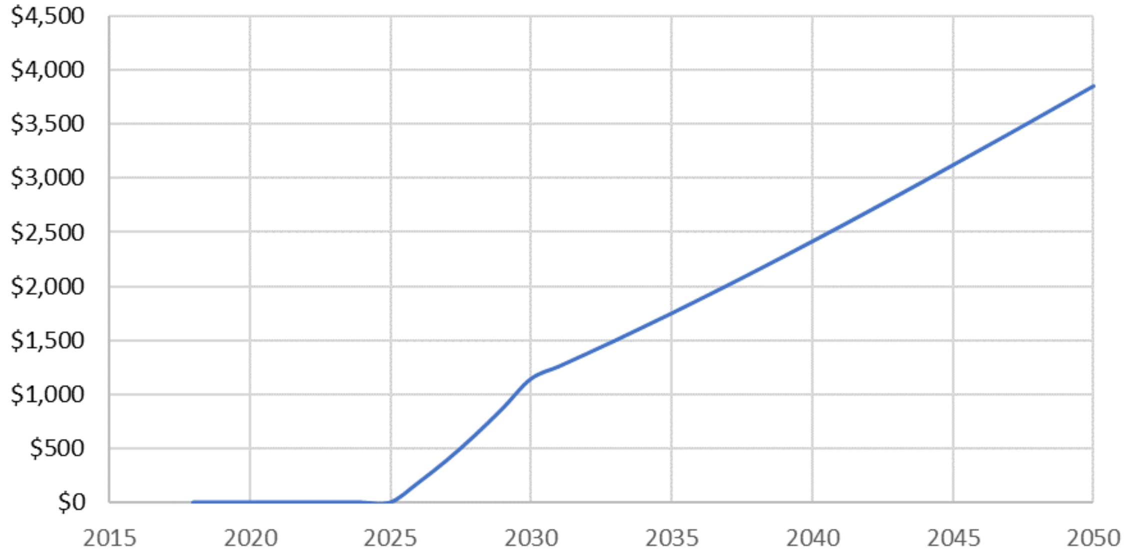
Source: MJB&A Analysis

Figure D-10 Incremental Cost for More Efficient Conventional Light-Duty Vehicles (2015 $)



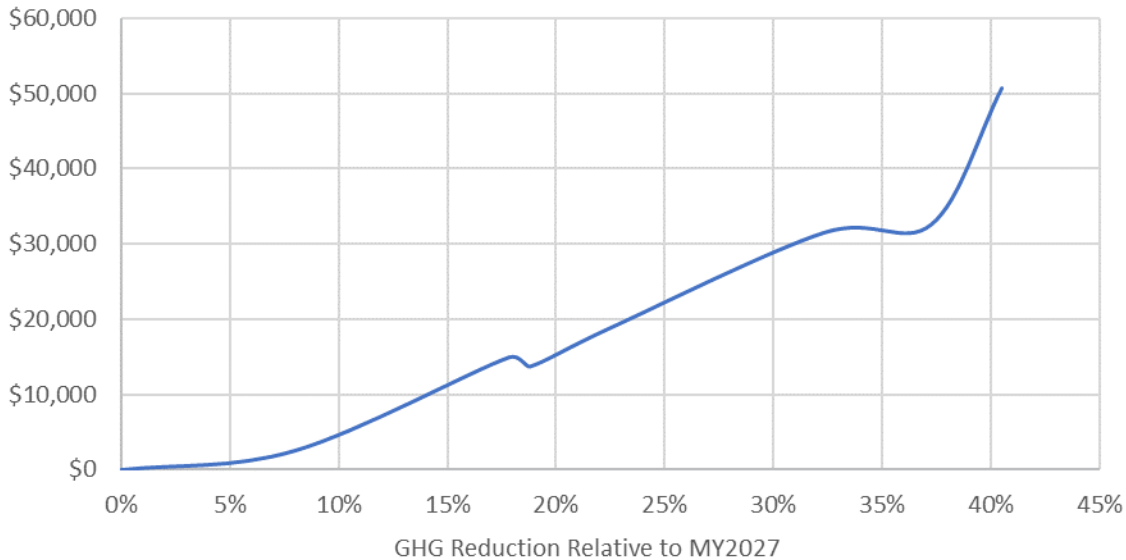
Source: ICCT

Figure D-11 Fleet Average Incremental Cost of New Conventional Light-duty Vehicles (2015 $) *to comply with Modeled scenarios for increased fuel efficiency standards*



