Health Benefits of Transition to Zero Emission Transportation Technologies

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I. Summary and Overview

Vehicle elecrification has the potential to signifcantly reduce air pollutant emissions, improve air quality, slow climate change, and reduce the public health burden associated with exposure to vehicular emissions. This is because, generally, electric vehicles produce fewer emissions that contribute to climate change and smog than conventionally fueled vehicles.[1] As of 2018, transportation was responsible for about 28% of the nation's greenhouse gas emissions.[2] Direct emissions from on-road vehicles alone were responsible for accounting for about 33% of the nation's total nitrogen oxides and about 13% of its emissions of volatile organic species, together the primary contributors to smog, about 39% of the nation's emissions of carbon monoxide, and about 3% of the nation's primary emissions of fine particulate matter.[3] Meanwhile, more than 45 million people in the U.S. live within 300 feet of a major transportation facility such as a busy roadway, which increases their exposure to air pollution and may contribute to adverse health effects including asthma, cardiovascular disease, and premature death.[4]

ICF conducted a comprehensive analysis for the American Lung Association (ALA) of the potential health and climate benefits of a potential scenario for increasing on-road vehicle electrification across the United States. This report documents the benefits of this ambitious but achievable nationwide vehicle electrification scenario.

The study has four principal components:

1. Analysis of a current baseline and projected business as usual (BAU), national, on-road transportation fleet and its associated air pollutant emissions.
2. Creation of an increased on-road vehicle electrification *Scenario* including both light- and heavy-duty vehicles, and modeling of the national vehicle fleet in this Scenario. We considered ten categories of vehicles.
3. Modeling of air pollutant and greenhouse gases emissions associated with vehicle travel in two time horizons:
   - a short-term projection for year 2030 and
   - a long term projection to year 2050.

   We assessed changes in emissions nationwide resulting from the electrification Scenario considering both *downstream* (tailpipe exhaust, evaporative, brake and tire wear) and *upstream* (reduced fuel production, transport, and refining activities for internal combustion vehicles and increased electrictiy generation for electric vehicles) emissions components. Furthermore, we

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[1] US Department of Energy, Reducing Pollution with Electric Vehicles (2020). https://www.energy.gov/eere/electricvehicles/reducing-pollution-electric-vehicles.

[2] US EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018 (2020). https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2018.

[3] US EPA, National Annual Emissions Trends: Criteria pollutants National Tier 1 for 1970 – 2019 (2020). https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data. All are relative to national totals from all sources excluding wildfires.

[4] US EPA, Research on Near Roadway and Other Near Source Air Pollution (2020). https://www.epa.gov/air-research/research-near-roadway-and-other-near-source-air-pollution.

considered the implications of two potential cases for the future electricity production on the upstream emissions to the Scenario.

4. Estimation of the public health and climate benefits associated with the predicted changes in emissions due to the vehicle electrification Scenario relative to BAU conditions in the same projection years.

Our approach and results are documented in the following sections of this report:

- Section II describes the analysis of national-scale, BAU, on-road vehicle population, engine technology, age distribution, and emissions.
- Section III describes the approach taken to determine an aggressive vehicle electrification scenario and simulate the penetration of electric vehicles (EVs) in the overall fleet according to the scenario.
- Section IV discusses the national level emission changes resulting from implementation of the vehicle electrification scenario, including both upstream and downstream emissions and two variations in upstream electricity generation associated with the scenario.
- Section V describes the results and approach taken to quantify and monetize the decreases in adverse health impacts resulting from improved air quality associated with the scenario.
- Section VI monetizes the climate benefits anticipated due to reductions in greenhouse gas (GHG) emissions from the vehicle electrification scenario.

Our modeling of the baseline and BAU national vehicle fleet, its related activity, fuel use, population, engine technology, age distribution, and downstream emissions relied on national default values from US EPA's MOVES emission model. We simulated emissions of

- Volatile organic compounds (VOC),
- Oxides of nitrogen (NO_x),
- Fine particulate matter less than 2.5 μm in size ($PM_{2.5}$),
- Sulfur dioxide (SO_2),[5] and
- Ammonia (NH_3),

and related pollutants to capture both direct PM emissions and precursors for secondary PM. We also modeled emissions of

- GHGs, characterized as CO_2-equivalent (CO_2e).

We determined an ambitious vehicle electrification Scenario and conducted fleet modeling that simulated the replacement of traditional internal combustion engine vehicles (ICEVs) with battery electric vehicles (BEVs) and determined the population of vehicles by vehicle and fuel categories based on sales targets. Our electrification scenario was scoped to achieve full transition to zero emission passenger vehicle sales by 2040. It also includes aggressive penetrations of electrified heavy-duty vehicles, which vary by vehicle category and transition at a slower pace than light duty vehicles. The scenario is based on a variety of recent progress, including California's recent Advanced Clean Trucks rule.[6] BEVs are used as a marker for zero

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[5] In this analysis, SO_2 and SOx are considered identical.

[6] California Air Resources Board (2020). https://ww2.arb.ca.gov/our-work/programs/advanced-clean-trucks.

emission technologies in this study, recognizing that a range of technologies (hybrid, plug-in hybrid, hydrogen, etc.) will factor in the marketplace across the fleet.

Although there is a single vehicle electrification Scenario, within it we also considered two potential *Cases* for the future electricity generation and the associated impact on national emissions and public health:

- One represents a conservative analysis based on the US Energy Information Administration's (EIA) Annual Energy Outlook (AEO). This is referred to here as the *AEO Case*.
- The other represents impacts from a scenario with reduced coal and increased renewables based on the Bloomberg New Energy Outlook (BNEO). This is referred to here as the *ALA Case*.

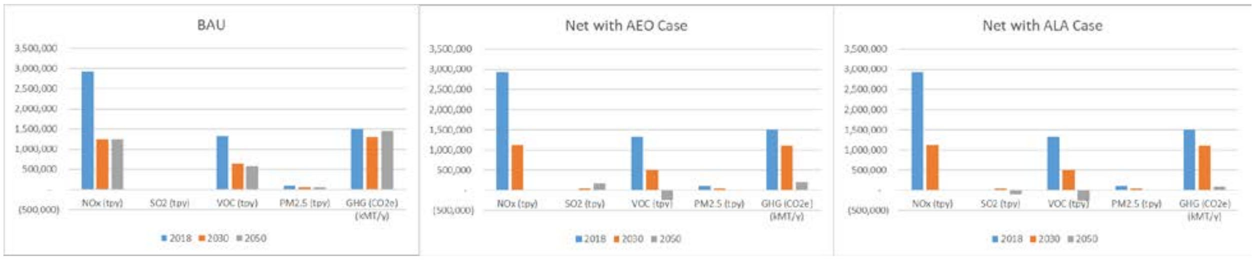
All analyses reflect national-scale simulations and rely on an average power approach. We do not assume that BEV demand causes low carbon intensity electricity growth or implement an incremental approach to future electricity generation that pairs the increased demand with cleaner electricity only. Our approach may be considered conservative.

We then calculated the direct emissions of vehicular pollutants nationally for the BAU and vehicle electrification Scenario. These downstream emissions are significantly lower under the Scenario than the BAU. In 2050, annual downstream emissions of NOx, VOC, and $PM_{2.5}$ are reduced below the values of a BAU scenario by approximately 1,000,000, 490,000, and 31,000 short tons, respectively. These values are 82, 83, and 62 percent below the BAU levels of emissions, respectively. 2050 levels of tailpipe GHG emissions are reduced by more than 1.3 billion metric tons, or 90 percent, below the BAU. Downstream emissions consider the ongoing contribution of brake and tire wear PM emissions, including for BEVs.

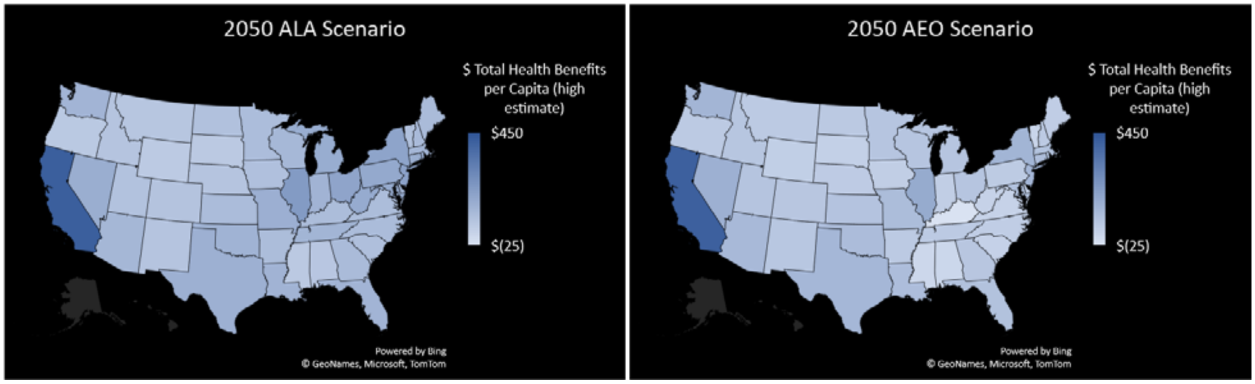
We also calculated the changes in upstream emissions associated with the vehicle electrification Scenario. These changes include reductions in upstream components of ICEV fuel production and distribution and increased electricity production. Upstream emissions rely on emission factors determined with the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model. We developed upstream emission factors for both the AEO and ALA electrification Cases. Upstream emissions also consider the increased efficiency of BEVs over ICEVs.

The Scenario's net national emissions are the sum of the total downstream emissions under the Scenario, the reduction in upstream emissions associated with reduced production and distribution of ICEV fuels, and the additional upstream emissions associated with increased electricity demand. Net national emissions from the Scenario are negative when the reduction in ICEV fuel production and distribution emissions is greater than the combined remaining tailpipe emissions and additional grid emissions following electrification. These net emission changes were then compared to the BAU emissions to gauge the changes. On net, the more conservative AEO Case results in roughly 1,300,000, 840,000, and 51,000 tons of NOx, VOC, and $PM_{2.5}$ reductions in 2050 in addition to roughly 1.4 billion metric tons of GHG emission reductions below that of the BAU level of direct emissions. These reductions are roughly 100 percent for NOx and $PM_{2.5}$, roughly 140 percent for VOC, and 86 percent for GHGs. Note that reductions of more than 100% are possible when the net reduction exceeds the BAU (downstream) emissions. With the AEO Case SO_2 shows an emissions increase when considering upstream and downstream emissions in combination. SO_2 is the only pollutant to exhibit an increase and is due to the combination of on-road fuels having very low sulfur content, so vehicles emit relatively little SO_2, and the higher coal component of the AEO Case. This scenario would result in a net national increase of SO_2 emissions. When the national electrification Scenario is paired with the ALA electricity generation Case – and its reduced reliance on coal and increased renewables – national reductions of NOx, VOC, and $PM_{2.5}$ are similar to the AEO scenario, at roughly 1,300,000, 840,000, and 53,000 tons in 2050, or roughly 100, 140, and 110 percent, respectively. Additional GHG reductions are realized, of roughly 1.5 billion metric tons or 94 percent reduction relative to the BAU downstream value. This scenario also leads to a dramatic reduction in national SO_2 emissions of more than 100,000 tons. This is a reduction nearly 10 times higher than the BAU on-road only emissions of SO_2, illustrating the importance of upstream emissions in cumulative changes.

The resulting emission impacts by pollutant and year are summarized by the following figure. Total downstream emissions from the ten modeled vehicle categories in the BAU (left panel) may be compared against the net emissions from the Scenario with both electricity generation Cases (AEO in the central panel and ALA in the right). As above, the net emissions impact of the electrification Scenario is downstream under the Scenario plus net changes in upstream emissions.



We then used these national-scale criteria pollutant emissions in EPA's COBRA model to evaluate the potential health benefits of the vehicle electrification Scenario. We quantified and monetized changes in the incidence of adverse health impacts resulting from reduced human exposure to downstream and upstream $PM_{2.5}$ emissions from the scenario. While the above emission results present net changes, our COBRA modeling treated emission sectors separately to preserve the source-receptor relationship for each source category. We prepared both national and state-by-state summaries of impacts. Nationally, the electrification Scenario predicted between about $1.5 and $3.5 billion in avoided health impacts due to decreased air pollutant emissions in 2030, including between approximately 150 and 340 avoided premature deaths aggregate over the next 20 years due to reductions in 2030, along with reductions in other non-fatal outcomes. (The ALA and AEO Cases are identical in 2030.) The impacts increase to between approximately $24 and $54 billion in avoided health impacts and between roughly 2,100 and 4,700 avoided premature deaths due to air quality improvements in 2050 with the AEO Case. The ALA Case shows an increase in benefits from reduced emissions in 2050 of between roughly $32 and $72 billion in health savings and between 2,800 and 6,300 avoided premature deaths. One example of this is the estimated monetized total health benefits per capita in each state, shown by the following figure.



Finally, we also estimated the benefits anticipated due to reductions in GHG emissions for the vehicle electrification scenario using the social cost of carbon (SCC). Using a 3% discount rate and considering the net emissions of each Case, we estimate more than $100 billion in climate related impact savings from the 2050 level of emission reductions with the AEO Case and more than $110 billion with the ALA Case.

The vehicle electrification Scenario considered here would have significant national and international benefits resulting from the cleaner air the scenario would create, including dramatic reductions in pollution from on-road sources. The climate benefits from reductions of GHGs are expected to reach into the hundreds of billions of dollars globally, while the domestic health benefits would range in the tens of billions of dollars, including thousands of avoided deaths due to reduced air pollution. Furthermore, in the ALA Case, the net health and air quality benefits would be extended to all states by the horizon year while the more conservative AEO Case still shows net benefits in 2050 to all but one state.

II. Baseline and Business as Usual (BAU) Fleet

We first developed a detailed model of the BAU fleet suitable as a baseline for comparison of later modeling results. This is needed to establish vehicle activities, population, emissions, and emission rates that are used to determine vehicle patterns and a baseline of emissions against which to evaluate emissions under the electrification Scenario.

This section discusses our determination of:

- The vehicle types considered in the Scenario
- The baseline vehicle population by vehicle type and model year for the baseline year, 2018
- The BAU fleet for the two projected years, 2030 and 2050, nationwide.
- Baseline and BAU on-road vehicle tailpipe (downstream) emissions used for later baseline setting.

1. Summary of Approach for Baseline and BAU Vehicle Population and Emissions

All national fleet and activity data for the baseline and BAU is based on default data in US EPA's MOVES vehicle emissions model.[7] We used MOVES2014b to simulate national values of vehicle population, age distribution, fuel distribution, and downstream emissions by vehicle category for all vehicles in the 50 US states plus DC. All simulations were made at MOVES' national default scale, with emissions, population, and activity determined for each state individually using MOVES' inventory mode, to produce annual total emissions for years 2018, 2030, and 2050 for all day types and hours.[8] Downstream emissions include criteria and GHG emissions from exhaust and evaporative processes and $PM_{2.5}$ emissions from brake and tire wear. All emissions processes and sources available in the model were included.

MOVES relies on AEO2014 to develop the growth projections for activity (population and Vehicle Miles Traveled).[9] MOVES then calculates emissions based on these activity values, current federal emission regulations, and other parameters.[10]

We conducted MOVES simulations nationwide for the three analysis years as described above. We reported all vehicle populations and emissions by the MOVES vehicle types, calendar year, model year and fuel type. We aggregated the individual states to national total values. We also

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[7] https://www.epa.gov/moves

[8] Due to the long processing times for evaporative runs but to continue to capture the seasonality of evaporative VOC emissions, annual evaporative emissions are extrapolated to annual values from MOVES runs for the months of January and July only. All months were included in annual totals for all other emission processes.

[9] Population and Activity of On-road Vehicles in MOVES2014, EPA-420-R-16-003a, March 2016. Available at: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100O7PS.pdf.

[10] Throughout this analysis, we rely on the current version of MOVES at the time of analysis, MOVES2014b, as it remains EPA's regulatory model for mobile source emissions. Other approaches are possible, such as determining emission factors in MOVES and growth rates from a newer version of AEO which would produce different results. We note this does not include effects of the recent Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule, issued March 2020.

included additional vehicle type resolution that was used to facilitate later vehicle categorization, as discussed below.

2. Vehicle Classification

For analysis of our vehicle electrification Scenario, we have grouped vehicles into ten categories, shown in Table 1.

We considered both MOVES vehicle type categories and regulatory classes (“regClassID”) in vehicle mapping.[11] To simplify vehicle mapping and allow better resolution for EV penetration, we used vehicle categories in our Scenario that aligned directly with those in MOVES for as many vehicle types as possible. Table 1 shows the ten vehicle categories considered here and their corresponding definitions in terms of MOVES vehicle classifications.

Table 1. Scenario Vehicle Type Description.

ID	Category		Subset	MOVES sourceTypeID
1	Light-Duty Vehicle Fleet for Electrification	Passenger Fleet	All	All: 11-Motorcycle, 21-Passenger Car, 31-Passenger Truck
			All	All: 32-Light Commercial Trucks that are regClassID 30
2	Heavy-Duty Vehicle Fleet for Electrification	Transit Bus	All	All: 42-Transit Bus
3		School Bus	All	All: 43-School Bus
4		Refuse Truck	All	All: 51-Refuse Truck
5		Long Haul	All	All: 53-Single Unit Long-haul Truck
6			All	All: 62-Combination Long-haul Truck
7		Airport Shuttles	Partial	0.1 percent of these categories: • 32-Light Commercial Truck, regClassID 40 • 52-Single Unit Short-haul Truck, regClassID 41, 42.
8		Drayage/Port	Partial	6 percent of 61-Combination Short-haul Truck
9		Delivery Vans	Partial	10 percent of 52-Single Unit Short-haul Truck, regClassID 41,42
10		Additional Single Unit Short-Haul (SUSH)	Partial	All 52-Single Unit Short-haul Truck, regClassID 46,47 (SUSH MHD67, HHD8) All 52-Single Unit Short-haul Truck, regClassID 41,42 not included as Airport Shuttles or Delivery Vans.
N/A	HDV Fleet Not Electrified		All	41-Intercity Bus
			All	54-Motor Home
			Partial	Remaining portion of 32-Light Commercial Truck regClassID 40 and of 61-Combination Short-haul Truck not included as Airport Shuttles or Drayage/Port trucks.

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[11] MOVES uses regulatory classes to group vehicles subject to similar emission standards in addition to source types. Other than motorcycle and light-duty vehicles, regulatory classes generally resolve vehicles by gross vehicle weight rating (GVWR) classification. See footnote 9 for more information.

2.1 Light Duty

Vehicle Category 1 represents the passenger vehicle fleet. We took MOVES categories 11, 21, and 31 directly for this category. (Tables in Appendix A provide definitions of the MOVES vehicle scheme.) We also included the smaller of MOVES category 32 in the passenger fleet. All these vehicles are considered for electrification in the Scenario. They are treated in aggregate as Category 1 here.

2.2 Heavy Duty

ALA identified seven categories of Heavy-Duty Vehicles for high likelihood of electrification. These are the seven vehicle types shown in the third column of Table 1 for heavy vehicles. They correspond to vehicle categories 2 – 9 here. The additional category is due to our maintaining the MOVES split between single and combination unit long haul trucks. We also added Category 10 to capture the large number of remaining single unit short haul vehicles.

Categories 2 – 6 match MOVES vehicles definitions. Thus, the Scenario fleet population is taken directly from MOVES values. Three of these, Transit Bus, School Bus, and Refuse Trucks (Category 2, 3, and 4) are direct matches to MOVES categories and are included in our Scenario unmodified from the MOVES outputs. Long Haul trucks were separated into two categories here (5 and 6) consistent with MOVES vehicle categories. While single and combination unit trucks may both be used for long haul applications, they are also treated separately due to differences associated with the corresponding potential for electrification.

Categories 7 – 10 are imperfect matches to MOVES categories. For these, we created a vehicle type mapping based on MOVES sourceTypeID and regClassID. (See Appendix A for MOVES vehicle definitions.) Each of these represent only a portion of, and/or a combination of, relevant MOVES categories. They are thus labeled “Partial” in Table 1. We determined populations by allocating MOVES values as follows.

Category 7 is airport shuttles. We based our definition on California Air Resources Board’s (ARB) research supporting its Zero-Emission Airport Shuttle Bus regulation.[12] This shows airport shuttles range from Class 2b vans to Class 8 articulated buses, with a majority being Class 4-5 Cutaways and more than 80% being either vans or cutaways. Accordingly, we represented airport shuttles as light commercial trucks (vans), single unit short haul trucks below 14,000 lbs. GVWR, or single unit short haul in Classes 4-5. There is no data on the national inventory of airport shuttle buses. Instead, we estimated the fraction of these MOVES categories that is used as airport shuttles based on information for California. The ARB’s Shuttle Bus research includes an inventory for the state. We used this value and the total number of vehicles in the state matching the specified MOVES vehicle categories from the EMFAC model to estimate that 0.1% of these vehicle classes in California are airport shuttles. We then applied that same 0.1% fraction to the national population of these MOVES vehicle types to estimate the national total of airport shuttles by age.

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[12] See, for example: https://ww3.arb.ca.gov/msprog/asb/workshop/workshop2slides.pdf?_ga=2.126706062.200207473.1582825450-265197299.1563404833

Category 8 is Drayage/Port trucks. Combination unit short haul trucks (MOVES category 61) may represent drayage or port trucks in some locations but not all. There is no national inventory of drayage trucks. As with Category 7 and 9, we first estimated the fraction of combination unit short haul trucks that are drayage for the California fleet using EMFAC. That fraction is about 9%. However, given the large coastline and number of ports in the state, we expect that fraction to be an upper limit on the overall national fraction of combination unit short haul trucks used in drayage applications. We refined that value based on goods movement data from the 2018 Commodity Flow Survey Data.[13] We took drayage movements as those involving short distance transfer of goods to a port zone preceding their export or from a port zone following their import. We took 'short distance' to mean any trip of less than 500 miles, given the available resolution in the Freight Analysis Framework (FAF) data. We extracted the total weight of goods moved by a short-distance truck trip to/from a port zone before/after they were exported/imported using the Export Flows and Import Flows databases. We then ratioed that to the national total short haul domestic commodity tonnage to approximate the population of short haul trucks engaged in drayage movements. This value was about 6%. Relying on FAF has two main limitations. It does not include any truck trips associated with exports/imports made by railroad and uses tonnage to estimate vehicle populations. However, we expect this to be a better estimate of the national drayage truck fraction than that in California. We took this 6% number as the best estimate of the fraction of combination short haul trucks nationally engaged in drayage movements. We then applied the 6% value to the national population of these vehicles in MOVES to estimate the national total number of drayage trucks by age.

