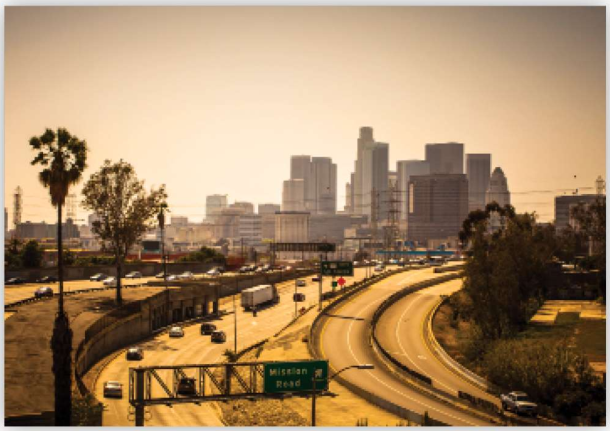
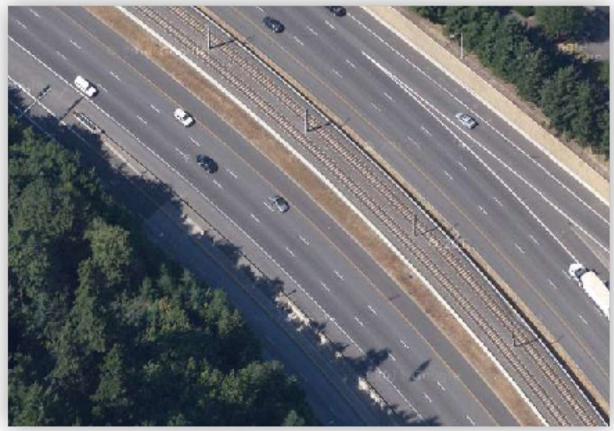
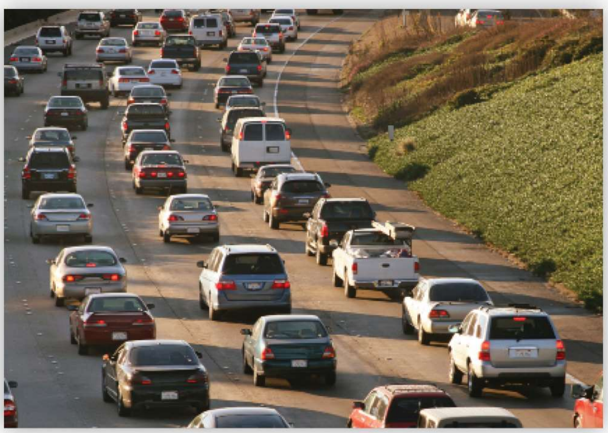
Benefits of State-Level Adoption of California Medium- and Heavy-Duty Vehicle Regulations







Final Report Prepared for

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Benefits of State-Level Adoption of California Medium- and Heavy-Duty Vehicle Regulations

Prepared by

Jeff Houk
Joey Huang
Shih Ying Chang
Doug Eisinger

Contact: Jeff Houk, jhouk@sonomatech.com
Sonoma Technology
1450 N. McDowell Blvd., Suite 200
Petaluma, CA 94954
Ph 707.665.9900 | F 707.665.9800
sonomatech.com

Prepared for

Ray Minjares

The International Council on Clean Transportation
595 Market Street, Suite 1250
San Francisco, CA 94105
Ph 415.818.0206
https://theicct.org/

Final Report

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Executive Summary

This report documents the technical steps and findings of our project to help the International Council on Clean Transportation (ICCT) support the Northeast States for Coordinated Air Use Management (NESCAUM) as they move to accelerate the introduction of medium- and heavy-duty electric and advanced technology vehicles into selected state fleets. In January 2021, ICCT contracted Sonoma Technology on behalf of 13 states and the District of Columbia to evaluate the effects of adopting California heavy-duty vehicle emissions control programs. These programs include the Advanced Clean Trucks (ACT) regulation (adopted summer 2020), the low-NO_x Omnibus regulation (not yet adopted as of July 2021), and full implementation of the California HD Vehicle Greenhouse Gas (GHG) Phase 2 regulation. As of July 2021, the vehicle emissions reduction requirements of this last program were being implemented, but the trailer efficiency improvements were not, as a result of litigation.