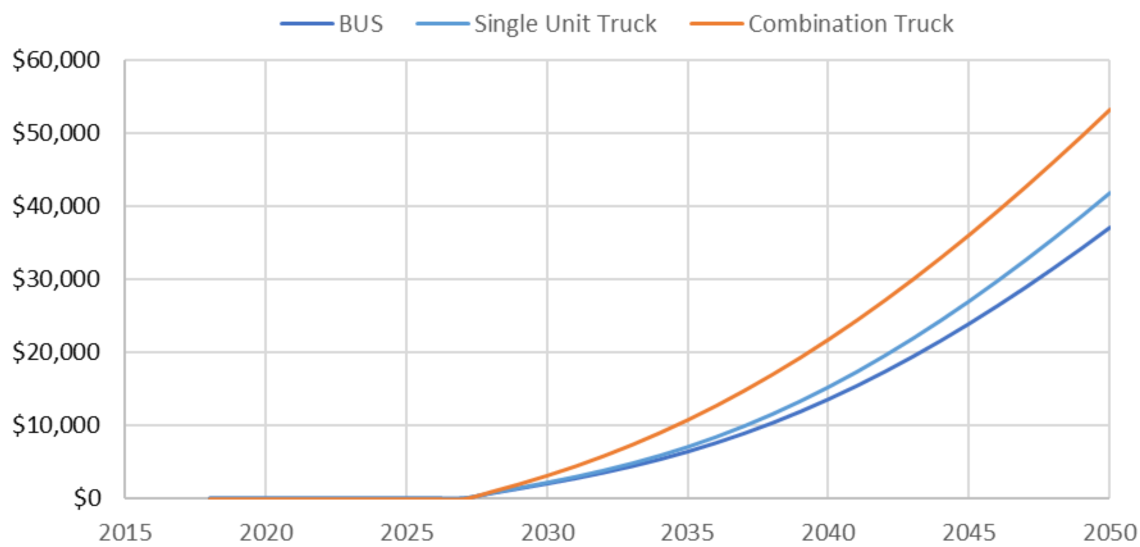
Source: ICCT; MJB&A Analysis

Figure D-12 Incremental Cost for More Efficient Combination Trucks (2015 $)



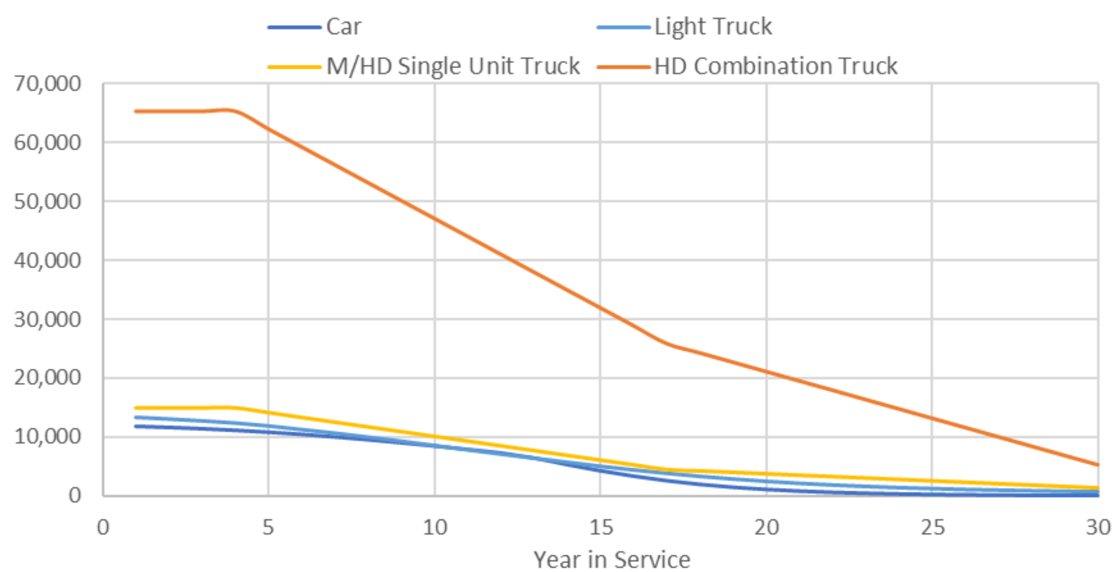
Source: ICCT; cost is for one truck and three trailers