Category 9 is Delivery Vans. Delivery vans vary widely. For this analysis, we considered delivery vans as a portion of MOVES sourceTypeID 52 in either regClassID 41 or 42 (single unit short haul trucks in class 2b-3 or 4-5), to focus on light- to medium-heavy duty single-unit short haul vehicles. As with airport shuttles, we estimated the fraction of vehicles in these MOVES categories nationwide that are delivery vans based on the ratios from California, using data from ARB rulemaking and EMFAC. In this case we took annual sales numbers from ARB's Advanced Clean Truck Rule ISOR.[14] We used the population age distribution of these vehicles from MOVES to determine total number of delivery trucks in California from ARB's sales numbers. Comparing this to the total population of these MOVES vehicle categories estimates about 10% of the vehicles in these categories are delivery trucks. We then applied that same 10% number to the national population of these MOVES vehicle types to estimate the national total of delivery vans nationwide by age.

Finally, Category 10 is intended to capture the remaining single unit short haul vehicles in MOVES. This is both the medium and heavy single unit short haul not matched to other vehicle categories, which is intended primarily to account for heavy duty last mile deliveries, and the remaining light-heavy duty single unit short haul vehicles not accounted for as Airport Shuttles or Delivery Vans. Note that some short haul delivery vehicles can be combination-unit trucks. Those are not considered in this category.

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[13] Determined from the Freight Analysis Framework (FAF), available at: https://faf.ornl.gov/fafweb/Extraction0.aspx.

[14] ARB, Appendix E: Zero Emission Truck Market Assessment. E.g., see p14. Available at https://ww3.arb.ca.gov/regact/2019/act2019/appe.pdf.

Not all HDVs are electrified in the Scenario. The final Category, labeled “NA” in Table 1 lists those not considered for electrification here. This includes all Intercity Buses and Motor Homes in MOVES, plus the remaining portion of the heavier Light Commercial Truck category (regClassID 40) not included as Airport Shuttles and combination short-haul trucks not included as Drayage trucks. This approach may be conservative, as excluding them here does not mean these vehicles cannot be electrified within the time horizon of this study. For example, Winnebago is building an electric Motor Home.[15] However, such applications are niche and are not treated here. Similarly, we have less data suggesting electrification of intercity buses, such as Greyhound, and are excluded here. However, some applications, such as Google Buses shuttling employees between home and work may be candidates for electrification, although niche. We anticipate such vehicles could be better represented in our Category 10 than as intercity buses.

3. Resulting Vehicle Population

Table 2 shows the population of vehicles we determined for each of the three analysis years in the categories listed in Table 1. Note that the values calculated for Categories 7-10 vehicle types are shown here to only one significant digit consistent with the resolution of the scaling factors discussed above.

Table 2. National Vehicle Population for Scenario Vehicle Types.

ID	Category		2018	2030	2050
1	LDV	Passenger Fleet	253,744,977	284,466,534	340,563,074
2	HDV	Transit Bus	83,520	100,768	129,918
3		School Bus	748,352	906,158	1,165,466
4		Refuse Truck	233,549	275,381	335,420
5		Long Haul	326,305	374,040	454,881
6			1,591,331	2,093,213	2,718,771
7		Airport Shuttles	4,000	5,000	6,000
8		Drayage/Port	80,000	90,000	120,000
9		Delivery Vans	500,000	700,000	800,000
10		Additional Single Unit Short Haul	7,000,000	8,000,000	10,000,000
N/A	HDV Not Electrified		6,000,000	6,000,000	8,000,000
Total			270,093,347	303,679,082	364,317,936

In total, only about 2% of the total vehicle fleet would not be available for electrification under this scheme. About 33% of the future HDV fleet would not be subject to electrification by 2050. All light-duty vehicles will be electrified.

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[15] https://www.curbed.com/2019/10/17/20919270/winnebago-rv-electric-camper-motiv-power-systems-investment.

4. Resulting Vehicle Age and Fuel Type Distribution

We also determined the model year and fuel type breakdown for each vehicle category in the BAU fleet. This was done using the same MOVES-based vehicle population calculations described above. The age distribution is critical as it reflects the effects of growth and scrappage on the vehicle fleet. The fuel breakdown is critical to assessing the emission impacts of substitution of conventional ICEV sales with EVs. Both were determined from the same MOVES simulations and using the same definitions used to calculate the populations discussed above. Figure 16 in Appendix A shows the BAU fleet age distribution predicted by MOVES for this study’s vehicle categories in the three analysis years.

III. Scenario Fleet

We analyzed a single vehicle electrification Scenario. This Scenario affects the 10 vehicle types described in Table 1. Table 2 showed the total BAU population of vehicles in this classification scheme. That analysis considered a BAU distribution of fuel types for each vehicle category. This section describes how we determined the vehicle fleet population by fuel type under the electrification Scenario in the mid-term (2030) and long-term (2050) years.

The Scenario Fleet explores the penetration of EVs in the same vehicle categories. This fleet is guided by a few principals:

- The vehicle electrification Scenario will achieve full transition to zero emission passenger vehicle sales by 2040.
- The penetration of heavy-duty vehicle electrification depends on the vehicle type and is generally slower than for light duty vehicles.
- The population of EVs is set by the sales penetration of each vehicle category and the growth and scrappage of vehicles, which is based on that in the MOVES model.

We identified electrification opportunities for each vehicle category based on a variety of information, but especially relied on California ARB inventories and projections, described below. We crafted growth profiles for EV sales in each of the ten vehicle categories. We made these calculations in a custom fleet turnover model that computes population by vehicle and fuel category based on sales. Battery Electric Vehicles (BEVs) are used as a marker for zero emission technologies, knowing that a range of technologies will factor in the marketplace across the fleet. The following section provides greater detail.

1. Scenario Fleet Population Modeling Approach

We estimated the vehicle population and age distributions by fuel type in every year between the baseline and horizon modeled years for each of the ten vehicle categories. We started with the BAU Fleet population distribution (Section II) for the three modeled years. We took new vehicle sales as the number of age 0 vehicles in each calendar year (i.e., where calendar year and model year match). The total sales in each vehicle category is the sum of all fuel types in that category.

We then developed a reasonable scenario for BEV[16] sales for each calendar year and vehicle category between the 2018 baseline and 2050 horizon year. This scenario is defined by the portion of each calendar year's sales that are BEV, as described next.

The model interprets additional BEV sales into the Scenario Fleet by moving gasoline or diesel vehicle sales from the BAU Fleet into the BEV category. ICEV sales are decreased proportionally to the original sales ratio in that year.[17] For example, if Vehicle Category 7 has 60% gasoline sales and 40% diesel sales in the baseline, 60% of the BEVs in the electrification Scenario would replace gasoline vehicle sales and the remaining would replace diesel vehicle

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[16] All EVs are considered to be battery electric vehicles (BEV) here.

[17] MOVES2014b includes no electric vehicles in its BAU fleet in any of the years analyzed here. Thus, there is no double counting of any electric vehicle sales with this approach.

sales. The model assumes that the scrappage rate of BEVs is identical to the ICEV it replaced. Once the new sales percentages are applied to each year, the model recalculates the total population distribution by vehicle type, fuel type and age.

2. Vehicle Sales Projections

The Scenario Fleet is defined by the BEV sales penetration values. We developed these values for each of the ten vehicle categories based on regulations, policies, and recommendations available to guide meeting of stringent emissions standards and requirements. These are summarized below. Note that these milestones are applied to the national fleet, and that some of the regulations and targets may be met using technologies other than BEVs. As mentioned above, this study considers only BEVs and is not designed to strictly adhere to the regulations or goals, but rather to incorporate them into the framework on which the Scenario is built.

- For vehicle category 1, LDVs, ICF utilized the California ZEV mandate as the baseline for 2020-2025.[18] This is 22% sales of ZEVs in 2025, when accounting for program design and manufacturer credits.[19] We assumed 50% sales in 2030 and 100% sales in 2040 and linearly interpolated for the intermediate years.
- For categories 2 and 3 (transit and school buses), ICF utilized the California Innovative Clean Transit requirements of 25% of new sales being zero emission by 2023, 50% by 2026 and 100% by 2029.[20]
- For truck categories 4 (refuse trucks), 5 (single unit long haul trucks), 9 (delivery vans), and 10 (additional single-unit short haul trucks), ICF utilized a combination of the California Advanced Clean Trucks (ACT) rules draft guidance and ARB's aggressive goals and pathways to 2045 Carbon Neutrality.[21] ICF utilized the ACT requirements to 2030 (50% ZEV sales) and the Carbon Neutrality goals (100% sales by 2040) with a linear interpolation between 2030 and 2040. The sales penetration for 2023 was assumed to be 50% of the 2024 requirements.
- For category 6 (combination unit long-haul trucks) and category 8 (drayage trucks), ICF utilized the ACT requirements to 2030 (15% ZEV sales[22]) and the Carbon Neutrality goals (100% sales by 2045). ICF assumed a doubling of 2030 sales by 2035 (30%), a further doubling by 2040 (60%) and a linear interpolation between 2030 to 2035, 2035 to 2040, and 2040 to 2045. ICF also assumed linear growth from 0 between 2022 and 2030.

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[18] https://govt.westlaw.com/calregs/Document/I505CA51BB0AD454499B57FC8B03D7856?viewType=FullText&originationContext=documenttoc&transitionType=CategoryPageItem&contextData=(sc.Default)

[19] We understand the program to be 22% ZEV credits. For the scenario, we represented that as 22% sales in 2025, which may be more aggressive than the CA program in 2025, but meeting the end goal of 100% sales by 2040. It is also important to note that ZEV through 2025 is not included in the BAU, which relies on MOVES national default values and does not capture this CA-specific program.

[20] https://ww2.arb.ca.gov/sites/default/files/2019-10/ictfro-Clean-Final_0.pdf

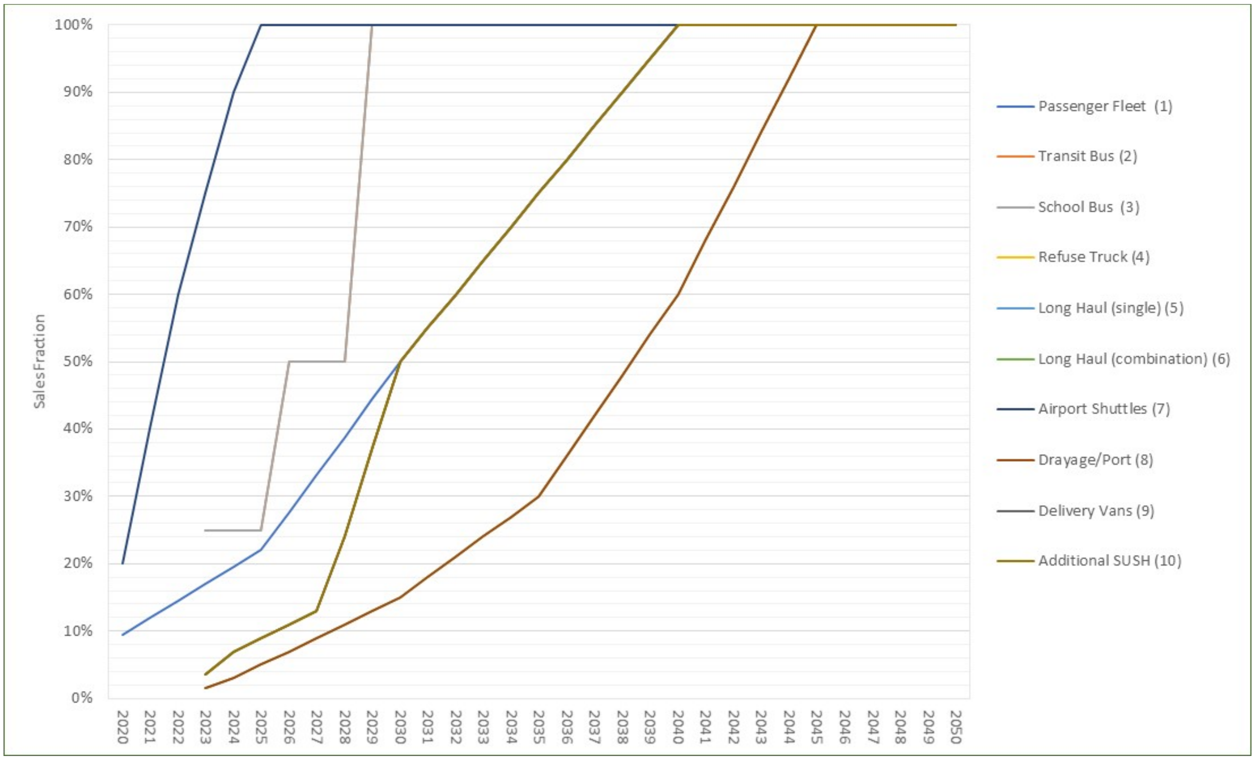
[21] Based on the goals current at the time of analysis, presented February 20, 2020. https://ww2.arb.ca.gov/sites/default/files/2020-02/200220presentation_ADA_0.pdf

[22] Note that the final ACT rule adopted by CARB increased the stringency for this category. https://ww2.arb.ca.gov/our-work/programs/advanced-clean-trucks

- For vehicle category 7 (airport shuttles), we started with the California Zero-Emission Airport Shuttle Regulation.[23] Unlike other regulations that are sales based, this regulation has population requirements of electrifying 100% of the fleet by 2035. We used the model and other calculations to determine the vehicle sales values that match these population thresholds. This calculation required more aggressive retirement of older vehicles than the normal fleet turnover. Aggressive BEV sales and gas and diesel vehicle retirement were used to achieve 100% ZEV population by 2035.

Figure 1 shows the national BEV sales fractions resulting from the above milestones. Table 3 shows the date by which complete electrification is achieved for the vehicle category.

Figure 1. National BEV Sales Fractions by Vehicle Categories for the Electrification Scenario.



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[23] https://ww2.arb.ca.gov/sites/default/files/2019-10/asb_reg_factsheet.pdf

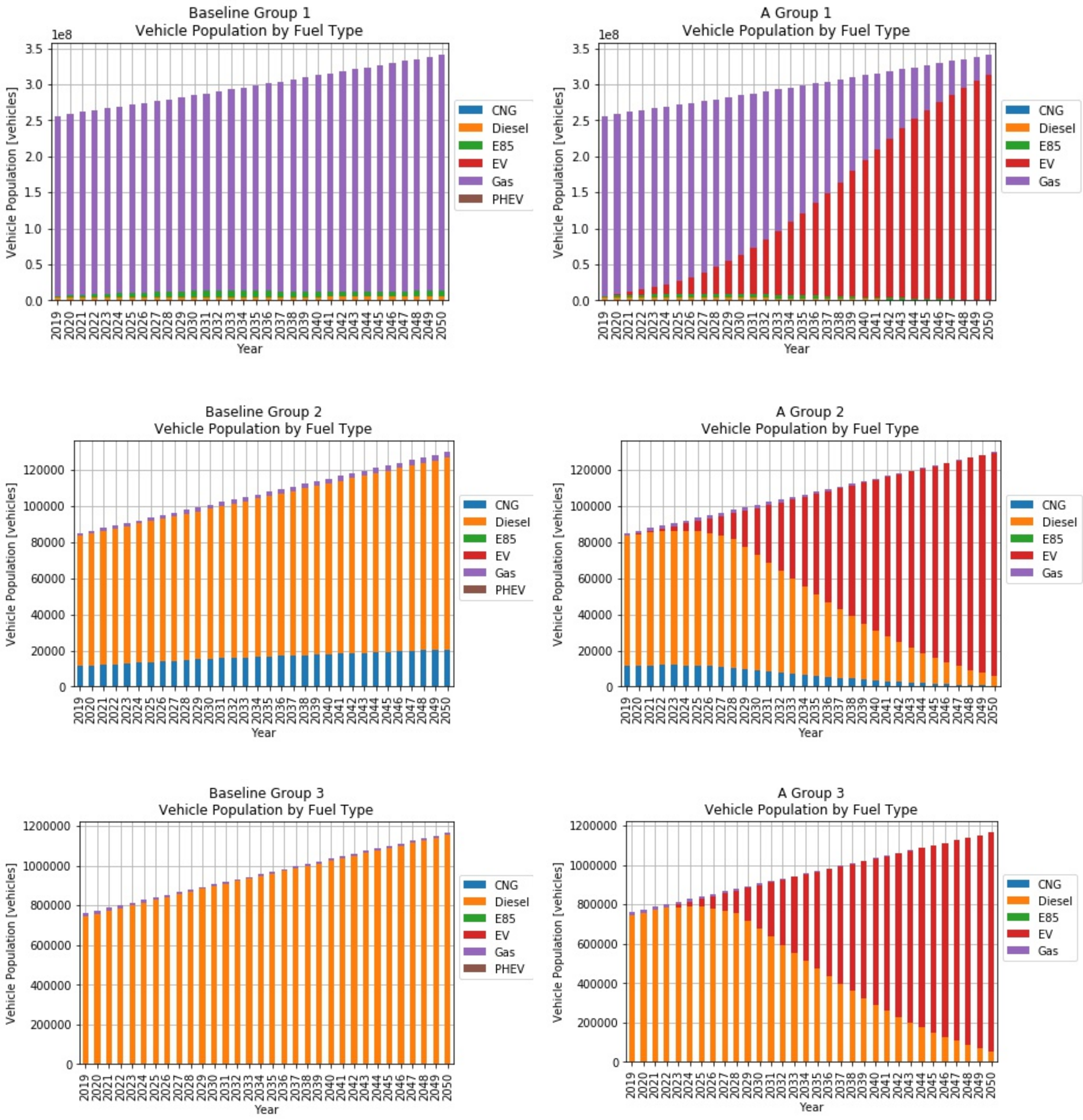
Table 3. Date by which 100% Electrification Achieved.

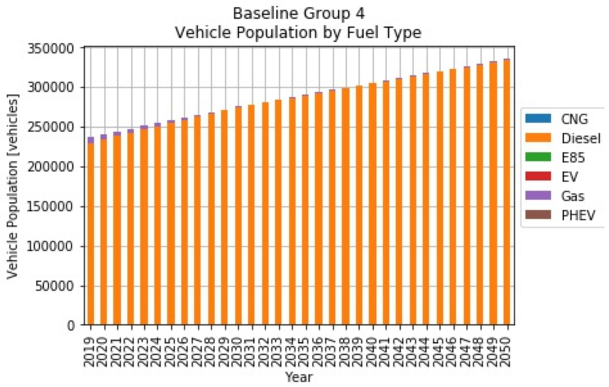
Category	Year by which 100% Sales Achieved
Passenger Fleet (1)	2040
Transit Bus (2)	2029
School Bus (3)	2029
Refuse Truck (4)	2040
Long Haul (single) (5)	2040
Long Haul (combination) (6)	2045
Airport Shuttles (7)	2025
Drayage/Port (8)	2045
Delivery Vans (9)	2040
Additional SUSH (10)	2040

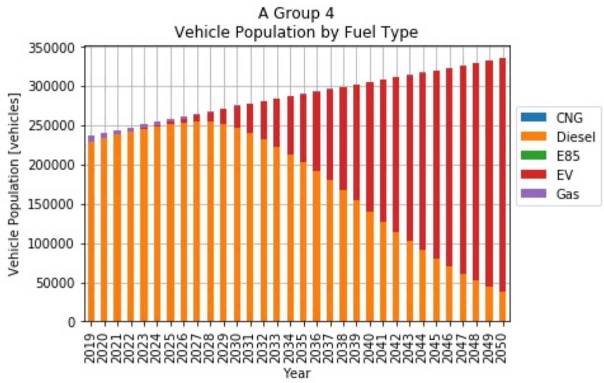
3. Resulting Vehicle Populations

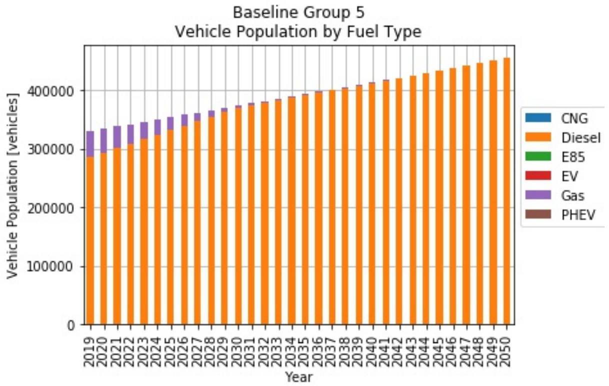
Figure 2 shows the national vehicle populations for each vehicle type by calendar year and fuel resulting from our fleet modeling. The BAU Fleet is shown on the left and the Scenario Fleet on the right. Figure 2 shows total population, not the model year breakdown, although that is included in all emissions calculations (Section IV). Appendix B shows the corresponding charts for vehicle sales. Note that, while labeled “EV” in these charts, all electric vehicles are BEV as noted above, and “Gas” is gasoline-fueled.

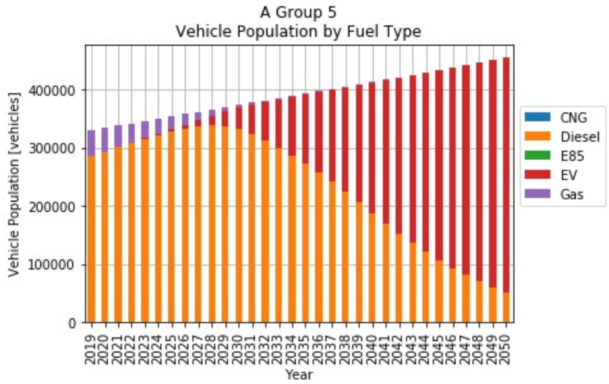
Figure 2. Total Population of Vehicles by Vehicle and Fuel Type and Calendar Year.