Sonoma Technology conducted MOVES3 emissions modeling and developed a post-processing approach to apply the air quality benefits associated with these regulatory options to the MOVES3 emissions projections for these 14 areas. A variety of Scenarios were evaluated, reflecting different combinations of the California programs. Sonoma Technology also projected the annual change in well-to-tank emissions for both fossil-fueled and electric vehicles using emissions factors from the Department of Energy for upstream power generation and petroleum refining emissions. Finally, Sonoma Technology projected in-use electrical vehicle populations and new electric vehicle sales in the calendar years being evaluated.

Emission reductions for the California programs vary by calendar year, program Scenario, and state. Reductions ranged from 1%-53% for NO_x, 3%-23% for $PM_{2.5}$, and 1%-55% for well-to-wheels CO_2e. There are several reasons for differences in emissions trends among these states. First, individual states have different vehicle age distributions (which influence the rate of fleet turnover), and different mixes of vehicle population by vehicle class (some states may have more or fewer large heavy-duty vehicles than others). A few states provided state-specific estimates of vehicle miles traveled and vehicle population growth, which drive overall emissions levels. The largest determining factor for well-to-wheels CO_2e was the electrical grid emissions factors. These emissions factors vary by region of the country, and the analyses for seven areas (Colorado, the District of Columbia, Massachusetts, New Jersey, New York, Oregon, and Washington) reflect state-specific projections for future penetration of renewable energy in their grids (for the other states, 2020 emissions rates were used for all years). These seven areas had the largest net reductions for all pollutants.

1. Introduction

In January 2021, the International Council on Clean Transportation (ICCT) contracted Sonoma Technology on behalf of 13 states and the District of Columbia to evaluate the effects of adopting California heavy-duty vehicle emissions control programs. Fifteen states[1] and the District of Colombia have signed a memorandum of understanding (MOU) which calls for them to work toward a goal that 100% of new medium-duty (MD) and heavy-duty (HD) truck and bus sales will be zero emission by 2050, with an interim target of 30% by 2030. ICCT is supporting the Northeast States for Coordinated Air Use Management (NESCAUM) with the implementation of the MOU. To this end, ICCT and the states that have signed the MOU are exploring a variety of regulations that mirror those adopted or that are under consideration in the state of California. These include the Advanced Clean Trucks (ACT) regulation (adopted summer 2020), the low-NO_x Omnibus regulation (not yet adopted as of July 2021), and full implementation of the California HD Vehicle Greenhouse Gas (GHG) Phase 2 regulation. As of July 2021, the vehicle emissions reduction requirements of this last program were being implemented, but the trailer efficiency improvements were not, as a result of litigation.

Sonoma Technology is providing MOVES3 emissions modeling and further air quality analyses to characterize the air quality benefits associated with these regulatory options for ICCT, which is acting on behalf of the individual states that signed the MOU. This project provides signatories to the June 2020 multi-state MOU with technical analyses reflecting implementation of these California programs.

ICCT defined the scope of the analysis for all medium- and heavy-duty vehicles as (Regulatory Source types 41, 42, 46, 47, and 48):

1) Forecast baseline annual change in tailpipe exhaust emissions of NO_x and $PM_{2.5}$ from 2020-2050
2) Forecast baseline annual change in energy consumption and GHG emissions (CO_2e) from 2020-2050
3) Forecast baseline annual change in vehicle activity (VMT) from 2020-2050
4) Forecast baseline annual change in vehicle population from 2020-2050

Sonoma Technology was asked to use the latest available version of the MOVES3 model to generate calendar year estimates for the years of 2030, 2040, and 2050, based on MOVES3 default data and the 2017 National Emissions Inventory (NEI) data for representative counties in each state. We then generated interpolated estimates for four additional years so that the overall analysis covered 2020 through 2050 in five-year increments (for seven estimated years total: 2020, 2025, 2030, 2035, 2040, 2045, 2050). Sonoma Technology was also asked to project the annual change in well-to-tank

[1] California and Hawaii have also signed the MOU, but are not included in this analysis.

emissions for both fossil-fueled and electric vehicles using emissions factors from the Department of Energy's GREET[2] model for upstream power generation and petroleum refining emissions.