Figure D-13 Fleet Average Incremental Cost of New Conventional M/HDVs (2015 $) *to comply with Modeled scenarios for increased fuel efficiency standards*



Source: ICCT; MJB&A Analysis

Figure D-14 Annual Mileage Over A Vehicle's Life (miles/year)



Source: Environmental Protection Agency, MOVES Model

APPENDIX D – Cost Benefit Analysis Data Inputs

Figure D-15 Medium & Heavy-duty Electric Vehicle Charging Scenario

VEHICLE USAGE AND ENERGY		*unit*	VEHICLE TYPE: Transit Bus	Other Bus	Single-unit Truck	Combination Truck
Annual VMT/vehicle		mi	43,228	12,960	12,960	61,975
Annual Usage		Days	270	220	250	270
Daily VMT/vehicle		mi	160	59	52	230
Energy Use		kWh/mi	3.0	1.8	1.8	2.3
Daily Energy/Vehicle		kWh	480	107	94	523
Annual Energy/Vehicle		kWh	129,684	23,587	23,587	141,303
% Vehicles in-service each day			85%	90%	95%	95%
CHARGING SCENARIOS		***unit***	**VEHICLE TYPE: Transit Bus**	**Other Bus**	**Single-unit Truck**	**Combination Truck**
Overnight Charging	% of vehicles	%	50%	80%	80%	20%
	Daily Charge	kWh	480	107	94	523
	Daily Charge Time	hr	8.0	8.0	8.0	8.0
	Avg Charge rate	kW	60.0	13.4	11.8	65.4
	Charger Size	kW	100.0	19.0	19.0	100.0
Day-time Charging (DCFC)	% of vehicles	%	50%	20%	20%	80%
	Daily Charge	kWh	480	107	94	523
	Daily Charge Time	hr	1.0	2.0	1.5	2.0
	Avg charge rate	kW	480.3	53.6	62.9	261.7
	Charger Size	kW	300.0	100.0	100.0	300.0
Daytime (DCFC) charging hours available		hr	20.0	12.0	12.0	22.0
Number of Charge Ports per in-use Vehicle		Overnight Charger	0.425	0.720	0.760	0.190
		Daytime Charger	0.042	0.056	0.042	0.121

Source: M.J. Bradley & Associates

Figure D-16 Fuel Mix and Implied Emission Rate for Incremental Electricity Demand