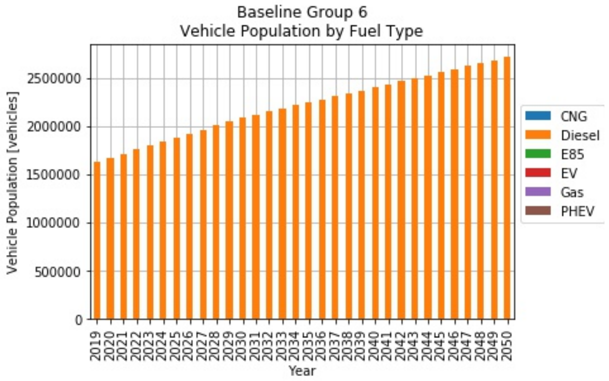


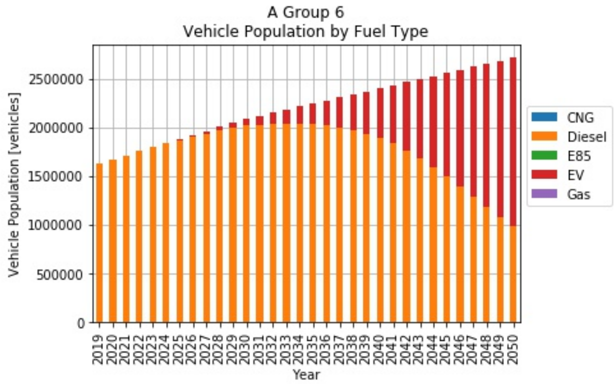

Baseline Group 4
Vehicle Population by Fuel Type
Vehicle Population [vehicles]
0
50000
100000
150000
200000
250000
300000
350000
2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 2047 2048 2049 2050
Year
CNG
Diesel
E85
EV
Gas
PHEV

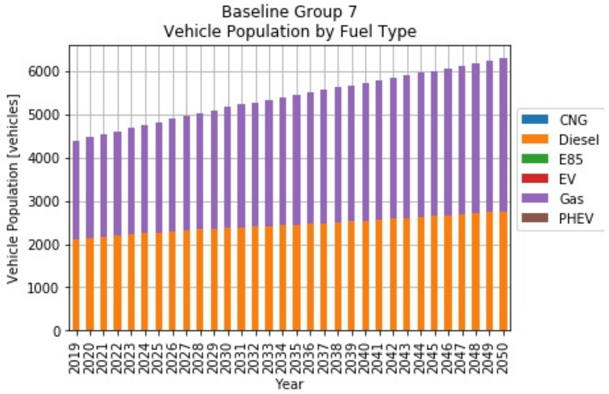

A Group 4
Vehicle Population by Fuel Type
Vehicle Population [vehicles]
0
50000
100000
150000
200000
250000
300000
350000
2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 2047 2048 2049 2050
Year
CNG
Diesel
E85
EV
Gas

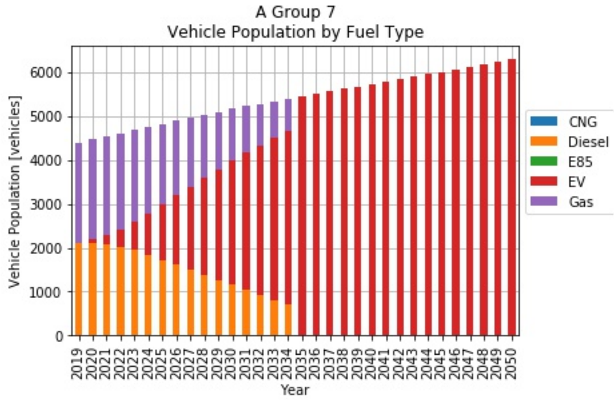

Baseline Group 5
Vehicle Population by Fuel Type
Vehicle Population [vehicles]
0
100000
200000
300000
400000
2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 2047 2048 2049 2050
Year
CNG
Diesel
E85
EV
Gas
PHEV

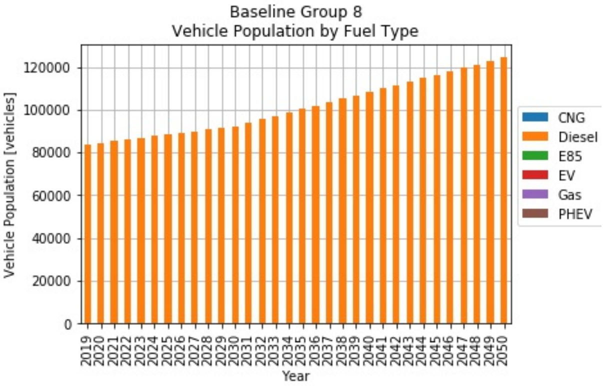

A Group 5
Vehicle Population by Fuel Type
Vehicle Population [vehicles]
0
100000
200000
300000
400000
2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 2047 2048 2049 2050
Year
CNG
Diesel
E85
EV
Gas

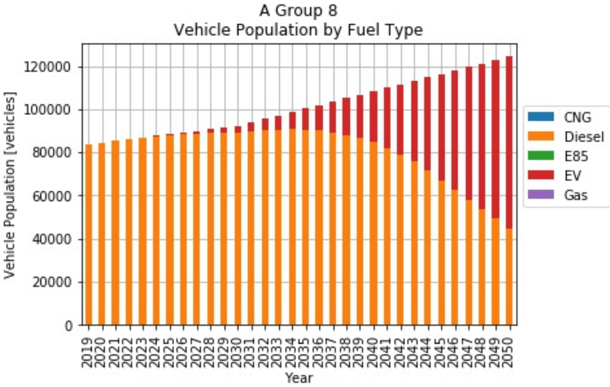

Baseline Group 6
Vehicle Population by Fuel Type
Vehicle Population [vehicles]
0
500000
1000000
1500000
2000000
2500000
2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 2047 2048 2049 2050
Year
CNG
Diesel
E85
EV
Gas
PHEV

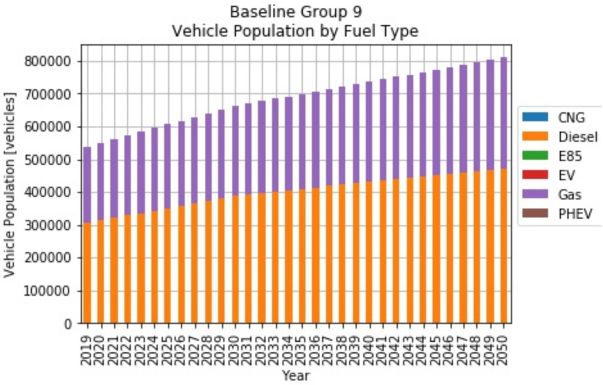

A Group 6
Vehicle Population by Fuel Type
Vehicle Population [vehicles]
0
500000
1000000
1500000
2000000
2500000
2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 2047 2048 2049 2050
Year
CNG
Diesel
E85
EV
Gas

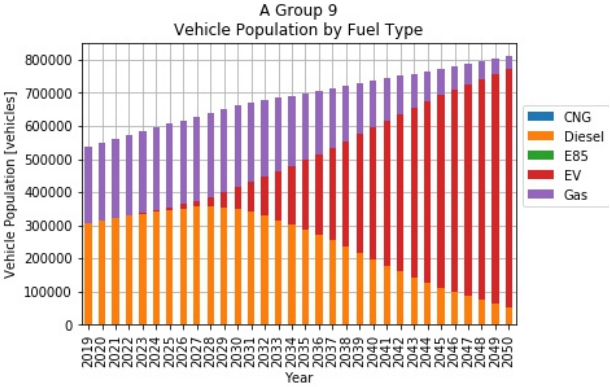

Baseline Group 7
Vehicle Population by Fuel Type
Vehicle Population [vehicles]
0
1000
2000
3000
4000
5000
6000
2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 2047 2048 2049 2050
Year
CNG
Diesel
E85
EV
Gas
PHEV

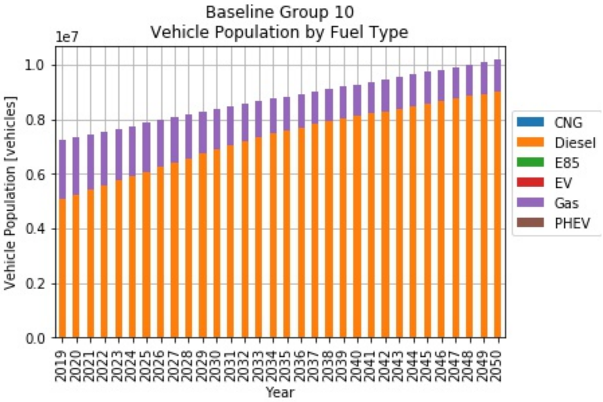

A Group 7
Vehicle Population by Fuel Type
Vehicle Population [vehicles]
0
1000
2000
3000
4000
5000
6000
2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 2047 2048 2049 2050
Year
CNG
Diesel
E85
EV
Gas

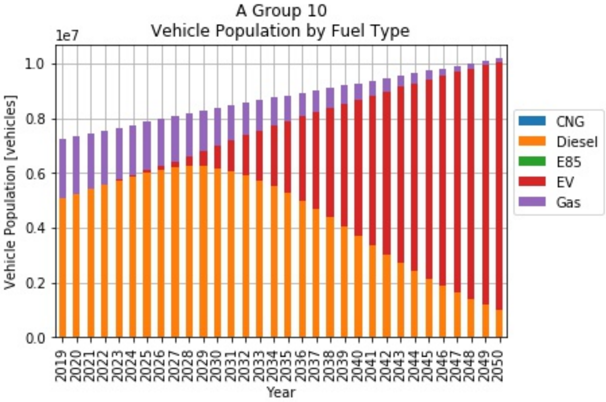

Baseline Group 8
Vehicle Population by Fuel Type


A Group 8
Vehicle Population by Fuel Type


Baseline Group 9
Vehicle Population by Fuel Type


A Group 9
Vehicle Population by Fuel Type


Baseline Group 10
Vehicle Population by Fuel Type


A Group 10
Vehicle Population by Fuel Type

IV. National Scale Emissions Impacts

We modeled the change in national emissions the vehicle electrification Scenario would cause. To fully represent the change in emissions from vehicle electrification, we included changes in both:

- **Downstream.** These are emissions directly released from the vehicle fleet, including exhaust, evaporative, and fugitive emissions such as brake and tire wear from vehicles. Section 1, below, describes this approach.
- **Upstream.** These are emissions associated with changes in fuel extraction, transport, refining, and related emissions and changes in emissions from both the feedstock and fuels used in electricity generation associated with changes in electricity demand driven by the Scenario. Section 2, below, describes this approach and the components included. Note that our approach uses an average grid mix electricity approach for electricity used for electric vehicle charging.

Here, the term, “Scenario”, refers to the vehicle electrification scenario. We further analyzed the impact of two different cases for future electricity generation. These two cases represent two distinct paths the electricity grid could follow and flow through to two distinct levels of national emissions associated with upstream electricity generation in the Scenario.

- **ALA Case.** The first electrification case represents a projection of the electric generating sector with a trend to lower coal use and increased renewables. This is based on projections found in the Bloomberg New Energy Outlook (BNEO) 2019.[24] The ALA Case is designed to include the impact of changes in upstream emissions from the electricity generation sector, such as through adoption of renewable portfolio standards that could increase renewable energy generation or otherwise modify the grid emission assumptions.
- **AEO Case**. The second national electrification case represents a conservative analysis based on the US Energy Information Administration’s (EIA) 2020 Annual Energy Outlook (AEO).[25] This case is likely overly conservative as it relies on an assumption that coal will hold onto a high (14%) market share out to 2050, which is largely inconsistent with market trends away from building new coal plants in the US due to costs and expected retirements due to age. The AEO Case is revealing as a basis for comparison since it is commonly used as a metric for future evaluation, even though EIA considers it a scenario rather than a forecast.[26]

1. Downstream Emissions

Here we present the findings of downstream only emission changes due to implementation of the national electrification Scenario discussed in Section III. There are no differences in downstream emissions or activity between the two upstream electricity generation cases.

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[24] https://about.bnef.com/new-energy-outlook/

[25] https://www.eia.gov/outlooks/aeo/

[26] https://insideclimatenews.org/news/28012019/eia-annual-energy-outlook-coal-renewable-wind-utility-analyst-projections-impact

1.1 BAU Emissions Modeling

We determined national total emissions and energy consumption for on-road vehicles nationwide by vehicle type and age. This was based on the same simulations with EPA's current mobile source emissions model, MOVES2014b,[27] used to determine the BAU fleet populations and corresponding age and fuel distributions. The emissions were processed from the MOVES vehicle categories into the 10 Scenario vehicle categories using the same approach determined for vehicle population. Note that MOVES2014b remains EPA's current regulatory emissions model for mobile sources. It is consistent with on-the-books regulations at the time of its release including the Tier 3 gasoline rule, heavy duty GHG regulations for model years 2014-2018, and light duty GHG regulations for model years 2017-2025.[28] Notably it does not include impacts of changes to vehicle fuel economy changes under the recently proposed SAFE rule.[29]

All emission processes were considered for each pollutant. That is, running, starting, evaporative, extended idle, and Auxiliary Power Unit (APU) were all modeled for the relevant vehicle types and pollutants. These were aggregated together into total emissions per year. They were then further aggregated into national level emissions for those same 10 Scenario vehicle categories subject to electrification in terms of vehicle type, fuel type, and age. This determined the BAU fleet emissions levels. National totals for all pollutants are computed from the MOVES simulations described in Section II.1.

Table 20 in Appendix A summarizes the pollutants and emissions processes included in the MOVES modeling. Note that some of these pollutants are required for processing of the final pollutants included in the Scenario modeling but are not directly included in the results. For example, only CO_2e is reported here, but it is composed of CO_2, CH_4, and N_2O, all of which were included in the MOVES modeling.

1.2 Scenario Fleet Emissions Modeling

The vehicle populations and corresponding age and fuel distributions for the Scenario fleet were described in Section III. We determined the corresponding emissions for the Scenario fleet based on the MOVES-based BAU emissions rate for each vehicle type, described above. That is, the emission rate from the MOVES BAU modeling (g/year) was normalized to the corresponding vehicle count to produce an emission rate per (g/year/vehicle) for each pollutant, fuel, vehicle category, and age. For most pollutants, BEVs produce no downstream emissions. Thus, the scenario emissions are the product of the remaining ICEVs in the Scenario fleet and the BAU annual emission rate.

The exception to this is brake wear (BW) and tire wear (TW) emissions. Both BEV and ICEV produce brake and tire wear emissions, although BEVs have reduced brake wear emissions due to regenerative braking. We determined BAU BW and TW annual emission rates for each of the 10 Scenario vehicle types based on the MOVES emissions and population similar to the

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[27] https://www.epa.gov/moves

[28] EPA-420-F-14-049, July 2014. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100JWJ5.pdf

[29] US EPA, The Safer Affordable Fuel Efficient (SAFE) Vehicles Proposed Rule for Model Years 2021-2026 (2020). https://www.epa.gov/regulations-emissions-vehicles-and-engines/safer-affordable-fuel-efficient-safe-vehicles-proposed.

other pollutants. We assumed that BEV BW emissions are half that of equivalent ICEV based on ARB findings,[30] but that ICEV TW emissions are identical to the category the EV is replacing.[31]

Finally, an artifact of the Scenario fleet modeling approach described in Section III is that the Fleet model simulates both the BAU and Scenario cases for comparison. This is because the Fleet model requires every year for analysis, but the MOVES data on which it is based are only available for three years. As a result, the BAU fleet population from MOVES does not exactly match the BAU fleet simulated in the Fleet model. To properly account for the fleet changes predicted by the Fleet model, we also modeled emissions corresponding to a third case, the “modeled BAU”. This represents emissions for a fleet that corresponds to the BAU vehicle fleet predicted by the Fleet model, which differs slightly from the BAU case derived from MOVES. To determine the emission changes relative to the BAU vehicle fleet that accommodates the inter-model discrepancy, we used a relative reduction approach. We first determined a relative reduction between the Scenario and modeled BAU, then applied this ratio to the MOVES-based BAU emissions. We did not consider any rebound-type effects that could alter per-vehicle activity from the default values in the MOVES model.

1.3 Resulting Changes in Downstream Emissions from Business as Usual Conditions

Table 4 summarizes the changes in national-level, on-road, downstream emissions from the implementation of the national vehicle electrification Scenario. Table 5 provides these same annual total emissions further broken down by the ten vehicle categories and presented for both the BAU and electrification Scenario.

Figure 3 shows these same changes graphically for three pollutants. In each case, the BAU results are shown by solid lines and the Scenario by dashed lines. Please note that the scale for each of the three pollutants differs. Blue lines represent NOx in tons per year, orange represent total $PM_{2.5}$ in tons per year but scaled up by 10 to properly display on the chart, and grey represents CO_2e in thousands of metric tons per year.[32] All of these represent downstream emissions only. As noted above, total PM emissions are presented, which includes tailpipe, BW, and TW in aggregate. Although Figure 3 only shows three pollutants – those presenting the most significant health and climate impacts – all modeled pollutants are described by Table 5.

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[30] Attachment C Updated Costs and Benefits Analysis for the Proposed Advanced Clean Trucks Regulation. See, https://ww3.arb.ca.gov/regact/2019/act2019/30dayattc.pdf.

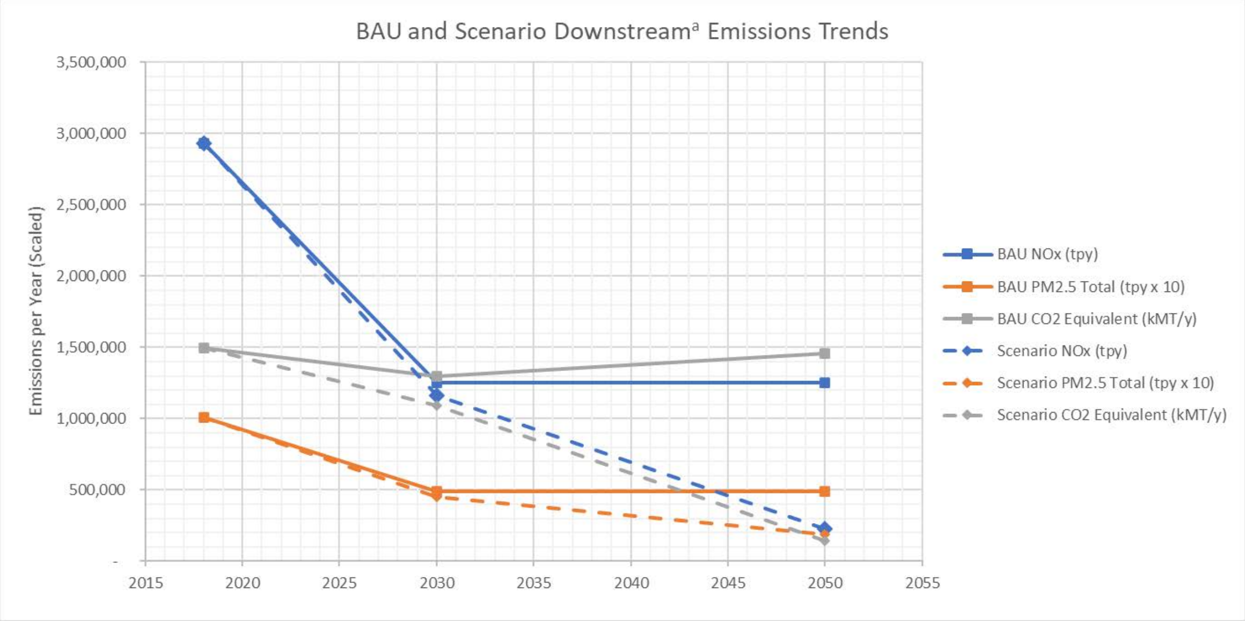
[31] Note that some research has claimed that BEVs may have higher tire emissions than ICEVs due to the generally improved torque performance and higher vehicle weight. However, this is still under research and we have seen no such approach adopted by regulatory agencies. Thus, we have not included that here. If this is the case, our TW PM2.5 emissions in the scenario will be underestimated.

[32] As noted above, the downstream emissions represent the vehicles only, and are independent of any upstream changes under either of the two electrification Cases.

Table 4. Total Downstream Emission Reduction Nationwide, Short Tons per Year and Percent

Year	NOx	SO_2	VOC	$PM_{2.5}$ Total	CO_2e	NH_3
Reduction, Tons						
2018	-	-	-	-	-	-
2030	86,580	1,570	63,577	4,087	226,516,613	15,379
2050	1,022,054	10,400	485,858	30,599	1,448,701,004	92,863
Reduction, Percent						
2018	-	-	-	-	-	-
2030	7	15	10	8	16	18
2050	82	89	83	62	90	92

Figure 3. Downstream Emission Trends for the Modeled Years, BAU and Scenario (units are scaled to fit on the chart)



a. Downstream is tailpipe emissions plus PM brake and tire wear (BW, TW)

Figure 4 shows the same total, national, annual downstream emissions resolved by vehicle category and year in Table 5 graphically. BAU values are shown in the left two columns and the Scenario in the right two. The two columns for each break the vehicle categories into two groups according to the magnitude of their national emissions totals. The three vehicle categories with large national totals (LDV (1), Combination Long Haul (6), and Additional Single Unit Short Haul (10)) are shown on the left; the remaining seven vehicle categories are shown on the right. This is done to allow the trends to also be visible among the vehicle categories with lower national total emissions. In all cases, electrification dramatically reduces the downstream emissions, even in cases where the BAU increases. NOx and PM are reported in tons, CO_2e in thousands of metric tons.

Note that $PM_{2.5}$ is reduced less due to the presence of BW and TW emissions from BEVs, also seen in Figure 3. This is illustrated by Figure 5, which breaks out the contribution of BW and TW to total downstream emissions by vehicle type and year for the electrification Scenario. BEVs have zero tailpipe emissions but continue to emit $PM_{2.5}$ from BW and TW. Thus, even though the fleet is nearly completely electrified, the downstream PM emissions do not decrease at the same rate as other pollutants. These pollutants are presented in aggregate here as they are incorporated into the health impact evaluation (Section V).