ICCT defined the following Scenarios for analysis:

Scenario 1: Business as Usual (reflecting current Federal programs only, and non-implementation of the GHG Phase 2 trailer requirements)

Scenario 2: Dual Harmonization (Advanced Clean Trucks Rule, Low-NO_x Omnibus Rule w/urban buses) from model year (MY) 2025

Scenario 2a: Full Harmonization (Dual Harmonization plus implementation of the GHG Phase 2 trailer requirements) from MY2025

Scenario 3: Advanced Clean Trucks Rule from MY2025

Scenario 4: Low-NO_x Omnibus Rule w/urban buses from MY2025

Scenario 5: Full implementation of the Phase 2 GHG Standard from MY2025 (benefits of Phase 2 trailer rule)

ICCT requested that Sonoma Technology provide analysis results in spreadsheet form, with output tables including:

1) Medium- and Heavy-Duty Vehicle Stock Projections (vehicles per year) by MOVES3 Regulatory Source Category, 2020-2050
2) Medium- and Heavy-Duty Vehicle Activity Projections (miles per year) by MOVES3 Regulatory Source Category, 2020-2050
3) Tank-to-Wheel NO_x Emissions by Scenario (tons per year), 2020-2050
4) Tank-to-Wheel $PM_{2.5}$ Emissions by Scenario (tons per year), 2020-2050
5) Tank-to-Wheel CO_2e Emissions by Scenario (tons per year), 2020-2050
6) Well-to-Wheel CO_2e Emissions by Scenario
7) Zero-Emission Medium- and Heavy-Duty Fleet Projections for Advanced Clean Truck Rule Adoption, 2020-2050. Projections to include Annual MDHD ZEV Sales, Annual MDHD ZEV Sales Share, and Annual MDHD ZEV Population.

Sonoma Technology's overall approach for this analysis was to (1) run MOVES3 to develop baseline emissions and vehicle activity data for the 14 areas and seven calendar years; (2) evaluate the California programs and develop adjustment factors for the MOVES3 output to reflect these programs; and (3) post-process the MOVES3 results using these adjustment factors to develop the emissions and activity projections for each area, year, and Scenario. These steps are described in more detail below.

[2] Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model, https://greet.es.anl.gov/

2. Data Preparation for MOVES3 Modeling

Sonoma Technology first created a MOVES3 run design sheet to summarize the project scope, scale, geographic bounds, pollutants, vehicles, and input files needed for all the MOVES3 runs. Sonoma Technology then extracted MOVES3 default data for each county and target year from the MOVES3 default database to .csv and/or Ascii files. NEI 2017 data were also downloaded[3] and representative county data from the NEI 2017 database were extracted to .csv and/or Ascii files. The vehicle miles traveled (VMT) and vehicle population (VPOP) data for each representative county from NEI 2017 are the sum of VMT and VPOP for all the counties in the group containing the representative county, not the values for only that county. When the VMT, VPOP, and emissions data for the representative counties are summed, they reflect statewide totals.

Sonoma Technology modeled 2017, 2030, 2040, and 2050[4] at the MOVES3 County scale, using the mix of NEI 2017, state-provided, and MOVES3 defaults for input data, as described below. In most cases, MOVES3 default VMT and VPOP output were used to calculate VMT and VPOP growth factors for future years, and NEI 2017 VMT and VPOP data were used with MOVES3-based growth factors to project VMT and VPOP for future years. However, the state of Massachusetts and three New Jersey Metropolitan Planning Organizations (MPOs) submitted future VMT and population estimates, and these data were used instead of MOVES3 defaults to calculate growth rates for those counties. The New Jersey MPOs also submitted future age distribution files that were used in the modeling. The final sources of MOVES3 County-scale input data are summarized in **Table 1**.