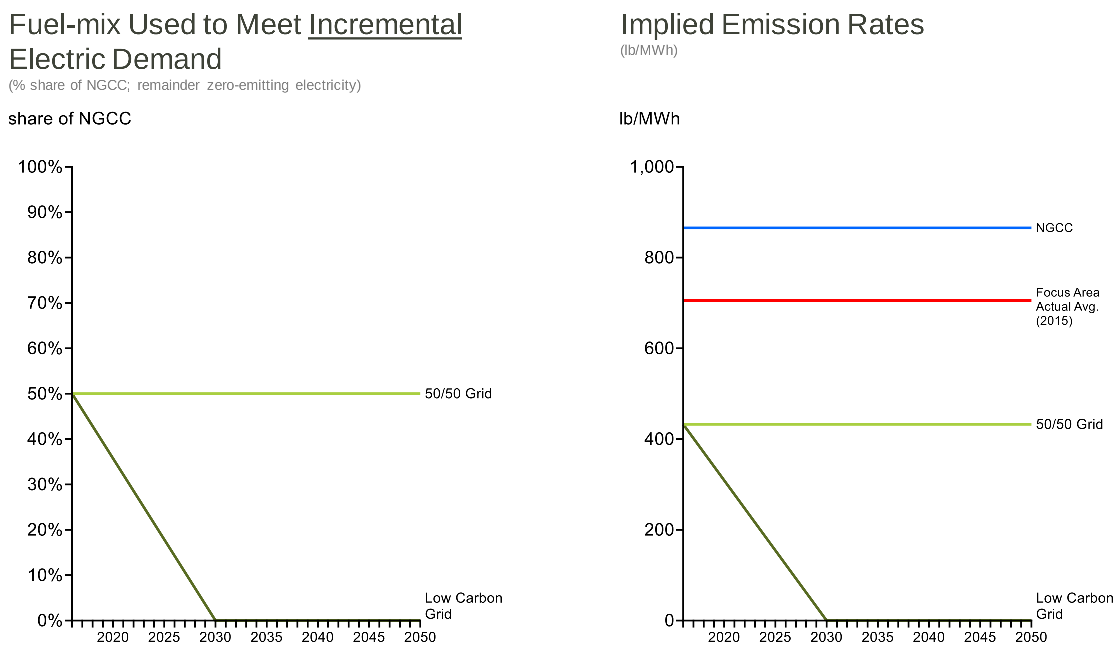
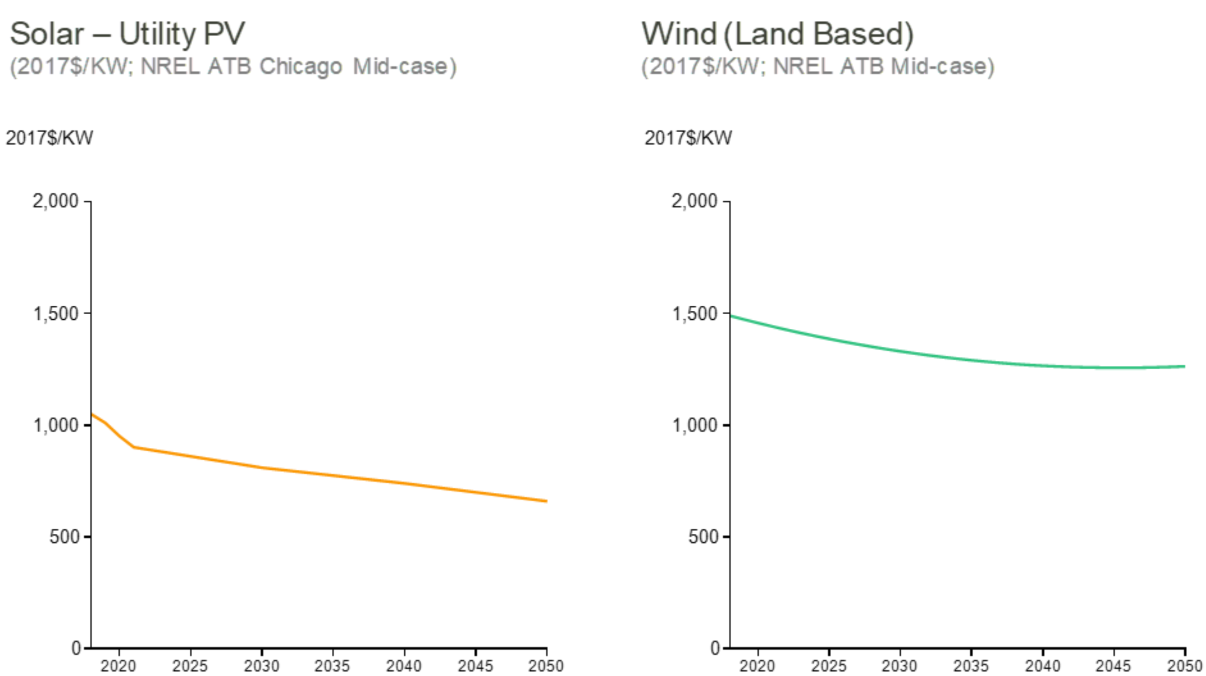
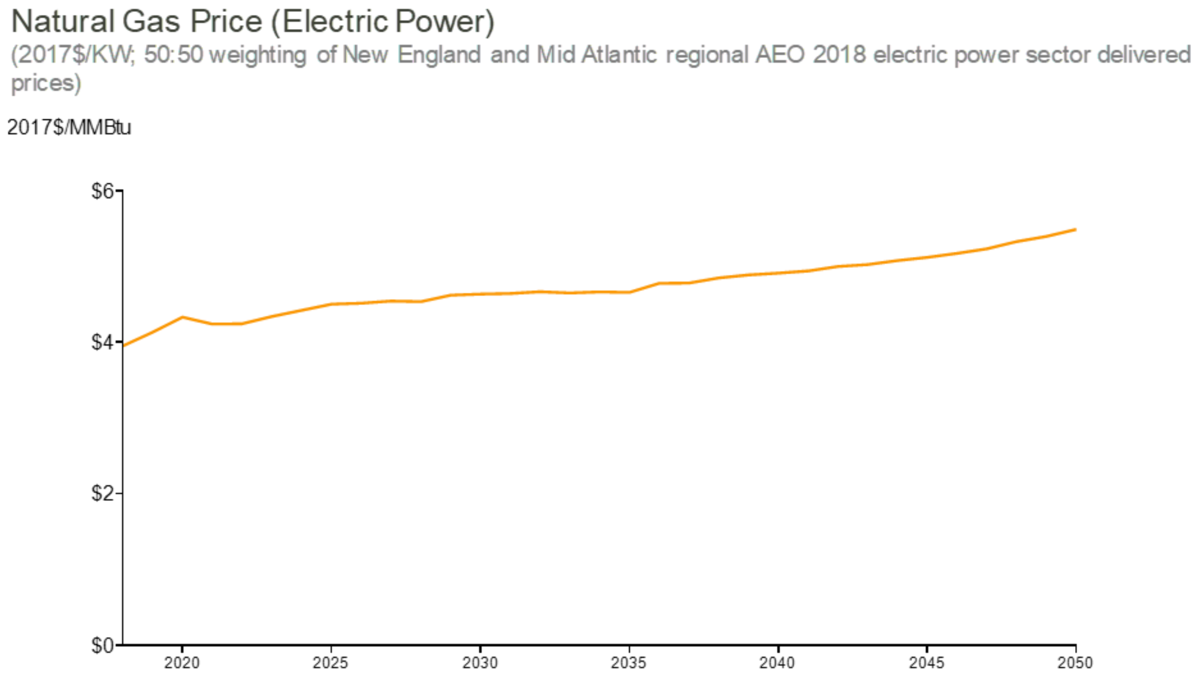