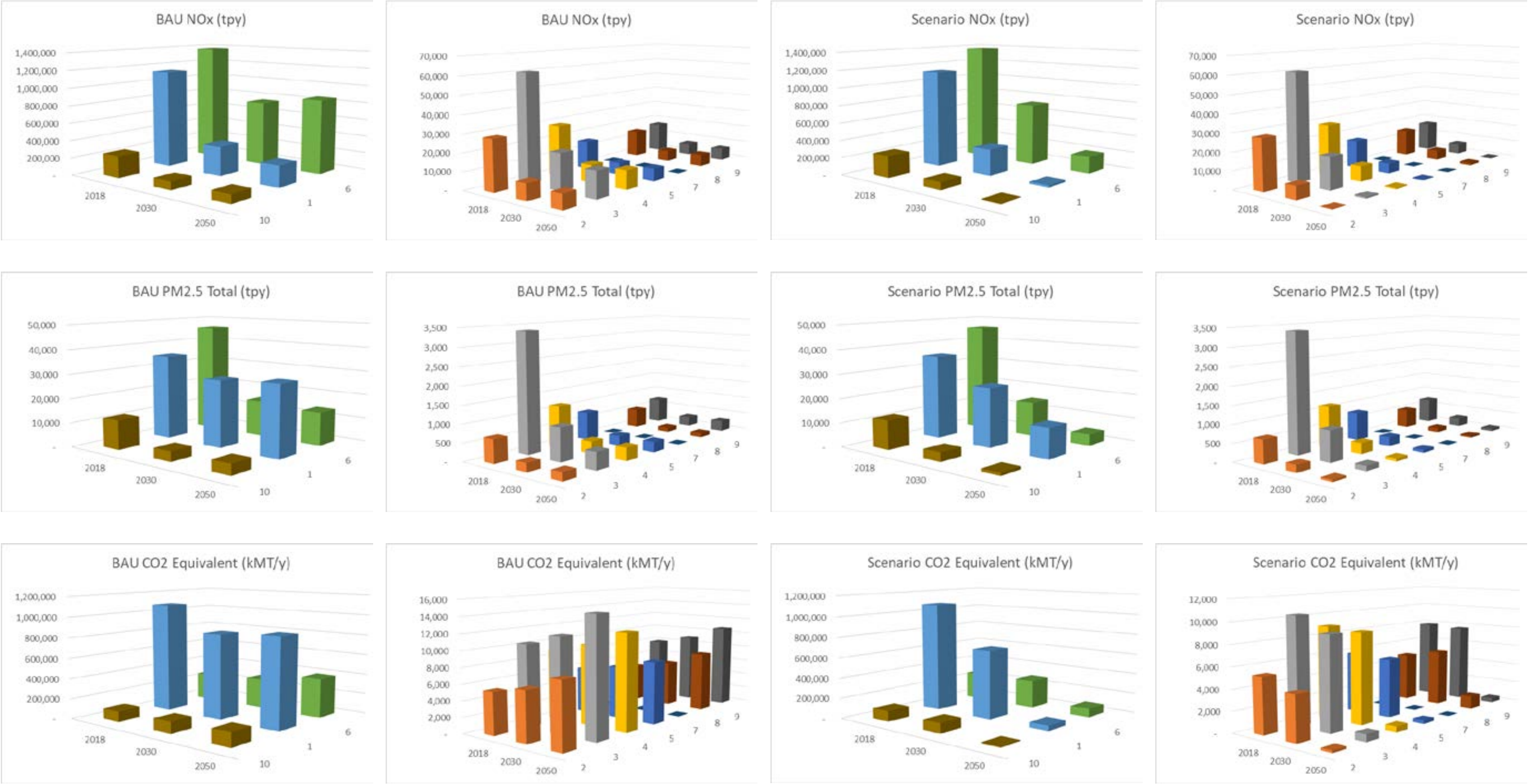


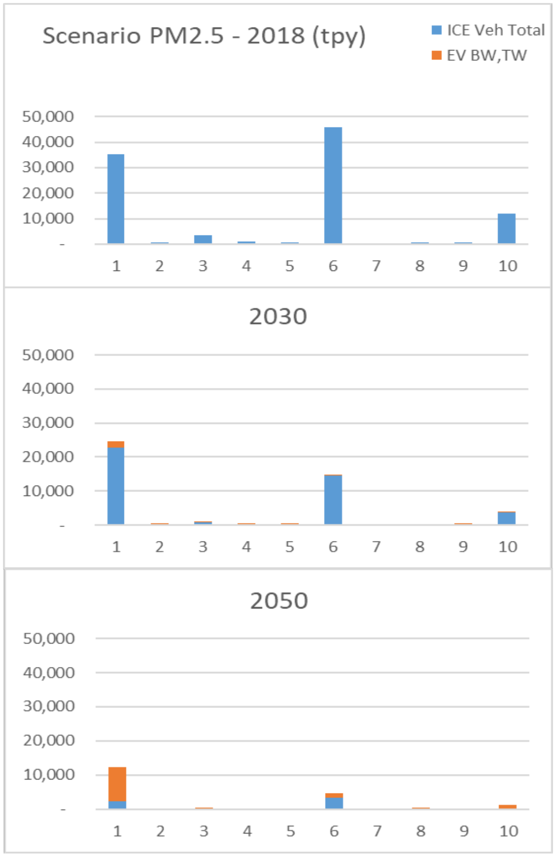
Figure 4. Downstream emissions by vehicle category and year, BAU and Scenario (short tons per year; thousands of metric tons per year for CO$_2$e)

Table 5. Downstream Emissions Changes by Pollutant, Year, and Vehicle Category from the Electrification Scenario, short tons per year

	Year	1	2	3	4	5	6	7	8	9	10
BAU											
NOx	2018	1,136,051	28,293	60,494	28,562	15,829	1,375,853	117	15,319	16,758	251,330
	2030	340,611	9,146	20,252	9,720	6,592	753,742	46	5,842	6,766	96,335
	2050	241,668	8,168	14,786	10,557	6,908	855,652	44	6,695	6,846	100,386
SO_2	2018	7,816	47	98	84	54	2,514	0	44	66	890
	2030	6,122	54	109	93	61	2,727	0	54	75	977
	2050	6,387	69	134	111	72	3,539	1	70	89	1,163
VOC	2018	1,121,780	2,226	8,452	1,902	3,055	128,418	37	878	5,209	60,922
	2030	516,935	827	2,673	728	805	83,208	18	430	2,636	28,591
	2050	450,319	752	1,659	815	773	98,312	19	504	2,852	30,713
$PM_{2.5}$ Total	2018	35,295	658	3,365	1,171	804	45,925	5	545	721	12,120
	2030	27,722	241	932	339	284	15,194	2	128	281	4,105
	2050	29,179	229	480	359	294	13,868	2	125	307	4,422
CO_2e	2018	1,192,141,066	5,818,377	11,402,962	9,907,160	6,462,827	295,577,686	58,489	5,249,146	8,695,581	113,293,314
	2030	924,705,453	6,886,824	12,977,592	11,167,234	7,351,225	327,734,992	64,819	6,433,739	9,866,023	125,820,166
	2050	965,728,896	8,908,326	16,178,580	13,337,503	8,715,771	426,634,822	77,059	8,373,494	11,761,611	149,927,315
NH_3	2018	78,119	98	240	147	170	5,121	2	78	263	3,225
	2030	72,813	123	285	171	199	5,884	3	100	321	3,836
	2050	86,987	161	364	206	238	7,731	3	131	387	4,607
Scenario											
NOx	2018	1,136,051	28,293	60,494	28,562	15,829	1,375,853	117	15,319	16,758	251,330
	2030	303,704	7,401	17,923	8,691	5,897	720,947	23	5,580	6,105	86,200
	2050	23,577	259	784	551	333	197,231	-	1,281	397	5,244
SO_2	2018	7,816	47	98	84	54	2,514	0	44	66	890
	2030	4,913	37	83	80	52	2,584	0	50	64	837
	2050	372	2	6	5	3	785	-	12	4	47
VOC	2018	1,121,780	2,226	8,452	1,902	3,055	128,418	37	878	5,209	60,922

	Year	1	2	3	4	5	6	7	8	9	10
	2030	460,830	664	2,370	640	719	79,267	9	409	2,366	26,000
	2050	76,012	24	84	44	40	21,993	-	94	262	2,307
$PM_{2.5}$ Total	2018	35,295	658	3,365	1,171	804	45,925	5	545	721	12,120
	2030	24,663	203	872	308	258	14,733	1	124	256	3,722
	2050	12,336	57	138	81	81	4,727	0	54	74	1,118
CO_2e	2018	1,192,141,066	5,818,377	11,402,962	9,907,160	6,462,827	295,577,686	58,489	5,249,146	8,695,581	113,293,314
	2030	743,009,461	4,712,972	9,866,526	9,646,951	6,291,549	310,488,723	19,458	6,056,732	8,462,455	107,936,626
	2050	56,336,543	243,937	781,658	628,820	344,467	94,670,576	-	1,423,281	474,108	6,038,983
NH_3	2018	78,119	98	240	147	170	5,121	2	78	263	3,225
	2030	58,507	82	215	148	170	5,572	1	94	275	3,293
	2050	5,977	4	18	10	9	1,715	-	22	15	182

Figure 5. Downstream emissions of $PM_{2.5}$ by vehicle category and year for the Scenario (tons) Showing the Contribution of BW and TW to the Totals.



2. Upstream Emission Changes

Here we present the findings of the changes in upstream emissions due to implementation of the electrification Scenario discussed in Section III. There are two components of upstream emissions affected by the electrification Scenario: those associated with ICEV fuel production and distribution and those associated with electricity generation. We first discuss the fuel production component and then the electrification component.

2.1 Upstream ICEV Fuel Emissions

2.1.1 Emission Factors

The changes in upstream (well-to-tank) life cycle emissions due to reduced consumption of transportation fuels projected to result from implementation of the electrification Scenario were determined with the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET1_2019) model. The GREET model, developed at Argonne National Laboratory[33] is an analytical tool that simulates the fuel lifecycle, also known as well-to-wheels

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[33] https://greet.es.anl.gov/

(WTW), energy use and emissions output of vehicle/fuel systems. The GREET model is widely recognized as a reliable tool for life cycle analysis (LCA) of transportation fuels and has been used by several regulatory agencies (e.g., U.S. Environmental Protection Agency for the Renewable Fuel Standard (RFS) and California Air Resource Board for the Low-Carbon Fuels standard (LCFS)) for evaluation of various fuels. Note that the upstream (well-to-tank) emissions do not include the tailpipe emissions generated from burning the fuels, which was described previously. We used GREET to determine upstream emission factors from refining for VOC, NO_x, PM_{10}, $PM_{2.5}$, SO_2, and GHG.

The upstream emissions of liquid fuels (*i.e*., gasoline, diesel, E85) use an average approach and include:

- Crude for Use in U.S. Refineries
- Refining: Feed Inputs
- Refining: Intermediate Product Combustion
- Refining: Non-Combustion Emissions
- Transportation
- Distribution[34]
- Ethanol (for gasoline and E85)

The gasoline in the U.S. contains 10% ethanol, thus the upstream emissions of corn ethanol production in the U.S. were also included in the calculations. For E85, we assumed a gasoline-ethanol blend with 83% ethanol[35]. Finally, for CNG, the upstream emissions include

- The extraction and recovery of fossil natural gas,
- Gas processing,
- Transportation, and
- Compression.

Table 6 shows the upstream fuel emission factors.[36]

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[34] Note that the emission factors determined from GREET (Table 4) do not include the impacts of the vehicle electrification Scenario on the distribution vehicles. That is, the transportation and distribution of refined ICEV fuels could be made by electrified vehicles after implementation of the Scenario, which was not included in the GREET emission factors. This is a minor inconsistency in the overall modeling approach. First, many of the fuel transport vehicles would be combination unit short haul vehicles which were not targeted for electrification in the Scenario (Table 1). Furthermore, the transportation and distribution fraction of upstream emissions is a small minority of the overall upstream contribution for ICEV fuels. On average it accounts for only about 5% of the total upstream emissions across all pollutants and years, with a maximum contribution for VOC with a transportation and distribution component of 16%. Thus, the overall impact of ignoring electrification of fuel distribution vehicles was considered negligible and not included in the GREET modeling.

[35] https://afdc.energy.gov/fuels/ethanol_e85_specs.html

[36] Note that these emissions are upstream emissions only, based on the newest GREET version (GREET1_2019).

Table 6. Upstream ICEV Fuel Emission Factors, GREET

Upstream Refining Emission Factors	Diesel Emissions (g/gal)			Gasoline Emissions (g/gal)			E85 Emissions (g/gal)			CNG Emissions (g/MJ)		
	Total			Total			Total			Total		
	2018	2030	2050	2018	2030	2050	2018	2030	2050	2018	2030	2050
VOC	0.984	0.948	0.962	3.317	3.275	3.285	4.451	4.331	4.333	0.010	0.010	0.010
NOx	3.407	2.267	2.605	3.825	2.729	3.000	7.635	5.880	5.942	0.042	0.038	0.038
$PM_{2.5}$	0.193	0.137	0.164	0.256	0.203	0.225	0.464	0.384	0.394	0.001	0.000	0.000
SO_2	1.282	0.711	0.913	1.823	1.165	1.325	5.859	4.173	4.237	0.016	0.013	0.013
GHG (CO_2e)	2,181	1,979	2,075	2,658	2,463	2,538	4,448	4,146	4,171	17	16	16

2.1.2 Upstream ICEV Emissions

The refining component of the upstream emissions is independent of the scenario chosen for electricity generation (Sections 2.2.1 and 2.3).

We used MOVES2014b to determine fuel consumption for each vehicle, age, and fuel type in the BAU case (Section II) for the 10 vehicle types subject to electrification under the scenario (Table 1). MOVES does not compute fuel consumption, but does track energy consumption and CO_2 emissions. We computed fuel consumption from CO_2 emissions using emission factors from EPA.[37] We then computed the BAU fuel consumption rates (gal/year/vehicle) by vehicle, age, and fuel type based on the BAU fuel consumption and BAU population. This same rate was applied to the remaining ICEVs in the Scenario vehicle fleet. The difference in the total fuel volume consumed (gallons for all but CNG, which are reported in SCF) between the BAU and Scenario is the avoided fuel consumption due to electrification. The fuel consumption avoided by the Scenario multiplied by the upstream fuel emission factors (Table 6) is the change in upstream fuel production emissions due to implementation of the Scenario. This includes raw product extraction, raw product transport, fuel refining, and refined fuels transport.

Note that there is not necessarily any need for computation of a BAU level of refining activity. Instead, only the reduction in refining activity due to electrification is needed, so a change from BAU can be included. Accordingly, the emission reductions from reduced refining activity shown in this section are determined with this GREET-based approach, where GREET emission factors are applied to a reduction in refined fuels.

However, for computing the health benefits (Section V) we modified the upstream refining emissions somewhat. There we computed a relative reduction in refining emissions, applied uniformly to all of the “petroleum & related industries” emissions sector in COBRA, except natural gas extraction and asphalt manufacturing activity from the BAU.[38] This was required to mitigate any inter-model discrepancies between the GREET-MOVES model approach from this Section and that in the COBRA model that could lead to greater reductions than available in in the BAU in COBRA. See Section V.1.1 for more information on the approach used there.

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[37] https://www.epa.gov/sites/production/files/2018-03/documents/emission-factors_mar_2018_0.pdf

[38] No special treatment was given to ethanol plants, for example. The described reductions are applied uniformly to emissions and their spatial allocation, in the COBRA model. See Section V.

2.2 Upstream Electricity Generation Emissions

Two different approaches were considered for the electricity generation sector and its emissions associated with fueling BEVs. Both cases use an average electricity approach.[39] Both consider emissions associated with both the feedstock and fuels used in electricity production. Specifically:

- Feedstock
  - Coal mining/extraction and transport
  - Natural gas extraction, processing, transport (including by pipeline)
- Fuel combustion of fuels for thermal electricity production

2.2.1 AEO Electricity Generation Case

IV.2.2.1.1 Emission Factors

The upstream emissions factors representing electricity generation from the utility grid associated with powering EVs were also determined from modeling with GREET. The AEO Case represents average electricity grid emissions consistent with EIA's mix projection.[40]

Originally, our GREET emission factors were based on Emissions & Generation Resource Integrated Database (eGRID) and allocated according to the average resource mix used in the U.S. grids. It is important to note that this project is not intended to model marginal power mixes in the future (which may result in greater reductions from the use of potentially lower carbon intensive electricity for EV charging than presented here, or may not, depending on the marginal power's coal content, for example). However, the US Average Grid Mix in eGRID anticipates a coal mix that is even higher than the EIA, which we consider unlikely. Accordingly, we modified the GREET emission factors to use EIA's mix projection. This updated the 2050 mix from about 19% to about 14% coal and from about 28% to about 38% renewables.

Table 7 shows the upstream electricity generation emission factors for the AEO Case. Table 8 shows the grid mix used in this AEO-based approach corresponding to Table 7. The "Others" category in the GREET model is inclusive of hydroelectric, solar, and wind. Upstream electricity generation emission factors include contributions from both feedstock and fuels.

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[39] It is important to note that our approach relies on average electricity, projected to all analysis years. This project is not intended to model marginal power mixes in the future. Rather both base and incremental electricity demand is treated the same, with the two grid mix approaches described here. A marginal grid approach could result in lower upstream emissions if the trends seen in low carbon electricity were extracted and applied solely to BEV-driven electricity demand. However, this is unknown. Instead, we treat all power demand similarly.

[40] Annual Energy Outlook 2020: Table 8. Electricity Supply, Disposition, Prices, and Emissions, Reference case, Electricity: Electric Power Sector: Power Only. Available at: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=8-AEO2020&region=0-0&cases=ref2020&start=2018&end=2050&f=A&linechart=ref2020-d112119a.6-8-AEO2020~ref2020-d112119a.7-8-AEO2020~ref2020-d112119a.8-8-AEO2020~ref2020-d112119a.9-8-AEO2020~ref2020-d112119a.10-8-AEO2020~ref2020-d112119a.11-8-AEO2020~ref2020-d112119a.12-8-AEO2020~ref2020-d112119a.13-8-AEO2020&map=&sourcekey=0

Table 7. AEO Case: Upstream Electricity Emission Factors, GREET

Upstream EGU Emission Factors	(g/kWh, U.S. Mix, AEO Projection)		
	2018	2030	2050
VOC	0.051	0.037	0.035
NOx	0.319	0.169	0.159
$PM_{2.5}$	0.025	0.010	0.009
SO_2	0.784	0.318	0.253
GHG (CO_2e)	483.4	337.2	303.1

Table 8. National Scenario Electric Grid Mix, AEO Case

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Others[41]
2018	0%	37%	24%	19%	1%	19%
2030	0%	35%	17%	15%	1%	32%
2050	0%	36%	14%	12%	0%	38%

IV.2.2.1.2 Upstream Electricity Generation Emissions

A similar approach was used to determine the additional energy required by the electric grid to fuel EVs as described for fuel consumption of ICEVs and upstream fuel emissions. In this case, the metric taken from the MOVES modeling is total energy consumption, in kilojoules (kJ), again for the BAU fleet subject to electrification. This is normalized to the vehicle population to produce the BAU energy consumption rate by vehicle, age, and fuel type. The additional electricity consumed was calculated according to the energy consumption of the type of vehicle the EV replaced. That is, if a gasoline passenger vehicle is replaced with a BEV, the energy consumption of the BEV was first assumed to equal that of the gasoline vehicle. However, EVs are more efficient than ICEVs, due to energy lost to heat and never converted to mechanical energy in ICEVs. We accounted for the energy efficiency differences between ICEVs and EVs by including the increased efficiency of electric engines over internal combustion via Energy Efficiency Ratios (EER). EERs for each vehicle and fuel type were taken from an ICF analysis for the California Electric Transportation Coalition.[42] Table 9 shows these EER values.

This adjusted energy consumption, when summed over all EVs, is the additional grid load from the Scenario. This additional load is multiplied by the GREET grid emission factors (Table 7) to produce the additional grid emissions caused by the implementation of the electrification scenario.

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[41] Note that GREET lumps most of the zero carbon intensity electricity sources such as solar, wind, and hydropower into one category. These cannot be broken out further. Hence "Others" and renewables may be considered synonymous here.

[42] Comparison of Medium- and Heavy-Duty Technologies in California, ICF. Prepared for California Electric Transportation Coalition and the Natural Resources Defense Council, in partnership with the Union of Concerned Scientists, Earthjustice, BYD, Ceres, and NextGen Climate America, and with Advisory Support From the University of California, Davis Policy Institute for Energy, Environment and the Economy and East Yard Communities for Environmental Justice. December 2019.

Note that, as with fuel refining emissions, in our approach no computation of BAU electricity generating emissions is necessary here, only the change associated with additional vehicle electrification. Only the resulting change in electric generation emissions are computed and used. Note also that the COBRA modeling (Section V) includes source-receptor relationships in the modeled area. That means that the distance between sources (upstream and downstream) figures into the health impacts of these emissions, in addition to the total emission reductions noted in this section.

Table 9. EV-to-ICEV Energy Efficiency Ratios Used in this Analysis.

Vehicle Category	Diesel Fuel	CNG, Gasoline, and E85
1	3.4	3.4[43]
2	5.0	5.6
3	5.0	5.6
4	4.2	4.7
5	5.0	5.6
6	5.0	5.6
7	4.2	4.7
8	5.0	5.6
9	3.4	3.8
10	4.2	4.7

2.3 ALA Electricity Generation Case

The second electricity generation case for upstream emissions reflects the ALA's upstream scenario of increasing renewables and decreasing coal power approach.

We developed the electricity generation component of upstream emissions for the ALA Scenario similar to that of AEO Scenario. The primary difference is the difference in the U.S. national mix used. Based on information in the U.S. summary of the BNEO we used the same national vehicle electrification Scenario but determined updated emission factors based on BNEO estimates for the U.S. to calculate emissions associated with the increased load on the grid. This ALA electricity generation scenario is anchored by an estimated 1.9% value for national coal share in 2050 predicted by that report, which is a significant reduction from the 14% used in the National Scenario (Table 8). We combined this with the estimated 43% renewable share in 2050 also from BNEO.[44] We then allocated the balance to natural gas. Consistent with BNEO projections the ALA Scenario keeps the same grid mix as in the AEO Scenario in 2030.

Table 11 shows the resulting national grid mix for 2050 under the ALA Case. Table 10 shows the emission factors determined for the ALA Case.

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[43] This value is a high estimate. In fact, the diesel EER for light duty vehicles is likely lower than 3.4. However, this estimate does not substantially impact this analysis as most light duty vehicles in the country are not diesel (less than 2% in all analyzed years, as determined with the MOVES simulations of the BAU fleet).

[44] "The US: "Coal and nuclear are pushed out by age and economics, such that by 2050 both technologies have almost disappeared from the electricity mix. … Utility-scale batteries for peaking purposes grow in significance from around 2035, supporting renewables penetration, which reaches 43% in 2050."

Table 10. ALA Case: Upstream Electricity Emission Factors, GREET

Upstream EGU Emission Factors	(g/kWh, U.S. Mix, ALA Projection		
	2018	2030	2050
VOC	0.051	0.037	0.031
NOx	0.319	0.169	0.160
$PM_{2.5}$	0.025	0.010	0.007
SO_2	0.784	0.318	0.070
GHG (CO_2e)	483.4	337.2	218.2

Table 11. National Scenario Electric Grid Mix, ALA Case

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Others
2050	0.1%	43%	2%	12%	0.4%	43%

The emissions calculation methodology in the ALA Case is identical to that of the AEO Case, but with the preceding emission factors.