When assembling the input databases for the first states, Sonoma Technology identified an error with the scripting tools provided in MOVES3 to help automate this process. Sonoma Technology staff developed multiple R scripts to implement a workaround to this problem and wrote over a thousand lines of code to populate the required input databases, MOVES3 runspecs, and batch files. Finally, Sonoma Technology also found that the MOVES3 LEV and NLEV databases for light-duty vehicles were providing counterintuitive results (higher emissions) in test runs, and we were unable to resolve the issue with these databases. Sonoma Technology contacted the U.S. Environmental Protection Agency (EPA) and provided sample files to help them troubleshoot this issue, but because this issue did not affect the heavy-duty vehicle emissions estimates, Sonoma Technology continued the analysis without inclusion of these databases.

[3] ftp://newftp.epa.gov/air/emismod/

[4] For the initial two states, New Jersey and New York, Sonoma Technology modeled 2020, 2030 or 2035, and 2050.

Table 1. Sources of MOVES3 input data.

MOVES3 Input	Typical Data Source	State-Specific Variations
VMT, VPOP	NEI 2017, grown to future years using MOVES3 default growth rates	Growth rates based on MPO data for select counties (New Jersey) or the entire state (Massachusetts)
Fuel supply, fuel usage fractions, inspection/maintenance program parameters, VMT month, day, hour fractions	MOVES3 defaults	
Road type VMT distribution, vehicle age distribution	NEI 2017 data for corresponding county	MPO data where provided (New Jersey)
Vehicle technology distribution, speed distribution	NEI 2017 data for corresponding county	NEI 2017 data for corresponding county
Meteorology, retrofit program data	MOVES3 defaults	MPO data where provided (New Jersey)

Sonoma Technology also ran MOVES3 at the Default scale for each of the states and each of the seven analysis years, for the purpose of generating data for use in the development of County-scale inputs for future years, interpolation of County-scale results for the intermediate years described above, and for quality assurance purposes. The trend in default emissions was used to develop interpolated emissions estimates for the four analysis years not modeled at the County-scale (2020, 2025, 2035, and 2045).

Sonoma Technology output VMT and VPOP by regulatory class for detailed model quality assurance checks, and NO_x, CH_4, N_2O, $PM_{2.5}$, and energy by regulatory class for statewide emissions estimates. Representative county and statewide emissions of all target pollutants were summarized using an R script. NO_x emissions for all representative counties and the corresponding state were compared to NEI 2017 data and multiple-year emissions modeling platform data[5] (2016, 2023, and 2028) as a reasonableness check, and statewide emissions were compared to Default-scale MOVES3 runs for the corresponding state.

[5] EPA-developed emissions modeling platform with 2016 as the base year. The year 2023 and year 2028 inventories were projected by EPA from the 2016 inventory in support of the Revised Cross State Air Pollution Rule Update for the 2008 Ozone National Ambient Air Quality Standards. https://www.epa.gov/sites/production/files/2020-11/documents/2016v1_emismod_tsd_508.pdf

3. MOVES3 Post-Processing

As noted above, once MOVES3 runs were complete, Sonoma Technology applied post-processing adjustments to account for the effects of the two California regulations and the non-implementation of the trailer component of the Heavy-Duty GHG Phase 2 rule[6].

These adjustments are summarized in Table 2 and described in detail below; the regulatory classes are defined in Table 3.

Table 2. Summary of adjustments to MOVES3 results.

Topic	Description	EPA Regulatory Classes Affected	Pollutants Affected
GHG Phase 2 Trailer provisions	Adjustment to remove the benefit of the trailer component of the HDV Phase 2 GHG rule	46, 47	CO_2 (emissions increase)
Advanced Clean Trucks program	Adjustment to reflect phased introduction of electric HDVs into the fleet. Also includes use of GREET emissions factors to calculate resulting increase in grid emissions	41, 42, 46, 47	All (emissions decrease)
CA Low-NO_x Omnibus program	Adjustment to reflect ARB's proposed Low-NO_x Omnibus rule	42, 46, 47, 48[7]	NO_x (emissions decrease)

[6] Final Rule for Phase 2 Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles, October 25, 2016. https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-phase-2-greenhouse-gas-emissions-standards-and

[7] As designed by the state of California, this program does not include urban transit buses (regulatory class 48), but they were included in Sonoma Technology's analysis at the request of ICCT and the state of New York. The California program does include Class 3 trucks, but these are not reflected in the Sonoma Technology analyses because they cannot be modeled as a separate class in MOVES3.