Figure D-17 Projected Cost of New Renewable Generation



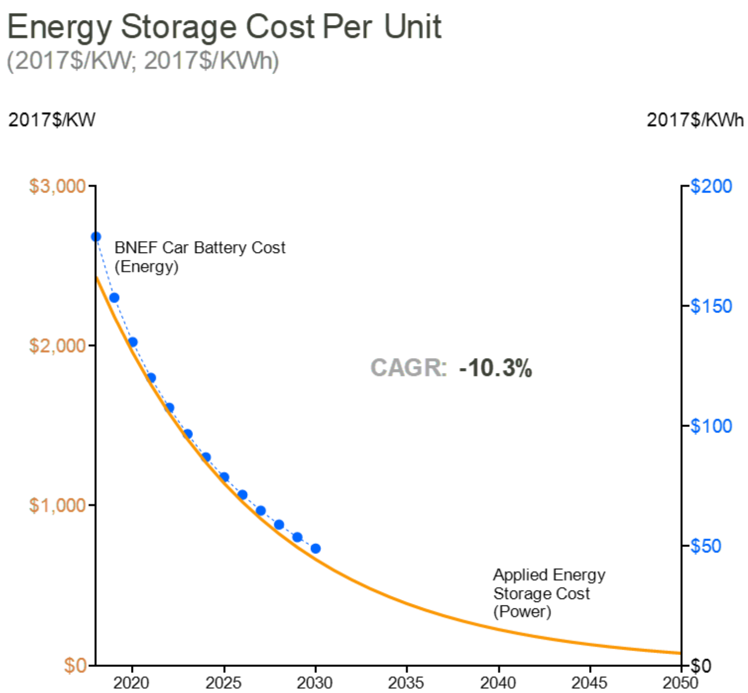
Source: National Renewable Energy Laboratory

Figure D-18 Projected Natural Gas Price for Electricity Generation



Source: Energy Information Administration

Figure D-19 Projected Grid-scale Energy Storage Costs



Source: Energy Information Administration; MJB&A analysis

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APPENDIX F – State Level Estimates of Cumulative Costs and Benefits

Appendix F in included in as separate document.