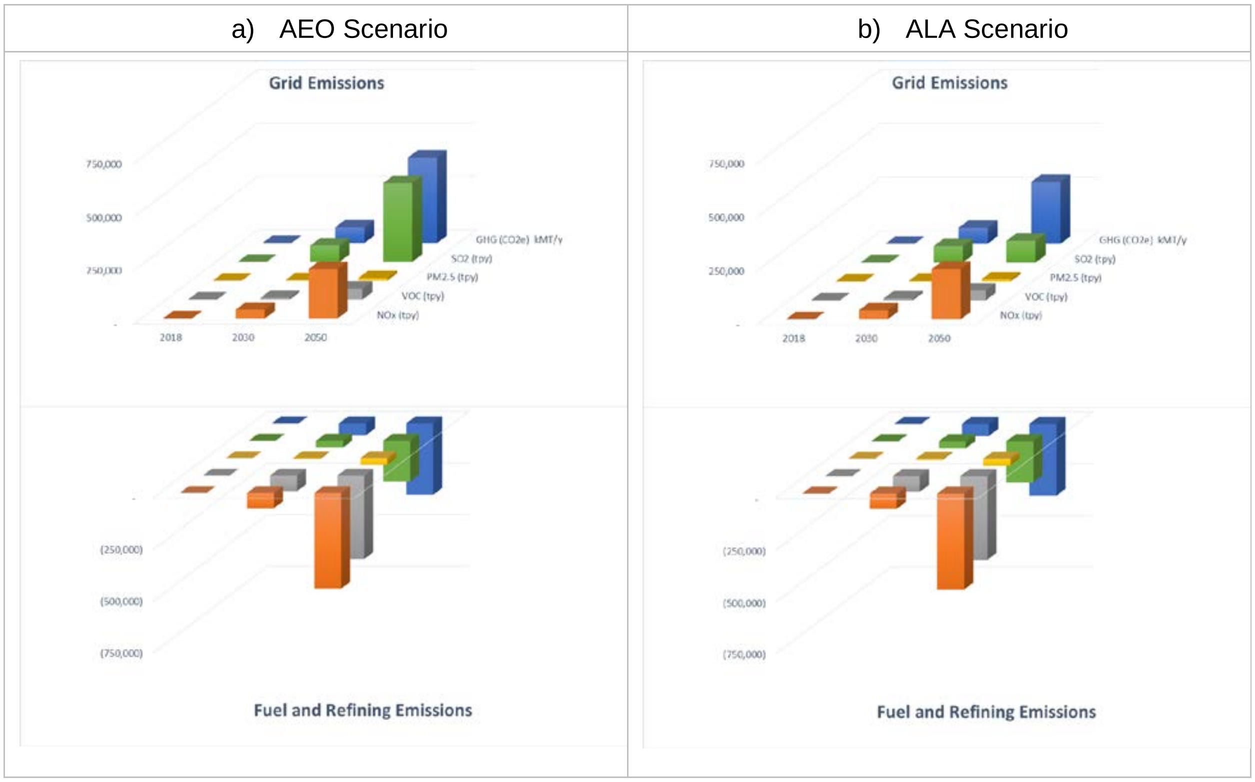
2.4 Net Changes in Upstream Emissions

Figure 6 shows the changes in upstream emissions from implementation of the vehicle electrification Scenario, by year and pollutant. The upper portion of each panel shows in the increase in emissions from increased load on the power grid due to increased BEV use. The lower portion of each panel shows the decreases in emissions associated with reduced ICEV fuel production activities. The left panel (Figure 6a) shows the results from the AEO Case. The right panel (Figure 6b) shows the results from the ALA Case. Note that only the electricity generation portion (the upper panels in the figure) of upstream emissions change between these two. The primary impact is to SO_2 emissions, with a secondary impact on CO_2e.

Nationally, the vehicle electrification scenario, when coupled with the AEO generation Case, leads to a net reduction in upstream emissions of NOx, VOC, and $PM_{2.5}$ and a net increase in national emissions of SO_2 and CO_2e for both 2030 and 2050. When coupled to the ALA generation Case, all pollutants show a net reduction in 2050 (although the net increase for SO_2 and CO_2e in 2030 remain since these scenarios are identical in that year).

Tabular results are presented in Section 2.5.

Figure 6. National Upstream Emission Changes due to the Vehicle Electrification Scenario for both the AEO (a) and ALA (b) Grid Scenarios, by Year


a) AEO Scenario

b) ALA Scenario

2.5 Net Changes in National Emissions

2.5.1 AEO Electrification Case

Table 12 summarizes the resulting net changes in national-scale emissions from the vehicle electrification Scenario. These reflect both upstream and downstream impacts and employ the AEO electricity generation Case.

Table 12 begins with the BAU-level, national emissions for the 10 vehicle categories for each of the three analysis years. The second section presents the corresponding emissions under the electrification scenario. Downstream (essentially on-road) emissions are presented first, followed by the reduced emissions associated with ICEV fuel refining/transport, additional emissions from electricity generation, and net emissions. Note that ammonia emission factors are not available in GREET. Also note that, in some cases, the net emissions shown in Table 12 are negative. This is because the reduction in ICEV fuel production and delivery emissions outweigh the remaining downstream and upstream grid emissions combined. Note we are not looking here at the total emission inventory from fuel production and electricity generation, only the change, which is the critical parameter for the COBRA modeling (Section V). Next is the change in emissions between the scenario and BAU, shown as both downstream and net, both in tons and percent, relative to the BAU. Note that reductions of more than 100% are possible, as the reduction from refining emissions outweighs the BAU downstream (on-road) emissions.

Note also that SO_2 is the only pollutant where emissions increase due to the Scenario when considering upstream and downstream emissions in combination. This is due to the combination of on-road fuels having very low sulfur content, so vehicles emit relatively little SO_2, and the higher coal component of the AEO scenario.[45]

2.5.1 ALA Electricity Generation Case

Table 13 summarizes the resulting changes in national-scale emissions from the ALA Scenario. This has an identical form to Table 12.

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[45] In this analysis, SO_2 and SOx are considered identical.

Table 12. National Summary of Emission Changes due to Electrification with the AEO Electricity Generation Case, short tons per year (percent when noted)

Year	NOx	SO_2	VOC	$PM_{2.5}$	GHG (CO_2e)	NH_3
BAU						
Total On-road Emissions for the 10 Vehicle Categories						
2018	2,928,607	11,612	1,332,878	100,609	1,648,606,606	87,462
2030	1,249,052	10,272	636,851	49,228	1,433,008,067	83,736
2050	1,251,711	11,636	586,717	49,265	1,609,643,377	100,815
Vehicle Electrification Scenario with the AEO Electricity Generation Case						
Total On-road Emissions for the 10 Vehicle Categories						
2018	2,928,607	11,612	1,332,878	100,609	1,648,606,606	87,462
2030	1,162,471	8,702	573,274	45,141	1,206,491,454	68,357
2050	229,658	1,236	100,859	18,666	160,942,372	7,952
Refinery and Transport Emissions Avoided by Electrification						
2018	0	0	0	0	0	NA
2030	-73,816	-33,558	-75,837	-5,238	-64,017,411	NA
2050	-462,476	-198,383	-403,788	-32,878	-381,340,813	NA
Additional Grid Emissions Due to Electrification						
2018	0	0	0	0	0	NA
2030	40,934	76,722	8,988	2,438	81,480,672	NA
2050	230,405	367,451	50,723	12,584	440,497,623	NA
Net with AEO Case						
2018	2,928,607	11,612	1,332,878	100,609	1,648,606,606	NA
2030	1,129,590	51,865	506,425	42,341	1,223,954,715	NA
2050	-2,413	170,304	-252,206	-1,628	220,099,183	NA
Change from BAU						
Downstream Only						
2018	0	0	0	0	0	0
2030	-86,580	-1,570	-63,577	-4,087	-226,516,613	-15,379
2050	-1,022,054	-10,400	-485,858	-30,599	-1,448,701,004	-92,863
Downstream Only, percent						
2018	0%	0%	0%	0%	0%	0%
2030	-7%	-15%	-10%	-8%	-16%	-18%
2050	-82%	-89%	-83%	-62%	-90%	-92%
Downstream and Upstream						
2018	0	0	0	0	0	NA
2030	-119,462	41,593	-130,426	-6,887	-209,053,352	NA
2050	-1,254,124	158,668	-838,923	-50,892	-1,389,544,194	NA
Downstream and Upstream, percent						
2018	0%	0%	0%	0%	0%	NA
2030	-10%	405%	-20%	-14%	-15%	NA
2050	-100%	1364%	-143%	-103%	-86%	NA

Table 13. National Summary of Emission Changes due to Electrification with the ALA Electricity Generation Case, short tons per year (percent when noted)

Year	NOx	SO_2	VOC	$PM_{2.5}$	GHG (CO_2e)	NH_3
BAU						
Total On-road Emissions for the 10 Vehicle Categories						
2018	2,928,607	11,612	1,332,878	100,609	1,648,606,606	87,462
2030	1,249,052	10,272	636,851	49,228	1,433,008,067	83,736
2050	1,251,711	11,636	586,717	49,265	1,609,643,377	100,815
Vehicle Electrification Scenario with the ALA Electricity Generation Case						
Total On-road Emissions for the 10 Vehicle Categories						
2018	2,928,607	11,612	1,332,878	100,609	1,648,606,606	87,462
2030	1,162,471	8,702	573,274	45,141	1,206,491,454	68,357
2050	229,658	1,236	100,859	18,666	160,942,372	7,952
Refinery and Transport Emissions Avoided by Electrification						
2018	0	0	0	0	0	NA
2030	-73,816	-33,558	-75,837	-5,238	-64,017,411	NA
2050	-462,476	-198,383	-403,788	-32,878	-381,340,813	NA
Additional Grid Emissions Due to Electrification						
2018	0	0	0	0	0	NA
2030	40,934	76,722	8,988	2,438	81,480,672	NA
2050	233,013	101,834	45,703	10,191	317,078,454	NA
Net with ALA Case						
2018	2,928,607	11,612	1,332,878	100,609	1,648,606,606	NA
2030	1,129,590	51,865	506,425	42,341	1,223,954,715	NA
2050	195	-95,313	-257,226	-4,020	96,680,013	NA
Change from BAU						
Downstream Only						
2018	0	0	0	0	0	0
2030	-86,580	-1,570	-63,577	-4,087	-226,516,613	-15,379
2050	-1,022,054	-10,400	-485,858	-30,599	-1,448,701,004	-92,863
Downstream Only, percent						
2018	0%	0%	0%	0%	0%	0%
2030	-7%	-15%	-10%	-8%	-16%	-18%
2050	-82%	-89%	-83%	-62%	-90%	-92%
Downstream and Upstream						
2018	0	0	0	0	0	NA
2030	-119,462	41,593	-130,426	-6,887	-209,053,352	NA
2050	-1,251,516	-106,949	-843,943	-53,285	-1,512,963,364	NA
Downstream and Upstream, percent						
2018	0%	0%	0%	0%	0%	NA
2030	-10%	405%	-20%	-14%	-15%	NA
2050	-100%	-919%	-144%	-108%	-94%	NA

2.5.2 ALA and AEO Electricity Generation Cases Compared

Figure 7 summarizes the net impact of the electrification scenario. This is identical to Figure 3, but includes the net impact of both the downstream and upstream emission changes. It also shows the impact of both electricity generation Cases. Although the curves in Figure 7 look similar, the reductions from moving to the ALA electricity generation Scenario are significant, especially for CO_2e and SO_2 (not shown in Figure 7). Net national SO_2 emissions in 2050 are reduced by 266,000 tons in the ALA Case below that of the AEO Case while GHG emissions are reduced by 112 million metric tons below the AEO Case. Emissions of all pollutants are reduced under the ALA Case except NOx for which the net reduction is slightly smaller under the ALA Case than the AEO Case due to the very slightly (<1%) higher electricity generation emission factor with the ALA mix. As with Figure 3, only NOx, PM2.5, and CO2e are shown in Figure 7, but all pollutants are shown in Figure 8 and Table 14.

Figure 8 shows the results from Table 12 – net changes with the AEO scenario – as bar graphs. National totals from on-road vehicles in the 10 categories under the BAU scenario are shown in the left image by pollutant and year. The right image shows the same categories, but as a net of upstream and downstream emissions due to the electrification scenario. All units are tons per year except CO_2e, which is in thousands of metric tons per year. Figure 9 shows the same results, but for the ALA scenario pulled from Table 13. Table 14 also provides the full breakdown by vehicle category and both components of the upstream emission changes for both Cases.

Figure 7. Upstream and downstream, combined, emission trends for the modeled years, BAU and Electrification Scenario with the ALA and AEO Cases (**Units are scaled to fit**)

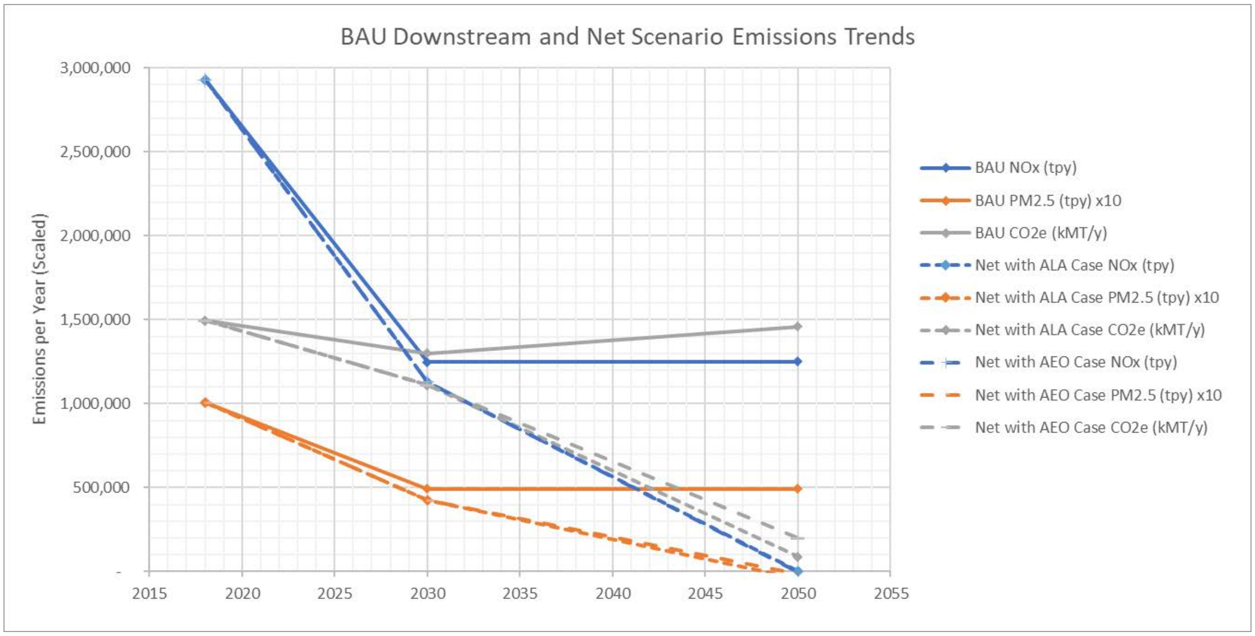

Figure 8. Bar Charts of BAU National Emissions and Net of Upstream and Downstream Emissions under the AEO Case, by Year.

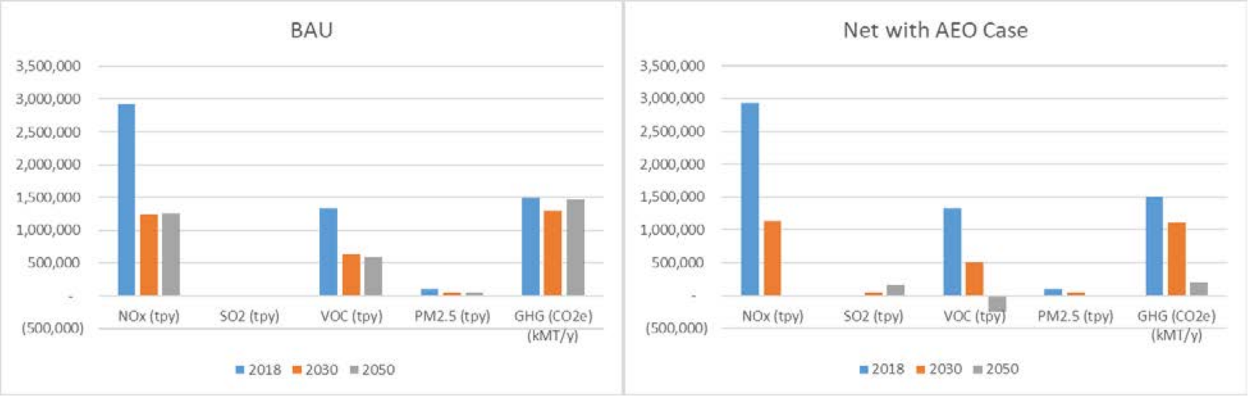

Figure 9. Bar Charts of BAU National Emissions and Net of Upstream and Downstream Emissions under the ALA Case, by Year.

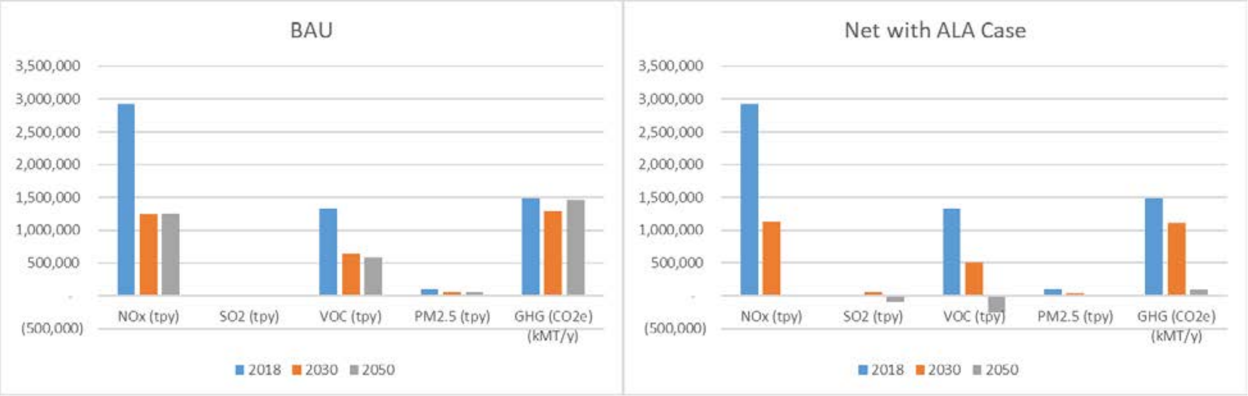

Table 14. Upstream Emissions Changes by Pollutant, Year, and Vehicle Category from the Electrification Scenario, short tons per year

Pollutant	Year	1	2	3	4	5	6	7	8	9	10
Refinery and Transport Emissions Avoided by Electrification											
NOx (tpy)	2030	63,134	684	692	338	235	3,809	12	84	364	4,466
	2050	320,588	2,714	3,931	3,242	2,130	84,246	23	1,771	3,284	40,547
SO2 (tpy)	2030	29,972	228	218	106	74	1,195	4	26	135	1,600
	2050	147,054	949	1,383	1,138	747	29,544	9	621	1,300	15,637
VOC (tpy)	2030	69,866	254	297	142	98	1,593	10	35	296	3,246
	2050	338,884	975	1,489	1,205	786	31,098	17	654	2,396	26,283
PM2.5 (tpy)	2030	4,580	27	42	20	14	230	1	5	25	295
	2050	23,775	129	248	204	134	5,306	2	112	226	2,741
GHG (CO2e) (tpy)	2030	54,766,871	462,717	604,318	294,779	204,967	3,326,077	10,537	73,010	322,866	3,951,268
	2050	267,766,411	1,856,144	3,134,055	2,582,714	1,696,989	67,108,544	18,550	1,410,813	2,696,639	33,069,955
Additional Grid Emissions Due to Electrification											
AEO Case											
NOx (tpy)	2030	34,742	281	396	231	135	2,192	7	48	254	2,647
	2050	162,576	1,041	1,835	1,806	998	39,479	11	830	1,913	19,915
SO2 (tpy)	2030	65,116	527	743	433	253	4,109	12	90	477	4,962
	2050	259,277	1,660	2,926	2,881	1,592	62,962	17	1,324	3,052	31,761
VOC (tpy)	2030	7,628	62	87	51	30	481	1	11	56	581
	2050	35,790	229	404	398	220	8,691	2	183	421	4,384
PM2.5 (tpy)	2030	2,070	17	24	14	8	131	0	3	15	158
	2050	8,879	57	100	99	55	2,156	1	45	105	1,088
GHG (CO2e) (tpy)	2030	69,155,053	559,837	788,638	459,712	268,889	4,363,362	13,250	95,779	506,363	5,269,789
	2050	310,819,272	1,990,252	3,507,378	3,453,440	1,908,644	75,478,572	20,168	1,586,775	3,658,170	38,074,953
ALA Case											
NOx (tpy)	2030	34,742	281	396	231	135	2,192	7	48	254	2,647
	2050	164,416	1,053	1,855	1,827	1,010	39,926	11	839	1,935	20,141
SO2 (tpy)	2030	65,116	527	743	433	253	4,109	12	90	477	4,962

Pollutant	Year	1	2	3	4	5	6	7	8	9	10
	2050	71,855	460	811	798	441	17,449	5	367	846	8,802
VOC (tpy)	2030	7,628	62	87	51	30	481	1	11	56	581
	2050	32,249	206	364	358	198	7,831	2	165	380	3,950
PM2.5 (tpy)	2030	2,070	17	24	14	8	131	0	3	15	158
	2050	7,191	46	81	80	44	1,746	0	37	85	881
GHG (CO2e) (tpy)	2030	69,155,053	559,837	788,638	459,712	268,889	4,363,362	13,250	95,779	506,363	5,269,789
	2050	223,733,544	1,432,620	2,524,677	2,485,851	1,373,878	54,330,892	14,517	1,142,190	2,633,219	27,407,066

V. Health Impact Evaluation

1. COBRA Health Effects Modeling

We used the U.S. EPA Co-Benefits Risk Assessment (COBRA Version 3.2) model[46,47] to quantify and monetize changes in the incidence of adverse health impacts resulting from changes in human exposure to $PM_{2.5}$ following the transition to zero emission transportation technologies. COBRA is a screening-level air quality health benefits model that provides estimates of the impact of air pollution emissions changes on ambient $PM_{2.5}$ concentrations, associated health effect impacts, and the monetary value of avoidable health impacts.[48]

1.1 Source Receptor Matrix and Emissions Changes

COBRA uses a source-receptor (S-R) matrix to translate changes in emissions of air pollutants into changes in ambient $PM_{2.5}$ concentrations. The S-R matrix consists of fixed transfer coefficients that relate annual average $PM_{2.5}$ concentrations at a single receptor in each county and the contribution of $PM_{2.5}$ precursors to this concentration from each emission source. The S-R matrix is based on the Climatological Regional Dispersion Model (CRDM), which includes summary data collected in 1990 from meteorological sites throughout North America.[49] The CRDM relies on simple dispersion-transport functions and chemical conversions at the receptor location.

The COBRA model contains detailed county- and source type-specific emissions estimates for the year 2025 in discrete categories. These estimates account for policy measures under consideration at the federal and state levels by December 2014.[50] ICF adjusted emissions for three categories of emissions sources related to the emissions changes driven by the electrification scenario, the 2030 AEO/ALA and 2050 AEO electricity generation Cases, and the 2050 ALA electricity generation Case discussed in Section IV. We also used results from GREET and MOVES modeling to scale the 2025 default emissions data within COBRA to values consistent with the interim (2030) and long-term (2050) analysis years considered here

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[46] https://www.epa.gov/statelocalenergy/co-benefits-risk-assessment-cobra-health-impacts-screening-and-mapping-tool

[47] A later version of COBRA, Version 4.0, was released June 22, 2020 and was not available until this project was nearly complete. The suite of health impact and valuation functions in COBRA 4.0 does not differ from that in COBRA 3.2 which we used. Therefore, we do not expect the COBRA release version to have material impacts on the results presented here.