Table 3. EPA regulatory classes.

EPA Regulatory Class Codes	Description
41	Class 2b and 3 Trucks (8,500 lbs < GVWR <= 14,000 lbs)
42	Class 4 and 5 Trucks (14,000 lbs < GVWR <= 19,500 lbs)
46	Class 6 and 7 Trucks (19,500 lbs < GVWR <= 33,000 lbs)
47	Class 8a and 8b Trucks (GVWR > 33,000 lbs)
48	Urban Transit Bus

3.1 GHG Phase 2 Trailer Provisions

EPA's MOVES3 model assumes the full implementation of the Federal and California Heavy-Duty GHG Phase 2 regulations. However, the trailer efficiency component of the HDV Phase 2 GHG rule was not in effect at the time work was completed as implementation of this portion of the rule was stayed in federal court as of July 2021. Thus, an adjustment to increase emissions to account for this was needed in Scenarios 1 through 4. This adjustment applies for all calendar years. In these Scenarios, ICCT and Sonoma Technology are assuming that this component of the rule will not be implemented. For Scenario 5, ICCT and Sonoma Technology assume that the program will be implemented starting in 2025.

ICCT provided spreadsheet estimates of the emissions reductions that can be attributed to different components of the HDV Phase 2 GHG rule, including the trailer component[8]. The "VMT" worksheet in this spreadsheet includes the information used in the calculation of the adjustment factors, including the percentage of tractor-trailer VMT that is subject to the regulation, the estimated percentage reductions from the regulation, and the baseline fuel use from these vehicles.

Because Sonoma Technology's MOVES3 output is reported by regulatory class, Sonoma Technology had to map the short-haul and long-haul tractor-trailer emissions estimates in ICCT's spreadsheet to the MOVES3 regulatory classes. Tractor-trailers ("combination vehicles" in MOVES terminology) are included in MOVES3 regulatory classes 46 and 47, but single-unit vehicles are part of these weight classes as well. Sonoma Technology ran MOVES3 at the Default scale for the entire U.S. to develop national VPOP estimates by vehicle sourcetype and regulatory class. We then used these data to determine the fractions of regulatory classes 46 and 47 that were comprised of combination

[8] Spreadsheet entitled "Trailer calcs for TTMA case_v2.xlsx," provided via email on 1/20/2021.

vehicles[9]. Then, these fractions and ICCT's fuel use and reduction estimates were combined to calculate the emissions increase for classes 46 and 47 attributable to not implementing the trailer requirements of the HDV Phase 2 GHG rule.

The GHG Phase 2 trailer program adjustments are derived in a spreadsheet named "ICCT trailer adjustments with MOVES trailer fractions 060921.xlsx."

3.2 Advanced Clean Trucks Program

ARB's Advanced Clean Trucks regulation[10] was adopted on June 25, 2020, and requires truck manufacturers to begin offering increasing percentages of electric heavy-duty trucks for sale in California, beginning with the 2024 model year. For this analysis, Sonoma Technology assumed that the program would start in the MOU states with the 2025 model year, per ICCT's direction. This program affects Scenarios 2 and 3 above. Because the MOVES3 model can only model EVs for a limited range of light-duty vehicle types, Sonoma Technology needed to develop post-processing adjustments to simulate the penetration of EVs into the heavy-duty fleet.

To develop adjustment factors for the ACT program, Sonoma Technology relied on ARB's emissions inventory methodology report[11], along with an accompanying spreadsheet provided by ARB staff[12]. ARB's EV penetration estimates account for the regulatory phase-in percentages by model year, the fractions of new vehicles sold in-state versus purchased out-of-state, and migration of California vehicles out of state over time. All of these assumptions vary by vehicle type, and, in some cases, by vehicle age. California also assumes that the ACT regulation applies concurrently with the GHG Phase 2 rule, and that EVs manufactured to meet the efficiency requirements of the Phase 2 rule count toward meeting the phase-in percentages of the ACT rule. Thus, ARB's estimates for EV sales under the ACT program account for only the incremental sales due to ACT that are above those estimated under the GHG Phase 2 program. ARB and Sonoma Technology assumed that individual electric trucks drive the same distance each day as their conventionally fueled counterparts.

The northeast states were interested in estimates of EV sales regardless of whether they were generated by the ACT or the GHG Phase 2 program, and in estimates of ongoing emissions reductions from EVs even after they had migrated to another state. In response, Sonoma Technology developed a second ACT post-processing Scenario (labeled "All EVs" in our spreadsheet reports) that eliminated ARB's "carve-out" of vehicles that would be sold under the GHG Phase 2 program, instead applying the full ACT sales fractions by model year, and eliminated ARB's adjustments for vehicle

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[9] Sonoma Technology could have used VMT by vehicle sourcetype and regulatory class rather than population to calculate these ratios; however, since the higher daily VMT accumulated by combination vehicles in operation is already reflected in the fuel use estimates in ICCT's projections, the population-based approach was assumed to be more appropriate.

[10] https://ww2.arb.ca.gov/our-work/programs/advanced-clean-trucks

[11] "Attachment D: Emissions Inventory Methods and Results for the Proposed Advanced Clean Trucks Regulation-Proposed Modifications," https://ww3.arb.ca.gov/regact/2019/act2019/30dayattd.pdf

[12] "CARB 2020b.xlsx," provided by Paul Arneja via email on February 24, 2021.

out-migration over time. At ICCT's direction, Sonoma Technology did continue to apply ARB's estimates of the fractions of new vehicles that would be purchased out-of-state and then registered in the state being analyzed. Figure 1 illustrates the assumptions used by ARB, and those reflected in each of the two Sonoma Technology Scenarios.

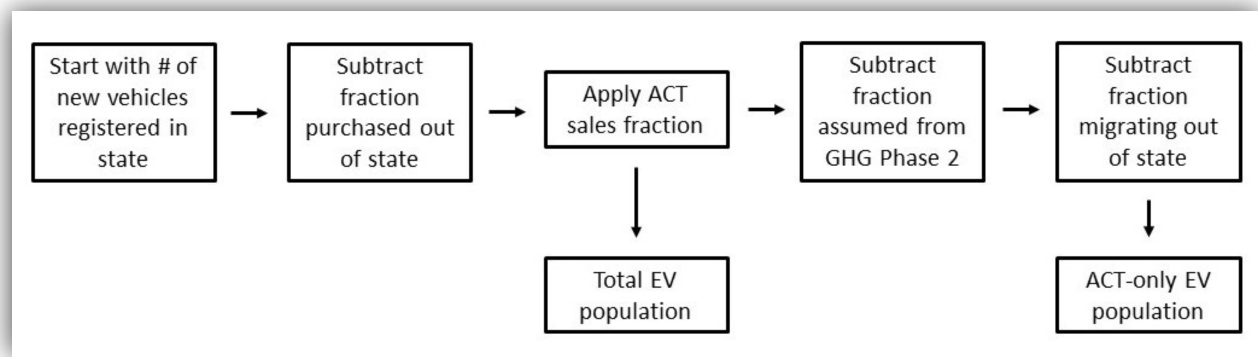

Figure 1. ARB process for estimating EV population.

Table 4 quantifies the interplay of the various ARB assumptions about the heavy-duty fleet in two calendar years: 2025, when the ACT program is first implemented, and 2035, when the program reaches "steady-state" and there are no further increases in the mandated sales percentages. ARB's assumptions regarding the percentages of vehicles that migrate out of state vary by vehicle age, so an age of five years is selected here as an example. For illustration purposes, Sonoma Technology applied these assumptions to a nominal group of 1000 new vehicles of each type.