[48] COBRA relies on a suite of health impact functions and valuation functions that closely approximate what EPA used in developing the Final 2006 National Ambient Air Quality Standards (NAAQS) for PM.

[49] The CRDM does not fully account for all chemical interactions that take place in the secondary formation of $PM_{2.5}$.

[50] Projected EGU emissions consider effects of the Final Mercury and Air Toxics (MATS) rule and the Cross-State Air Pollution Rule (CSAPR), both finalized in 2011. The Clean Power Plan is not included in the 2025 default emissions estimates.

for the BAU.[51] The three emission source categories (described as "tiers" in COBRA) adjusted for the BAU and electricity generation scenarios include highway vehicles, fuel combustion electric utilities, and petroleum and related industries.[52] ICF did not adjust emissions for the remaining categories in the default COBRA emissions dataset.

We scaled 2025 default COBRA emissions to the 2030 and 2050 BAU using emissions adjustment factors derived from MOVES and GREET modeling for the three COBRA emission source categories. ICF mapped the MOVES simulations used to determine the BAU downstream exhaust, fugitive, and evaporative emissions to highway vehicle emission source categories in COBRA and calculated the ratios of 2030 and 2050 BAU emissions, respectively, to the 2025 default COBRA emissions to develop adjustment factors. We applied these category-specific adjustment factors to the default county-level COBRA 2025 emissions. For the fuel combustion electric utilities category, ICF estimated BAU emissions based on factors derived from GREET modeling and total net electric power sector generation estimates for the years 2025, 2030, and 2050 from the U.S. Energy Information Administration Annual Energy Outlook (AEO) for 2020.[53] For the petroleum and related industries emissions category, ICF estimated BAU emissions based on differences in the total crude supply between 2025 and the interim (2030) and long-term (2050) analysis years from the U.S. Energy Information Administration AEO for 2020.[54][55]

To develop AEO and ALA Case emissions, we distributed modeled mass emissions changes (described in detail in Section IV) for each relevant emission source category to county-level BAU emissions proportional to the magnitude of county-level emissions under the BAU scenario or applied percent changes to county-level BAU emissions. Percent changes were applied only for petroleum and related industries categories, except natural gas extraction and asphalt manufacturing sub-categories. For the highway vehicle emission source category, modeled mass emissions changes varied by vehicle type sub-category, to capture the COBRA model's encapsulation of the different S-R matrix values by different vehicle types. Modeled mass emission changes for the fuel combustion electric utilities and petroleum and related industries emission source categories did not vary by emission source sub-category. The emissions in COBRA are organized around different sectors and subsectors and calculated with different models than employed here. To mitigate issues around emissions binning, emission strength, and emissions locations that differ between the models, we also calculated a "refining emission reduction factor". We calculated this reduction factor from the reduced on-road fuel amount and national average share of refining volume in 2018 that was on-road fuels, determined from

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[51] Default COBRA emissions estimates are available only for the 48 contiguous United States. Emissions changes applied to the COBRA model default emissions data reflect national-level changes for all 50 states.

[52] ICF did not adjust emissions for the subcategory of petroleum and related industries that relates to asphalt manufacturing.

[53] U.S. Energy Information Administration (U.S. EIA). 2020. Annual Energy Outlook 2020. Table 8: https://www.eia.gov/outlooks/aeo/pdf/aeo2020.pdf

[54] U.S. Energy Information Administration (U.S. EIA). 2020. Annual Energy Outlook 2020. Table 11: https://www.eia.gov/outlooks/aeo/pdf/aeo2020.pdf

[55] Note that COBRA operates on annual emissions and does not include seasonality that may be present in pollution sources, including evaporative emissions. As described in Section IV, all emissions calculated and used here represent annual totals.

EIA.[56] The Scenario would cause a national reduction in liquid on-road fuels of 16% in 2030 and 90% in 2050. Applying these with the refinery share of 76% predicts a net reduction in refining activity of 12% and 69% in 2030 and 2050, respectively. These reduction factors were applied to the COBRA BAU inventory for "Petroleum & Related Industries" emissions sector (excluding natural gas extraction and asphalt manufacturing). This approach resolved inconsistencies between the BAU emissions and reductions between the different models.

1.2 Health Incidence and Impact Functions

To estimate the absolute change in annual incidence of mortality using pre-loaded health impact functions, COBRA relies on baseline incidence rates for each health endpoint. We obtained age-, health endpoint-, and county-specific incidence rates in the United States projected for the interim and long-term electricity generation scenario years from the U.S. EPA Environmental Benefits Mapping and Analysis Program (BenMAP[57]) model database.

COBRA includes several pre-loaded health impact functions that estimate the impact of a change in air pollutant concentrations on adverse health effects based on epidemiological studies. Each function was developed based on data from cohort studies performed in various locations throughout the U.S. and uses different formulas and coefficients. The applicable ages for each health impact function reflect the age groups examined in the cohort studies. COBRA employs these health impact functions to assess the impact of $PM_{2.5}$ reductions on mortality incidence (for both infants and adults), nonfatal heart attacks, hospital admissions for respiratory and cardiovascular events, acute bronchitis, upper and lower respiratory symptoms, emergency room visits, minor restricted activity days, work loss days, and asthma exacerbation. (Note: Health outcomes related to changes in ambient Ozone levels are not included in the COBRA model.) For certain health endpoints, such as adult mortality and nonfatal heart attacks, COBRA employs multiple functions to obtain a lower bound and an upper bound estimate of potential health impacts. This is consistent with methods EPA employed when analyzing proposed National Ambient Air Quality Standards.[58] Appendix C shows the study authors and applicable ages of the health impact functions available in COBRA.

1.3 Population

The exposed population is the number of people affected by the reduction in $PM_{2.5}$ levels resulting from the transition to zero emission transportation technologies. ICF obtained age-specific population estimates for the interim (2030) and long-term (2050) electricity generation scenario years from the BenMAP model database. This database includes county-level

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[56] https://www.eia.gov/dnav/pet/pet_pnp_wprodr_s1_w.htm

[57] Environmental Benefits and Mapping Program-Community Edition (BenMAP-CE). BenMAP is US EPA's detailed model for estimating the health impacts from air pollution. Unlike COBRA, it relies on detailed input on air pollutant concentration changes, then applies concentration-response (C-R) health impact functions. See https://www.epa.gov/benmap For more information.

[58] U.S. EPA. (2006). Final Regulatory Impact Analysis: PM2.5 NAAQS. Research Triangle Park, NC: Office of Air and Radiation, Office of Air Quality Planning and Standards; U.S. EPA. (2009). *Proposed NO_2 NAAQS Regulatory Impact Analysis (RIA).* Research Triangle Park, NC.: Office of Air and Radiation, Office of Air Quality Planning and Standards

population data based on the 2010 U.S. Census[59] and uses annual population growth rates developed by Woods and Poole (2015) to project populations from 2010 to future years through 2060.

1.4 Valuation

The final step in the health benefits analysis is to estimate the economic value of avoided health impacts. COBRA includes several pre-loaded valuation functions for health endpoints associated with $PM_{2.5}$ concentrations. Depending on the health endpoint being considered, valuation methods may involve estimates of willingness to pay to avoid certain illnesses, the medical costs of treating illnesses, the value of lost wages, and the EPA-estimated value of a statistical life (VSL; applicable to mortality endpoints only).

Default valuation data for all health points in COBRA are reported in 2017$. For non-mortality health endpoints, ICF did not adjust valuation data to reflect changes in willingness to pay values, medical costs, or lost wages in 2030 and 2050.

Mortality, however, is typically found to be the driver for valuation given the magnitude of the VSL. Following EPA's guidance for economic analysis,[60] we use the VSL ($4.8 million in 1990$)[61] to estimate the value of avoided mortality. ICF used projected income growth data from the Organization for Economic Cooperation and Development (OECD) and consumer price index data from the Bureau of Labor Statistics (BLS) to project the original $4.8 million VSL estimate in 1990$ to the 2030 and 2050 analysis years.[62,63,64]

We do not consider other consumer costs in this valuation, such as differences in vehicle operations and maintenance, fuel costs, any tax revenue issues. etc. This valuation focuses entirely on monetized health and climate (Section VI) benefits.

2. Results

Table 15 presents total national estimates of the number of avoided adverse health effects and the economic value of these health risk reductions at 3% and 7% discount rates[65] from the national vehicle electrification Scenario when coupled with the AEO and ALA electricity generation Cases. These economic values reflect the US population's willingness to pay to

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[59] Because county-level data is based on the 2010 Census, FIPS county codes may be outdated. ICF did not adjust any FIPS-level county population information for the health impacts analysis.

[60] U.S. EPA. 2010. Guidelines for Preparing Economic Analyses. EPA 240-R-10-001.

[61] Our approach is consistent with EPA regulatory impact analyses which use this value for VSL and adjust it for inflation and changes in income over time.

[62] OECD (2020), "Long-term baseline projections, No. 103", OECD Economic Outlook: Statistics and Projections (database): https://www.oecd-ilibrary.org/economics/data/oecd-economic-outlook-statistics-and-projections/long-term-baseline-projections-no-103_68465614-en

[63] Bureau of Labor Statistics, 2020 (Series ID: CUUR0000SA0,CUUS0000SA0): https://data.bls.gov/pdq/SurveyOutputServlet

[64] Because ICF adjusted VSL for the adult mortality endpoint, but not other health endpoints, results may have a minor downward bias.

[65] The 3% discount rate reflects society's valuation of differences in the timing of benefits; the 7% discount rate reflects the opportunity cost of capital to society.

reduce risks of premature mortality or certain illnesses.[66] As such, these economic value represents monetized US public health benefits. Note that year 2030 is labeled “AEO/ALA” as the interim year is identical under both electricity generation Cases.

At a 3% discount, total monetized public health benefits range from approximately $1.5 billion to $3.5 billion in 2030 in the combined Cases. Under the AEO Case in 2050, benefits range from $24 billion to $54 billion. Adult mortality is the main driver of benefits of emissions changes under both scenarios, with an estimated decrease in the number of premature deaths among adults between 149 and 338 in 2030 and between 2,070 and 4,670 in 2050 under the AEO Case.

The rightmost columns in Table 15 present the total national estimates of the changes in the number of health effects cases and the resulting monetized benefits at 3% and 7% discount rates from the vehicle electrification Scenario emissions changes with the 2050 ALA Case. At a 3% discount, total monetized benefits range from approximately $32 billion to $72 billion. Adult mortality is the main driver of benefits of emissions changes, with an estimated decrease in the number of premature adult deaths between 2,790 and 6,293. (Note that year 2030, labeled “AEO/ALA”, is also the interim year under the ALA Case, as the electricity generation Cases are identical in the interim year.)

On a national level, reductions are seen in population-weighted, annual $PM_{2.5}$ concentrations with introduction of the vehicle electrification Scenario. These annual concentration reductions are 0.01 $\mu g/m^3$ with the 2030 AEO/ALA Case, 0.13 $\mu g/m^3$ with the 2050 AEO Case, and 0.17 $\mu g/m^3$ with the 2050 ALA Case. Figure 10 shows the population-weighted change in $PM_{2.5}$ concentration for each state. Under the 2050 ALA Case, California, Illinois, New York, Washington D.C., and New Jersey experience the largest reductions in population-weighted $PM_{2.5}$ concentration. Figure 11 shows the state-level distribution of reductions in premature adult mortality based on the high estimate from Lepeule et al. (2012). Under the 2050 ALA Case, California, Texas, New York, Florida, and Illinois experience the greatest reduction in premature mortality cases resulting from reduced net emissions. Similarly, Figure 12 and Figure 13 show the state-by-state monetized health benefits under the AEO and ALA Cases due to changes in 2050 emissions. Figure 12 shows total benefits, while Figure 13 shows these benefits normalized to state-level population in that year to show the impacts of parameters other than total population on benefits.

Figure 14 and Figure 15 also show state-level impacts of the vehicle electrification scenario with both the AEO and ALA electricity generation Cases in 2030 and 2050. In both cases, bar charts show the total health benefits of the scenario, however in Figure 15 these benefits are normalized per total state population to show per capita benefits. This illustrates impacts beyond the effect of total population on total benefits in high population states such as California. In both

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[66] For some health endpoints, the economic value estimates are based on the non-market valuation studies that estimate people’s willingness to pay for reductions in these health risks. For other endpoints, non-market valuation studies are not readily available and valuation is approximated using cost-of-illness methods that estimate medical costs and illness-related productivity losses.

cases, “high estimate” refers to decreases in adult mortality based on Lepeule et al. (2012), which related $PM_{2.5}$ and mortality based on a six-city cohort.[67,68]

In Figure 14, California results have been reduced by a factor of 10 to show the impacts on the same scale as other states. The California bar charts have a circle around them to highlight this change. This applies only to Figure 14.

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[67] The suite of health impact functions used to estimate changes in the number of mortality and nonfatal heart attack cases include separate PM-risk relationships that represent low and high estimates. The “high estimate” of total health benefits refers to the sum of health benefits that includes the high estimates for mortality and nonfatal heart attacks.

[68] COBRA reports the results of two health impact functions that relate PM2.5 and mortality, based on results of an epidemiological analysis of the American Cancer Society cohort by Krewski et al. (2009) and analysis of a six-city cohort by Lepeule et al. (2012). In Table 12, Morality, low estimate and Mortality, high estimate represent estimates of adult deaths avoided and their economic value based on Krewski et al. (2009) and Lepeule et al. (2012), respectively.

Table 15. Human Health Impacts from the Vehicle Electrification Scenario, under both the AEO and ALA Electricity Generation Cases.

Health Endpoint	2030 AEO/ALA Case			2050 AEO Case			2050 ALA Case		
	Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]		Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]		Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]	
		3% Discount	7% Discount		3% Discount	7% Discount		3% Discount	7% Discount
Mortality, low estimate[c]	149	$1,507,519,316	$1,357,753,277	2,070	$23,435,072,726	$21,106,891,600	2,790	$31,578,487,842	$28,441,290,862
Mortality, high estimate[d]	338	$3,412,352,173	$3,073,348,577	4,670	$52,856,397,378	$47,605,324,843	6,293	$71,226,581,847	$64,150,504,659
Infant Mortality	0	$3,235,266	$3,235,266	4	$39,633,350	$39,633,350	5	$53,440,417	$53,440,417
Nonfatal Heart Attacks, low estimate[e]	18	$2,277,762	$2,224,607	306	$39,647,545	$38,716,908	422	$55,011,596	$53,694,333
Nonfatal Heart Attacks, high estimate[f]	164	$21,151,508	$20,657,891	2,837	$367,338,938	$358,714,411	3,914	$509,791,547	$497,582,285
Hospital Admits, All Respiratory	43	$1,338,124	$1,338,124	737	$23,377,022	$23,377,022	1,015	$32,152,314	$32,152,314
Hospital Admits, Cardiovascular (except heart attacks)	51	$2,196,627	$2,196,627	879	$38,112,460	$38,112,460	1,216	$52,768,419	$52,768,419
Acute Bronchitis	268	$145,699	$145,699	3,749	$2,040,451	$2,040,451	4,955	$2,696,860	$2,696,860
Upper Respiratory Symptoms	4,871	$183,534	$183,534	68,449	$2,579,332	$2,579,332	90,489	$3,409,845	$3,409,845
Lower Respiratory Symptoms	3,411	$81,246	$81,246	47,816	$1,138,956	$1,138,956	63,205	$1,505,508	$1,505,508
Emergency Room Visits, Asthma	85	$40,851	$40,851	1,268	$606,541	$606,541	1,707	$816,614	$816,614
Minor Restricted Activity Days	134,828	$10,424,603	$10,424,603	1,868,496	$144,468,036	$144,468,036	2,462,322	$190,381,299	$190,381,299
Work Loss Days	22,891	$4,103,577	$4,103,577	316,634	$56,760,772	$56,760,772	416,793	$74,715,675	$74,715,675

Health Endpoint	2030 AEO/ALA Case			2050 AEO Case			2050 ALA Case		
	Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]		Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]		Change in the Number of Cases	Monetary Health Benefits (2017$)[a,b]	
		3% Discount	7% Discount		3% Discount	7% Discount		3% Discount	7% Discount
Asthma Exacerbation	5,002	$327,420	$327,420	70,523	$4,615,908	$4,615,908	93,337	$6,109,214	$6,109,214
Total, low estimate		$1,531,874,023	$1,382,054,830		$23,788,053,100	$21,458,941,337		$32,051,495,603	$28,912,981,360
Total, high estimate		$3,455,580,628	$3,116,083,415		$53,537,069,145	$48,277,372,083		$72,154,369,558	$65,066,083,108

Notes on Table 15:

[a] The discount rate expresses future economic values in present terms. Not all health effects and associated economic values occur in the year of analysis.

[b] Adult mortality valuation is based on a Value of a Statistical Life (VSL; grown from EPA 1990 VSL using standard income growth data) calculated by ICF and is lagged 20 years (per COBRA Model guidance), not the default valuation in COBRA.

[c] Low estimate based on Krewski et al. (2009)

[d] High estimate based on Lepeule et al. (2012)

[e] Low estimate based on four acute myocardial infarction (AMI) studies

[f] Low estimate based on Peter et al. (2001)

Figure 10. State-level Changes in PM2.5 Air Quality Concentrations in 2050 under the Vehicle Electrification Scenario with the AEO and ALA Electricity Generation Cases.

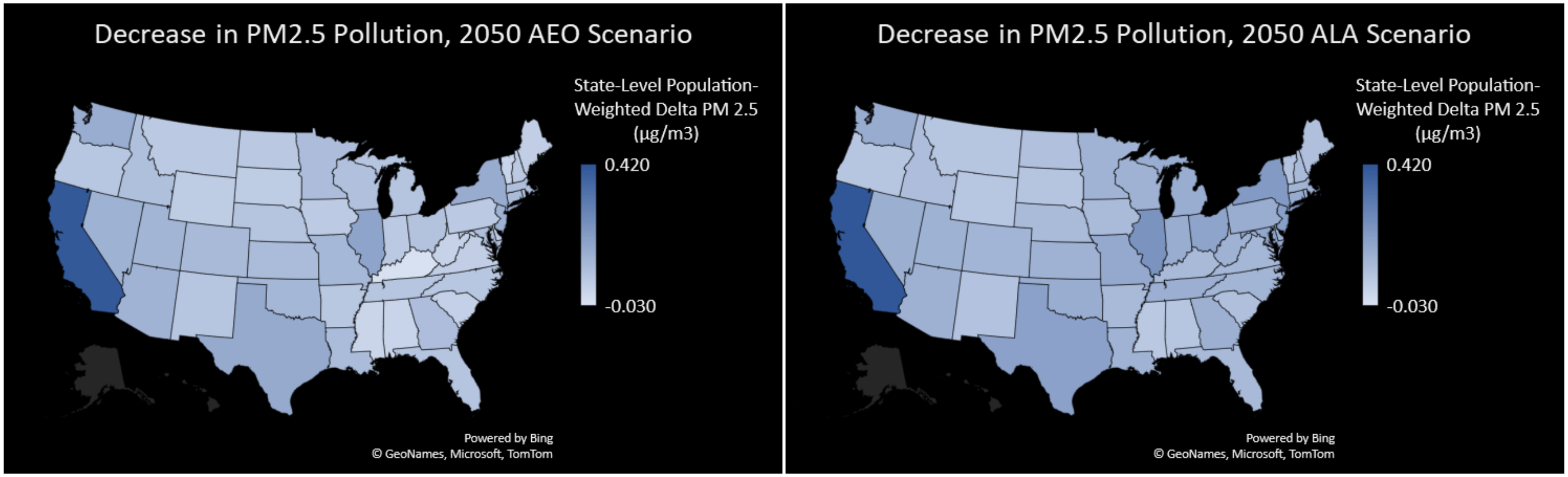


Figure 11. State-level Changes in Adult Mortality (High Estimate) in 2050 under the Vehicle Electrification Scenario with the AEO and ALA Electricity Generation Cases.

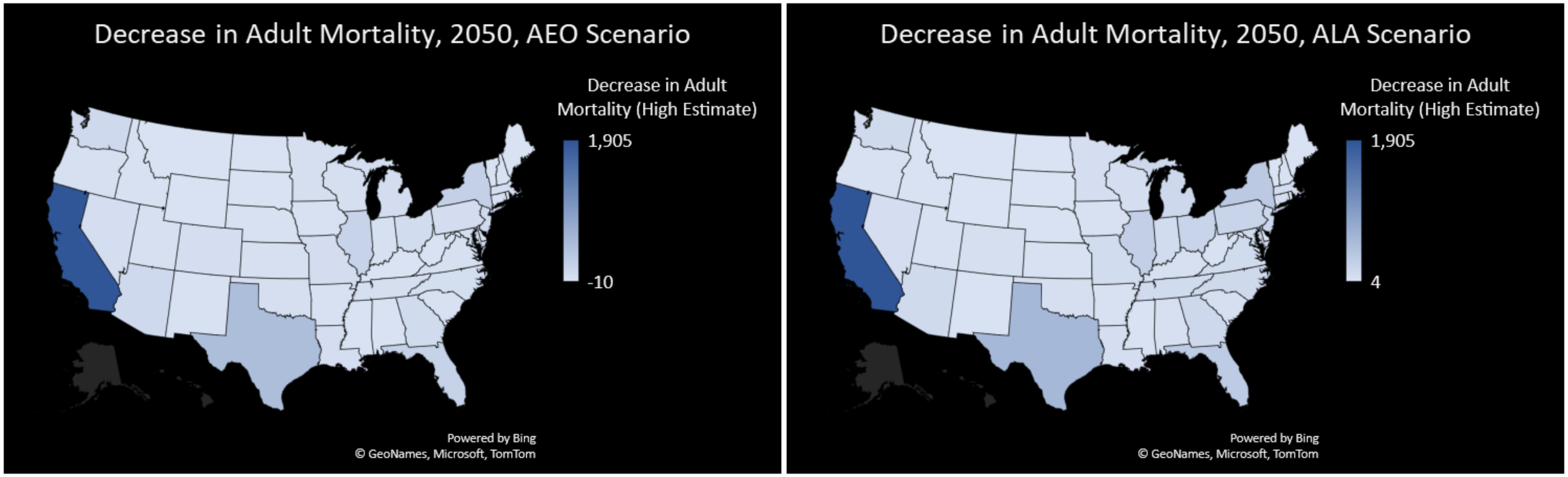


Figure 12. State-level Changes in Total Health Benefits (High Estimate) in 2050 under the Vehicle Electrification Scenario with the AEO and ALA Electricity Generation Cases.