Sonoma Technology's "ACT EVs" Scenarios reflect all of the assumptions illustrated in this table for the incremental ACT EVs only, and Sonoma Technology's "All EVs" Scenarios count all EVs (ACT or GHG Phase 2) and disregard the assumptions reflected in the far-right column regarding out-of-state migration. No EVs are sold under the requirements of the ACT program in 2025, because ARB's assumptions regarding the fraction of vehicles that will be sold under the GHG Phase 2 program are *higher* than the mandatory sales fraction under the ACT program in that year. This means that no additional EVs need to be sold to meet the ACT requirements.

Table 4. Examples of ARB adjustments for each 1000 new vehicles sold.

Calendar year 2025 (first year of ACT program)	Total new model year vehicles registered	New model year vehicles purchased in-state	EVs sold under either ACT or GHG Phase 2	Incremental EVs due to ACT program only	MY2025 EVs (ACT or GHG Phase 2) remaining in-state after 5 years (in 2030)
Regulatory class 41	1000	1000	130	0	130
Regulatory classes 42 & 46	1000	898	144	0	124
Regulatory class 47	1000	878	140	0	96

Calendar year 2035 (ACT program reaches steady state)	Total new model year vehicles registered	New model year vehicles purchased in-state	EVs sold under either ACT or GHG Phase 2	Incremental EVs due to ACT program only	MY2035 EVs (ACT or GHG Phase 2) remaining in-state after 5 years (in 2040)
Regulatory class 41	1000	1000	550	370	550
Regulatory classes 42 & 46	1000	897	654	475	564
Regulatory class 47	1000	880	421	252	295

Consistent with normal state emissions inventory methodology, Sonoma Technology did not make any adjustments to account for VMT from out-of-state vehicles (i.e., vehicles that travel into a state for work or deliveries, but are domiciled in another state, and vehicles making through trips on major highways where the vehicle trip has neither an origin nor destination in the state). Sonoma Technology has no available data to determine what fraction of the VMT in an individual state is represented by these types of vehicle trips. Therefore, Sonoma Technology's emissions estimates are best viewed as an estimate of the emissions of a state's heavy-duty vehicle *fleet*, and not as an estimate of the total emissions of heavy-duty vehicles within the geographic boundaries of that state.

ARB's spreadsheet provided projections of EV sales by vehicle type, model year, and calendar year. Sonoma Technology mapped California's vehicle types to the MOVES3 model vehicle types (by regulatory class), and then calculated EV percentages by regulatory class. The MOVES3 emissions output by regulatory class for each year were then adjusted using these fractions (i.e., MOVES3 emissions were reduced by the EV fraction, since EVs have no tailpipe emissions), with two exceptions (tire wear and break wear). ARB's emissions inventory methodology report includes an estimate that brake wear emissions from electric trucks are 50% lower than from conventional trucks because of regenerative braking. Sonoma Technology applied this same estimate to the MOVES3 output for brake wear particulate emissions. ARB did not document and Sonoma Technology did not apply any adjustment to particulate matter tire wear emissions. Table 5 summarizes the mapping between the California and MOVES3 vehicle types. ARB did not break out the sales fractions for the T6 trucks into the individual weight classes in that group, so Sonoma Technology applied the T6 fractions to both regulatory classes 42 and 46 in MOVES3.

Table 5. Mapping of ARB ACT program vehicle types to MOVES3 regulatory classes.

MOVES3 Regulatory Class Codes	ARB Vehicle Types
41	Class 2b and 3 Trucks (T4 and T5)
42 and 46	Class 4, 5, 6 and 7 Trucks (T6)
47	Class 8a and 8b Trucks (T7)

Sonoma Technology also developed a methodology for calculating new sales of EVs in the years being evaluated by using CARB's vehicle sales fractions along with the default MOVES3 fraction of new (age 0) vehicles applied to the MOVES3 VPOP estimate in each year. Supplemental projections of EV sales and in-use fractions for years 2026-2029 were developed to better define the initial phase-in during the first five years of the program.