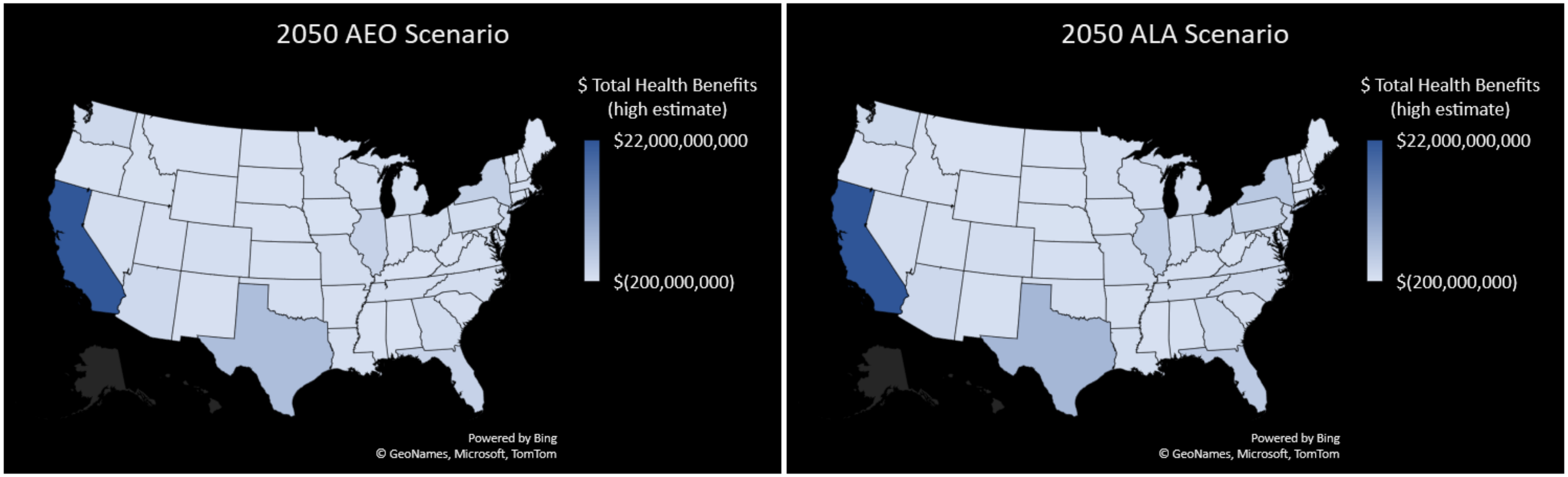


Figure 13. State-level Changes in Total Health Benefits (High Estimate) per capita in 2050 under the Vehicle Electrification Scenario with the AEO and ALA Electricity Generation Cases.

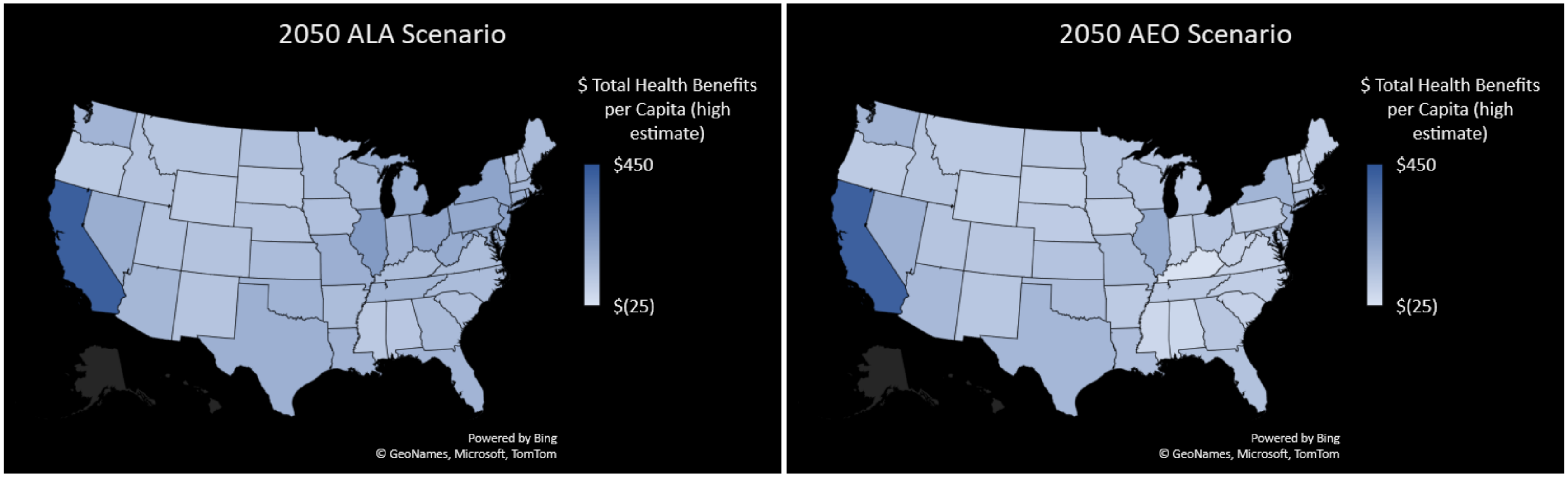


Figure 14. State-level Total Health Benefits (High Estimate) in 2030 and 2050 under the Vehicle Electrification Scenario with the AEO and ALA Electricity Generation Cases. Note California results (circled) in this figure are reduced by a factor of 10 for presentation here to appear on the same scale as other states.

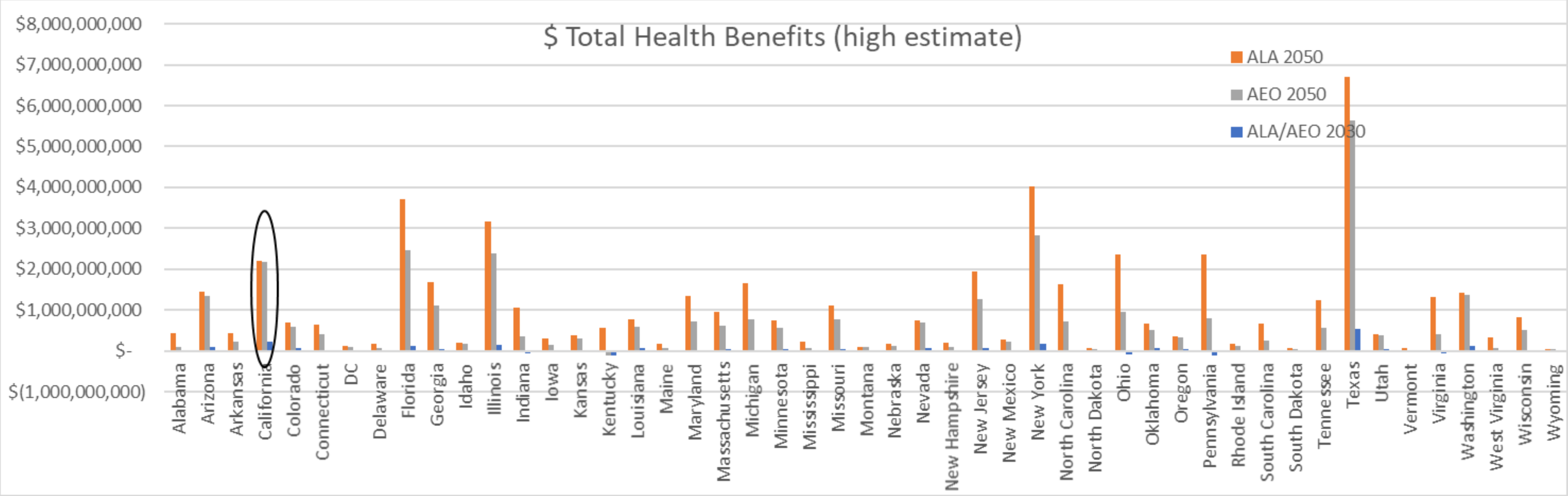
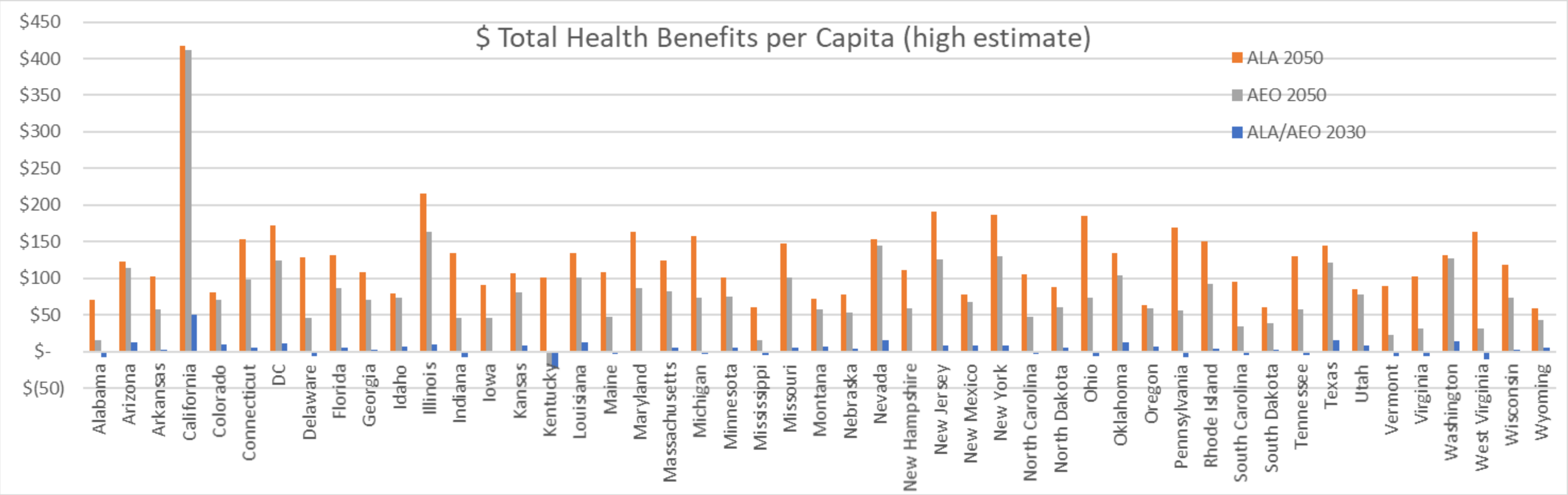


Figure 15. State-level Total Health Benefits per Capita (High Estimate) in 2030 and 2050 under the Vehicle Electrification Scenario with the AEO and ALA Electricity Generation Cases.



VI. Climate Benefits Evaluation

1. Social Cost of Carbon

In addition to the direct health benefit to populations who will be exposed to improved levels of PM air pollution from the Scenario, we also evaluated the benefits anticipated due to reductions in GHG emissions for the vehicle electrification Scenario. We considered both the reduction in direct (downstream) emissions from increased electrification as well as the upstream emission changes from fuel production and increased load on the electric grid under both the ALA and AEO electricity generation Cases.[69] We monetized these values using the Social Cost of Carbon (SCC).

The social cost of CO_2 emissions (SC-CO_2) is a measure, in dollars, of the long-term damage done by a ton of carbon dioxide (CO_2) emissions in a given year. This dollar figure also represents the value of damages avoided for a small emission reduction (i.e., the benefit of a CO_2 reduction). SC-CO_2 is intended to be a comprehensive estimate of climate change damages and includes changes in net agricultural productivity, human health, property damages from increased flood risk, and value of ecosystem services. However, not all important damages are included due to data limitations. SC-CO_2 is also politically sensitive. Under the Obama Administration, EPA used values that included global damages and also published SC-CH_4 and SC-N_2O values. Under the Trump Administration, EPA is currently using interim SC-CO_2 values that include domestic effects only and are significantly lower.[70], [71] For completeness, we present estimated impacts under both. Also, as emission reductions are for GHG emissions and reported in terms of CO_2-equivalent, we applied the SC-CO_2 metric to estimate the benefits from avoided greenhouse gas emissions due to implementation of the vehicle electrification scenario.

2. Benefits

Table 16 summarizes the results of the calculated benefits of the changes in GHG emissions expected under the electrification Scenario. In this case, we have used a 3% “average” discount rate, which is consistent with the typical $42/ton value for SC-$CO_2$ and with the COBRA values. We have also updated the values to 2017 dollars to be consistent with the COBRA results. values are shown in 2017 dollars and metric tons of GHG pollutant (as CO_2e). Note that the

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[69] The grid mixes used for each Case were discussed in Section IV.2.2. Note that the GREET emission factors used with these grid mixes include fugitive CH_4 emissions during natural gas extraction and transport.

[70] The Obama administration's values and guidance is available for historical purposes only is available on an archived EPA website at https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html. As disclaimed, this is no longer US EPA's approved approach. Interim domestic values are shown in the Trump Administration's EPA's Regulatory Impact Analysis (RIA) for the Review of the Clean Power Plan, Table 3-7 of https://www.epa.gov/sites/production/files/2017-10/documents/ria_proposed-cpp-repeal_2017-10.pdf.

[71] For comparison, Obama Administration values for the SC-CO2 for 2020 were $42/metric ton of CO2 at the 3% discount rate and $12/ metric ton of CO2 at the 5% discount rate (2007 $). Trump Administration interim domestic values for 2020 are $6/metric ton of CO2 at the 3% discount rate, and $1/metric ton of CO2 at the 7% discount rate (2011 $).

downstream and 2030 upstream emissions are identical under the two electricity generation scenarios.

Table 16. Avoided Social Costs from GHG Reductions (metric tons of CO_2e), in 2017$ with a 3% Average Discount Rate.

Year	AEO Case			ALA Case		
	GHG Reduction (MT CO_2e)	Obama-Administration Global Values	Trump-Administration Domestic Only Values	GHG Reduction (MT CO_2e)	Obama-Administration Global Values	Trump-Administration Domestic Only Values
	Downstream Only					
2030	205,492,474	$12,329,544,339	$1,582,291,524	205,492,474	$12,329,544,339	$1,582,291,524
2050	1,314,239,821	$108,819,021,159	$14,456,633,246	1,314,239,821	$108,819,021,159	$14,456,633,246
	Downstream and Upstream					
2030	189,650,065	$11,379,000,118	$1,460,305,015	189,650,065	$11,379,000,120	$1,460,305,015
2050	1,260,573,650	$104,375,463,666	$13,866,305,559	1,372,537,669	$113,646,081,410	$15,097,909,366

Appendix A: Additional Information on MOVES Vehicle Type Classifications, BAU Projections, and Emissions Modeling

Table 17. On-Road Vehicle Types in the MOVES2014 Model[72]

sourceTypeID	Source Type Name	HPMSVTypeID	Description
11	Motorcycles	10	Motorcycles
21	Passenger Cars	25	Light-Duty Vehicles
31	Passenger Trucks (primarily personal use)	25	Light-Duty Vehicles
32	Light Commercial Trucks (primarily non- personal use)	25	Light-Duty Vehicles
41	Intercity Buses (non-school, non-transit)	40	Buses
42	Transit Buses	40	Buses
43	School Buses	40	Buses
51	Refuse Trucks	50	Single Unit Trucks
52	Single Unit Short-Haul Trucks	50	Single Unit Trucks
53	Single Unit Long-Haul Trucks	50	Single Unit Trucks
54	Motor Homes	50	Single Unit Trucks
61	Combination Short-Haul Trucks	60	Combination Trucks
62	Combination Long-Haul Trucks	60	Combination Trucks

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[72] Population and Activity of On-road Vehicles in MOVES2014, EPA-420-R-16-003a, March 2016. Available at: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100O7PS.pdf. See Table 2-1.

Table 18. Matrix of the Allowable Source Type-Regulatory Class Combinations in MOVES2014.[73]

Regulatory Classes		Long-Haul Combination Trucks	Short-Haul Combination Trucks	Motor Homes	Long-Haul Single Unit Trucks	Short-Haul Single Unit Trucks	Refuse Trucks	School Buses	Transit Buses	Intercity Buses	Light Commercial Trucks	Passenger Trucks	Passenger Cars	Motorcycles
		62	61	54	53	52	51	43	42	41	32	31	21	11
10	MC													X
20	LDV												X	
30	LDT										X	X		
40	LHD<=10k										X	X		
41	LHD<=14k			X	X	X	X	X		X				
42	LHD45			X	X	X	X	X	X	X				
46	MHD67	X	X	X	X	X	X	X	X	X				
47	HHD8	X	X	X	X	X	X	X	X	X				
48	Urban Bus								X					

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[73] Population and Activity of On-road Vehicles in MOVES2014, EPA-420-R-16-003a, March 2016. Available at: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100O7PS.pdf. See Table 2-7.

Table 19. Regulatory Classes in MOVES2014.[74]

regClassID	Regulatory Class Name	Description
0	Doesn't Matter	Doesn't Matter
10	MC	Motorcycles
20	LDV	Light-Duty Vehicles
30	LDT	Light-Duty Trucks
40	LHD<=10k	Class 2b Trucks with 2 Axles and 4 Tires (8,500 lbs < GVWR <= 10,000 lbs)
41	LHD<=14k	Class 2b Trucks with 2 Axles and at least 6 Tires or Class 3 Trucks (8,500 lbs < GVWR <= 14,000 lbs)
42	LHD45	Class 4 and 5 Trucks (14,00 lbs < GVWR <= 19,500 lbs)
46	MHD	Class 6 and 7 Trucks (19,500 lbs < GVWR < =33,000 lbs)
47	HHD	Class 8a and 8b Trucks (GVWR > 33,000 lbs)
48	Urban Bus	Urban Bus (see CFR Sec. 86.091_2)

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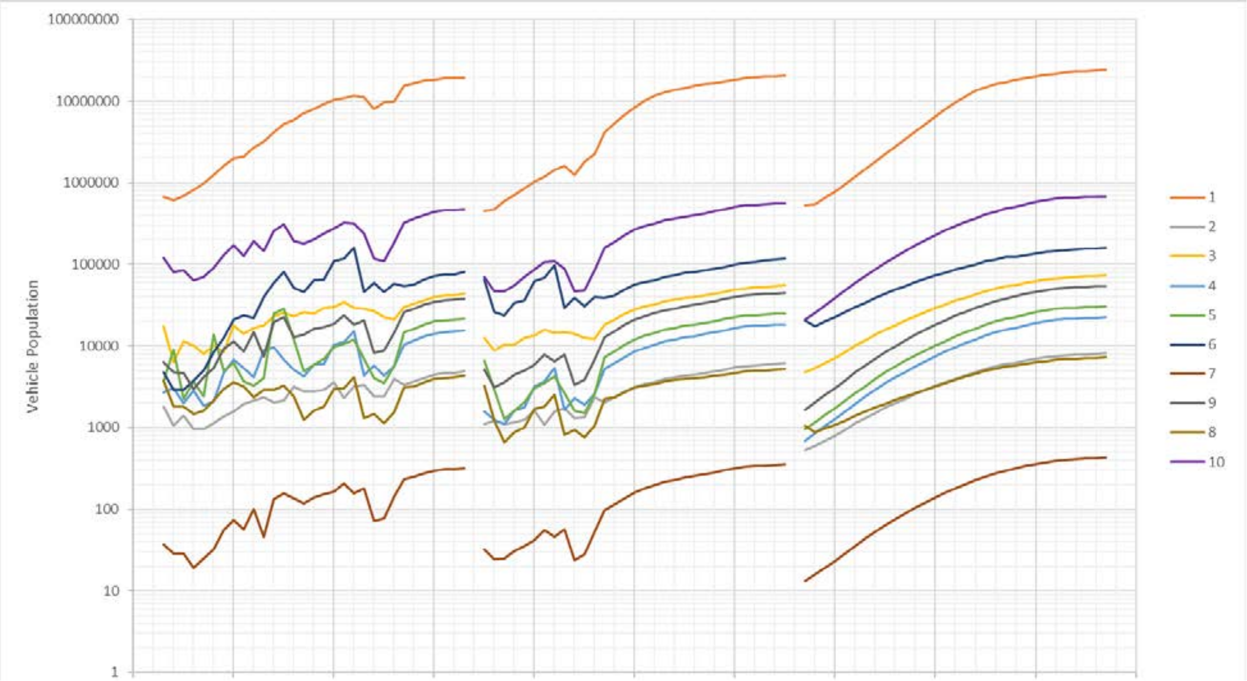
[74] Population and Activity of On-road Vehicles in MOVES2014, EPA-420-R-16-003a, March 2016. Available at: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100O7PS.pdf. See Table 2-2.

Figure 16 shows population trends as a function of age. Fuel types are not disaggregated in this figure but are tracked in the data. The population of the newest vehicles in each calendar year are shown at the right of each curve, the oldest at the left. Three groups of data can be seen. The baseline values, representing calendar year 2018, are shown in the leftmost group. The middle group shows calendar year 2030. The right group shows calendar year 2050. Each of the 10 curves in this group represents one of the vehicle categories subject to electrification in the Scenario. The top curve is vehicle type 1 (the LDV passenger fleet); the bottom curve is vehicle type 7 (airport shuttles).

The table accompanying and below the figure summarizes the vehicle categories. See Table 1 for more information on these categories.

Figure 16. Vehicle Age Distributions in 2018 (left-most group), 2030 (center), and 2050 (right) for the Scenario Vehicle Types.



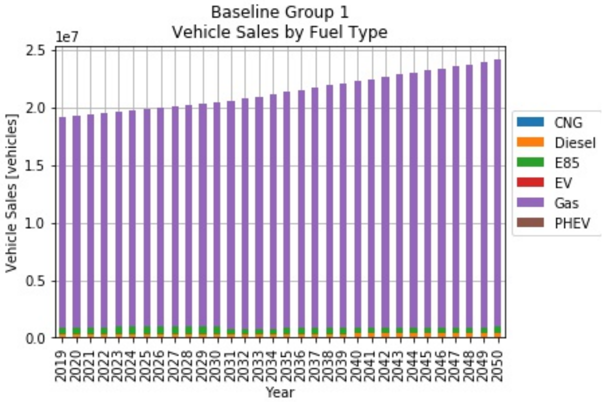
ID	Vehicle Category
1	Passenger Fleet
2	Transit Bus
3	School Bus
4	Refuse Truck
5	Long Haul
6	
7	Airport Shuttles
8	Drayage/Port
9	Delivery Vans
10	Additional Single Unit Short-Haul (SUSH)

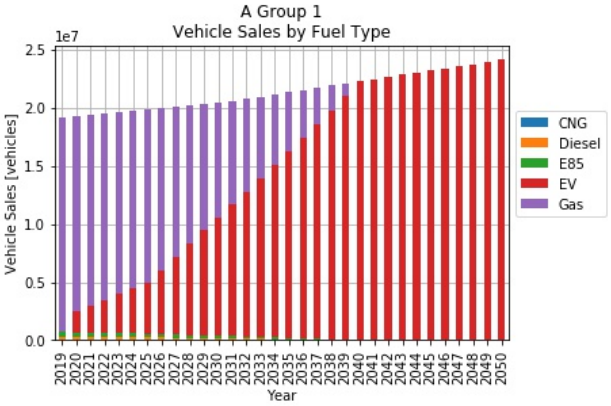
Table 20. Pollutants and Emission Processes Included in this analysis from the MOVES modeling.

Pollutant	Emission Process	
Atmospheric CO2	Auxiliary Power Exhaust	Running Exhaust
	Extended Idle Exhaust	Start Exhaust
CO2 Equivalent	Auxiliary Power Exhaust	Running Exhaust
	Extended Idle Exhaust	Start Exhaust
Composite - NonECPM	Auxiliary Power Exhaust	Running Exhaust
	Extended Idle Exhaust	Start Exhaust
Elemental Carbon	Auxiliary Power Exhaust	Running Exhaust
	Extended Idle Exhaust	Start Exhaust
H2O (aerosol)	Auxiliary Power Exhaust	Running Exhaust
	Extended Idle Exhaust	Start Exhaust
Methane (CH4)	Auxiliary Power Exhaust	Extended Idle Exhaust
	Crankcase Extended Idle Exhaust	Running Exhaust
	Crankcase Running Exhaust	Start Exhaust
	Crankcase Start Exhaust	
Nitrous Oxide (N2O)	Crankcase Running Exhaust	Running Exhaust
	Crankcase Start Exhaust	Start Exhaust
Non-Methane Hydrocarbons	Auxiliary Power Exhaust	Refueling Displacement Vapor Loss
	Evap Fuel Leaks	Refueling Spillage Loss
	Evap Fuel Vapor Venting	Running Exhaust
	Evap Permeation	Start Exhaust
	Extended Idle Exhaust	
Oxides of Nitrogen (NOx)	Auxiliary Power Exhaust	Extended Idle Exhaust
	Crankcase Extended Idle Exhaust	Running Exhaust
	Crankcase Running Exhaust	Start Exhaust
	Crankcase Start Exhaust	
Primary Exhaust PM2.5 - Total	Auxiliary Power Exhaust	Extended Idle Exhaust
	Crankcase Extended Idle Exhaust	Running Exhaust
	Crankcase Running Exhaust	Start Exhaust
	Crankcase Start Exhaust	
Primary PM2.5 – Brake wear Particulate	Brake wear	
Primary PM2.5 – Tire wear Particulate	Tire wear	
Sulfate Particulate	Auxiliary Power Exhaust	Running Exhaust
	Extended Idle Exhaust	Start Exhaust
Sulfur Dioxide (SO2)	Auxiliary Power Exhaust	Extended Idle Exhaust
	Crankcase Extended Idle Exhaust	Running Exhaust
	Crankcase Running Exhaust	Start Exhaust
	Crankcase Start Exhaust	
Total Energy Consumption	Auxiliary Power Exhaust	Running Exhaust
	Extended Idle Exhaust	Start Exhaust
Total Gaseous Hydrocarbons	Auxiliary Power Exhaust	Refueling Displacement Vapor Loss

Pollutant	Emission Process	
	Evap Fuel Leaks	Refueling Spillage Loss
	Evap Fuel Vapor Venting	Running Exhaust
	Evap Permeation	Start Exhaust
	Extended Idle Exhaust	
Volatile Organic Compounds	Auxiliary Power Exhaust	Evap Permeation
	Crankcase Extended Idle Exhaust	Extended Idle Exhaust
	Crankcase Running Exhaust	Refueling Displacement Vapor Loss
	Crankcase Start Exhaust	Refueling Spillage Loss
	Evap Fuel Leaks	Running Exhaust
	Evap Fuel Vapor Venting	Start Exhaust

Appendix B: Charts of Vehicle Sales by Vehicle and Fuel Type by Calendar Year


Baseline Group 1
Vehicle Sales by Fuel Type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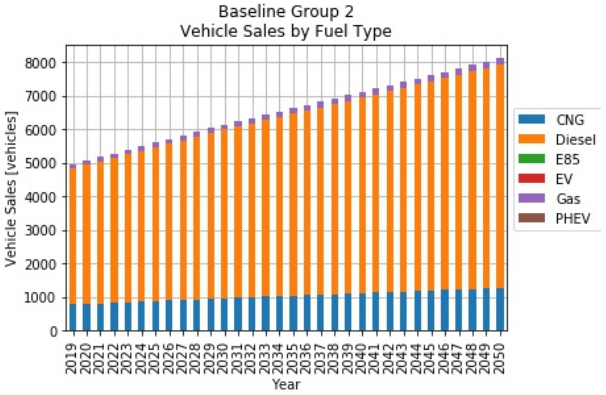
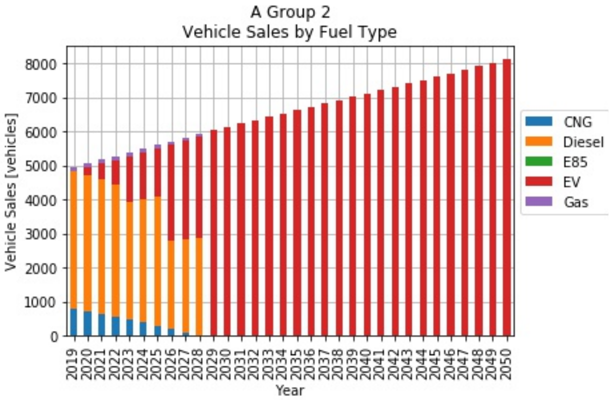
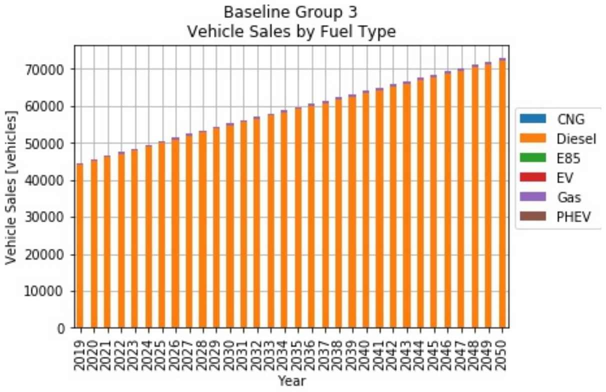
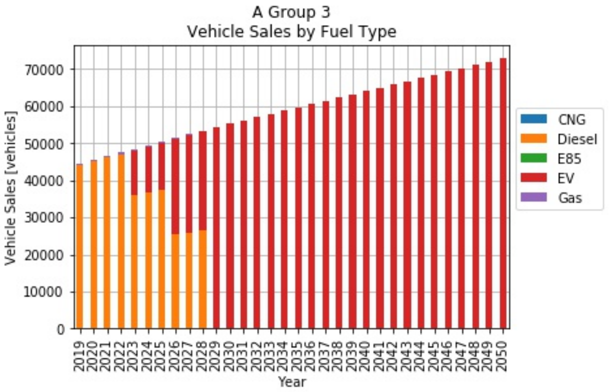
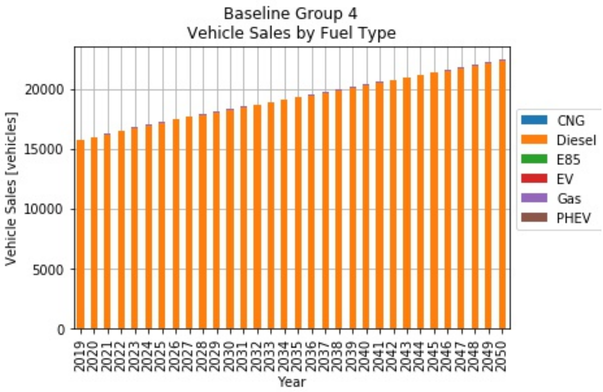
Vehicle Sales by Fuel Type

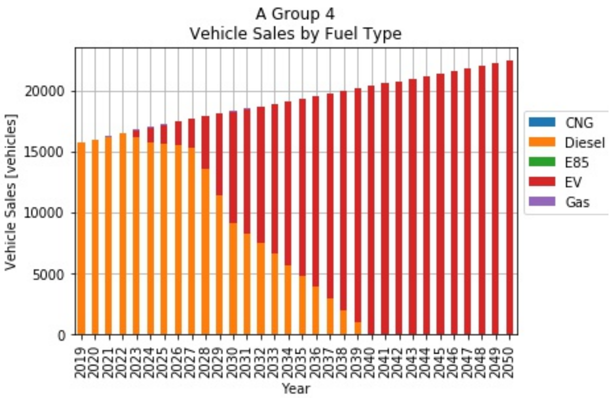

Baseline Group 2
Vehicle Sales by Fuel Type

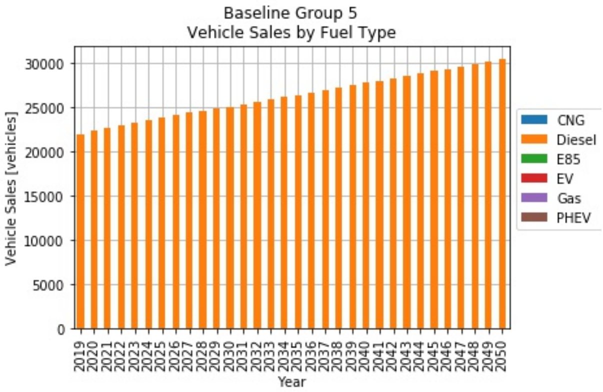

A Group 2
Vehicle Sales by Fuel Type

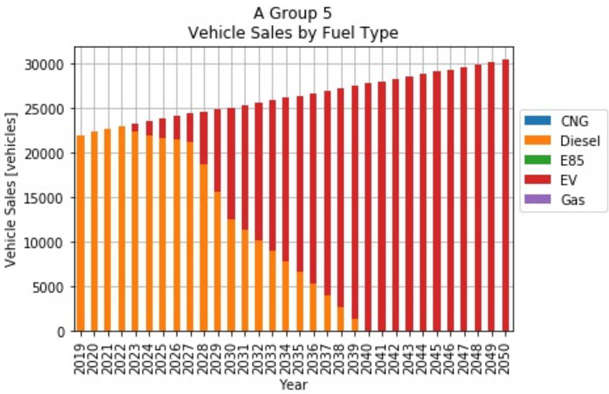

Baseline Group 3
Vehicle Sales by Fuel Type

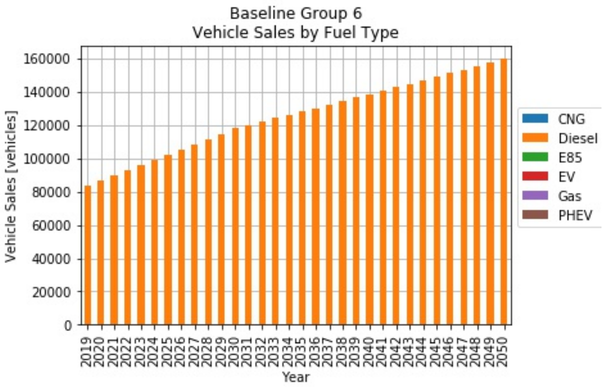

A Group 3
Vehicle Sales by Fuel Type

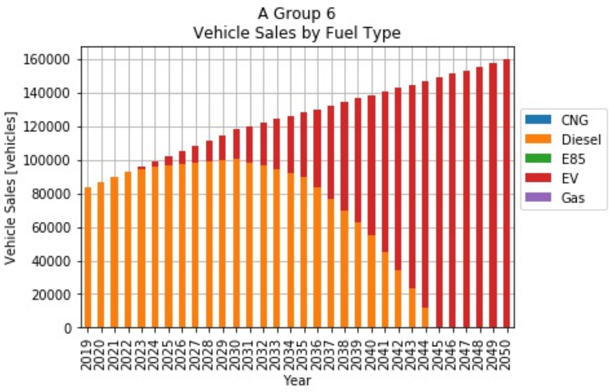

Baseline Group 4
Vehicle Sales by Fuel Type

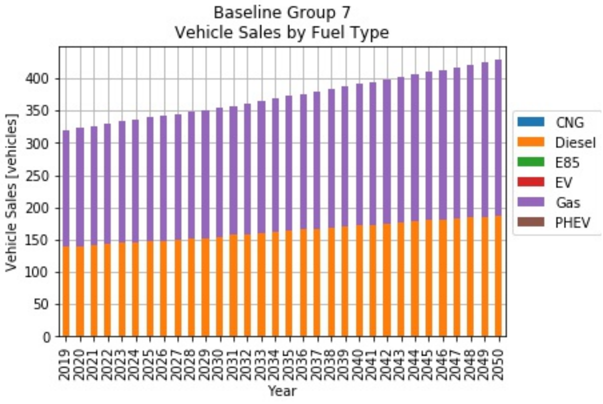

A Group 4
Vehicle Sales by Fuel Type

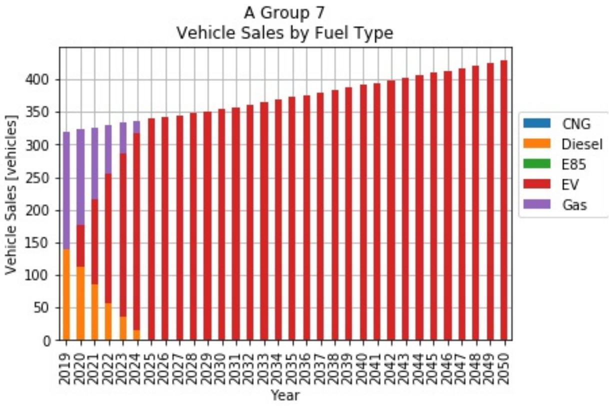

Baseline Group 5
Vehicle Sales by Fuel Type

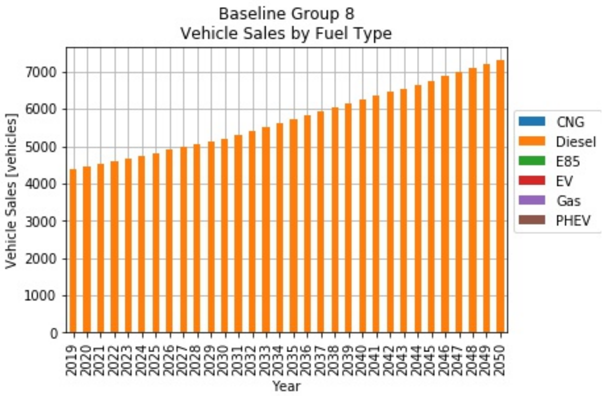

A Group 5
Vehicle Sales by Fuel Type

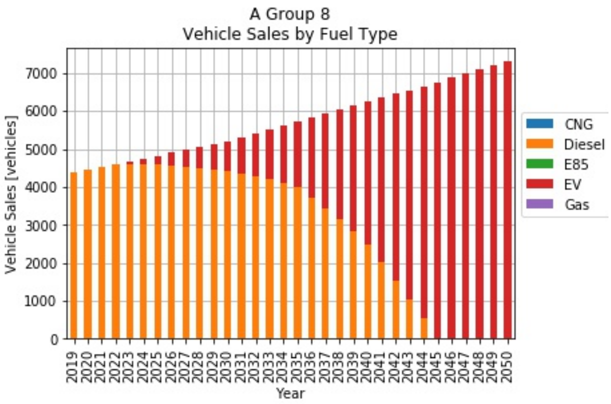

Baseline Group 6
Vehicle Sales by Fuel Type

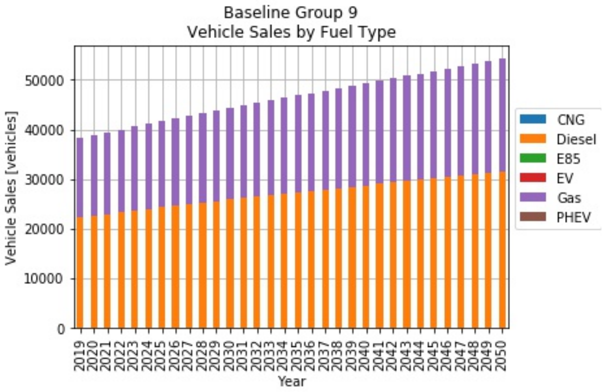

A Group 6
Vehicle Sales by Fuel Type

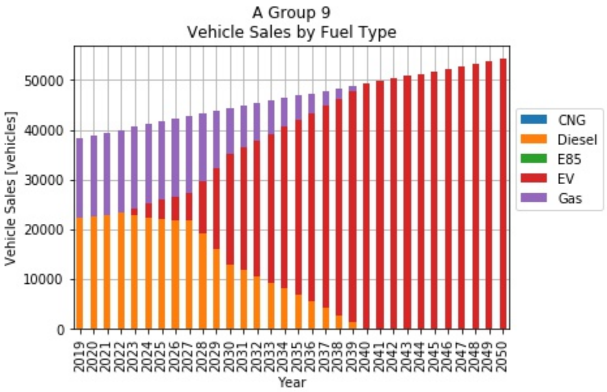

Baseline Group 7
Vehicle Sales by Fuel Type

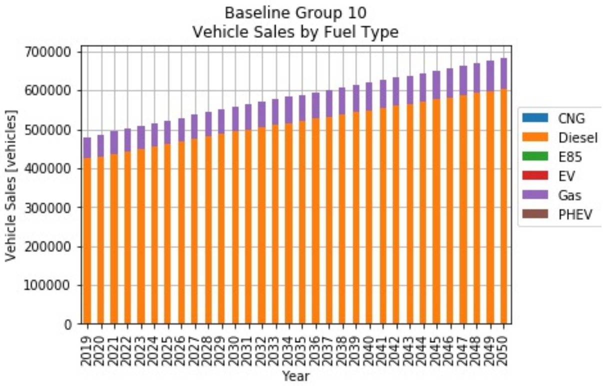

A Group 7
Vehicle Sales by Fuel Type

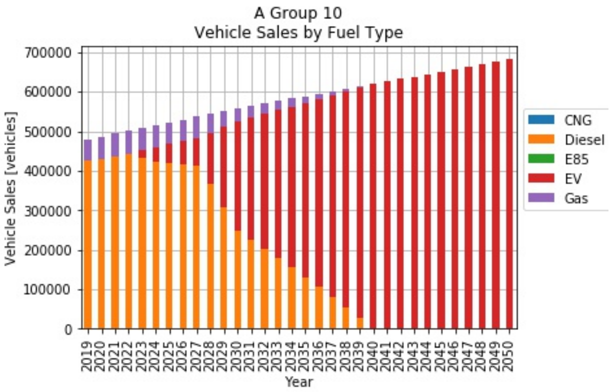

Baseline Group 8
Vehicle Sales by Fuel Type
Vehicle Sales [vehicles]
0
1000
2000
3000
4000
5000
6000
7000
Year
2019 … 2050
CNG
Diesel
E85
EV
Gas
PHEV


A Group 8
Vehicle Sales by Fuel Type
Vehicle Sales [vehicles]
0
1000
2000
3000
4000
5000
6000
7000
Year
2019 … 2050
CNG
Diesel
E85
EV
Gas


Baseline Group 9
Vehicle Sales by Fuel Type
Vehicle Sales [vehicles]
0
10000
20000
30000
40000
50000
Year
2019 … 2050
CNG
Diesel
E85
EV
Gas
PHEV


A Group 9
Vehicle Sales by Fuel Type
Vehicle Sales [vehicles]
0
10000
20000
30000
40000
50000
Year
2019 … 2050
CNG
Diesel
E85
EV
Gas


Baseline Group 10
Vehicle Sales by Fuel Type
Vehicle Sales [vehicles]
0
100000
200000
300000
400000
500000
600000
700000
Year
2019 … 2050
CNG
Diesel
E85
EV
Gas
PHEV


A Group 10
Vehicle Sales by Fuel Type
Vehicle Sales [vehicles]
0
100000
200000
300000
400000
500000
600000
700000
Year
2019 … 2050
CNG
Diesel
E85
EV
Gas

Appendix C: COBRA Health Endpoints

Health Endpoint	Author(s)	Year	Applicable Ages
Acute Bronchitis	Dockery et al.	1996	8-12
Acute Myocardial Infarction, Nonfatal (high)	Peters et al.	2001	18-99
Acute Myocardial Infarction, Nonfatal (low)	Pope et al.	2006	0-99
Acute Myocardial Infarction, Nonfatal (low)	Sullivan et al.	2005	0-99
Acute Myocardial Infarction, Nonfatal (low)	Zanobetti and Schwartz	2006	0-99
Acute Myocardial Infarction, Nonfatal (low)	Zanobetti et al.	2009	0-99
Asthma Exacerbation, Cough	Mar et al.	2004	6-17
Asthma Exacerbation, Cough	Ostro et al.	2001	6-17
Asthma Exacerbation, Shortness of Breath	Mar et al.	2004	6-17
Asthma Exacerbation, Shortness of Breath	Ostro et al.	2001	6-17
Asthma Exacerbation, Wheeze	Ostro et al.	2001	6-17
Asthma Exacerbation, Cough	Mar et al.	2004	18-18
Asthma Exacerbation, Cough	Ostro et al.	2001	18-18
Asthma Exacerbation, Shortness of Breath	Mar et al.	2004	18-18
Asthma Exacerbation, Shortness of Breath	Ostro et al.	2001	18-18
Asthma Exacerbation, Wheeze	Ostro et al.	2001	18-18
Emergency Room Visits, Asthma	Mar et al.	2010	0-99
Emergency Room Visits, Asthma	Slaughter et al.	2005	0-99
Emergency Room Visits, Asthma	Glad et al.	2012	0-99
HA, All Cardiovascular (less Myocardial Infarctions)	Moolgavkar	2000	18-64
HA, All Cardiovascular (less Myocardial Infarctions)	Bell et al.	2008	65-99
HA, All Cardiovascular (less Myocardial Infarctions)	Peng et al.	2008	65-99
HA, All Cardiovascular (less Myocardial Infarctions)	Peng et al.	2009	65-99
HA, All Cardiovascular (less Myocardial Infarctions)	Zanobetti et al	2009	65-99
HA, All Respiratory	Zanobetti et al	2009	65-99
HA, All Respiratory	Kloog et al.	2012	65-99
HA, Asthma	Babin et al.	2007	0-17
HA, Asthma	Sheppard	2003	0-17
HA, Chronic Lung Disease	Moolgavkar	2000	18-64
Lower Respiratory Symptoms	Schwartz and Neas	2000	7-14
Minor Restricted Activity Days	Ostro and Rothschild	1989	18-64
Mortality, All Cause (low)	Krewski et al.	2009	30-99
Mortality, All Cause (high)	Lepeule et al.	2012	25-99
Infant Mortality	Woodruff et al.	1997	0-0
Upper Respiratory Symptoms	Pope et al.	1991	9-11
Work Loss Days	Ostro	1987	18-64