Finally, it is important to note that Sonoma Technology did not make any adjustments to MOVES3 emissions rates to account for the presence of EVs in the heavy-duty fleet. MOVES3 GHG emissions rates assume that manufacturers will comply with the numerical GHG emissions standards in the GHG Phase 2 rule, and these emissions standards are applied on a fleet-average basis. MOVES3 makes no assumptions about the extent to which manufacturers might choose to meet the standard by selling EVs. If a manufacturer did sell some EVs, then the remaining (conventional) vehicles it sold could have emissions higher than the standard, and the manufacturer could still meet the standard on a fleet-average basis. MOVES3 simply assumes that manufacturers meet the standard but does not consider how they do this. Under Sonoma Technology's adjustment approach, we are taking fleetwide emissions from a fleet that meets EPA's GHG standards and that may or may not include some EVs, and then zeroing out the tailpipe emissions from the fraction of that fleet that would be EVs under the ACT program. This could result in some double counting of CO_2 reduction benefits.

However, lacking any information on future deployment of heavy-duty EVs without a sales mandate similar to ACT, the only other alternative would be to assume there will be no reduction in tailpipe CO_2 emissions from heavy-duty EVs, which is clearly not realistic.

The ACT program adjustments are derived in two external spreadsheets named "12 state ACT fleet fractions.xlsx" and "12 state ACT fleet fractions for 2026-2029.xlsx." The Appendix to this report includes tables providing ARB's fleet projection adjustments for all years and vehicle classes.

3.3 CA Low-NO_x Omnibus Rule

As part of its rulemaking process, ARB has developed an emissions inventory document[13] summarizing the NO_x emissions impacts of this program, which affects Scenarios 2 and 4. Tables 6 and 7 of ARB's emissions inventory report provide emissions estimates for the no-regulation baseline Scenario and for two control Scenarios: one in which the ACT program is not being implemented, and one in which the ACT program is in place. Like ARB's fleet projections for the ACT rule, ARB's NO_x projections account for out-of-state vehicle purchases and migration. Sonoma Technology did not develop alternative Scenarios reflecting the absence of out-of-state migration.

These two scenarios match the ICCT Scenarios that ICCT defined, so these "before and after" emissions estimates were used to calculate emissions reduction percentages which were then applied to the MOVES3 NO_x output (ARB Table 6 reductions were used for ICCT Scenario 4, which models the California Low-NO_x Omnibus rule only, and ARB Table 7 reductions were used for ICCT Scenario 2 where both programs are implemented). The program would start in the MOU states one model year later than in California, so Sonoma Technology adjusted the reduction estimates to remove the small incremental emissions reduction from model year 2024 vehicles. ARB's emissions estimates are not provided by vehicle type, so Sonoma Technology applied the calculated reductions equally across all affected vehicle types, under the assumption that the general mix of heavy-duty vehicle classes would be similar in California and the MOU states. Also, the state of New York was interested in expanding this program to cover urban transit buses (these vehicles are covered by other regulations in California, so they are not part of the Low-NO_x Omnibus program), and Sonoma Technology applied the reduction factors to urban buses (regulatory class 48) as well. Sonoma Technology did not apply reductions to Class 3 trucks, even though they are covered in the California program, because emissions for these vehicles cannot be reported separately in the MOVES3 model.

The Low-NO_x Omnibus program adjustments are derived in a spreadsheet named "12 state low NO_x omnibus factors with bus.xlsx" and are also calculated within the post-processing summary spreadsheet for each state.

[13] "Appendix D: Emissions Inventory Methods and Results for the Proposed Amendments," https://ww3.arb.ca.gov/regact/2020/hdomnibuslownox/appd.pdf

3.4 GREET Emissions Calculation

As part of the analysis, Sonoma Technology was asked to estimate the increase in electrical grid emissions due to the increased EV population under the ACT rule. To accomplish this, Sonoma Technology extracted grid electricity emissions factors (in units of tons of grams of emissions per million BTUs of electricity) from the U.S. Department of Energy's GREET model. These rates are provided for different regions of the country, as shown in Figure 2 and Table 6.

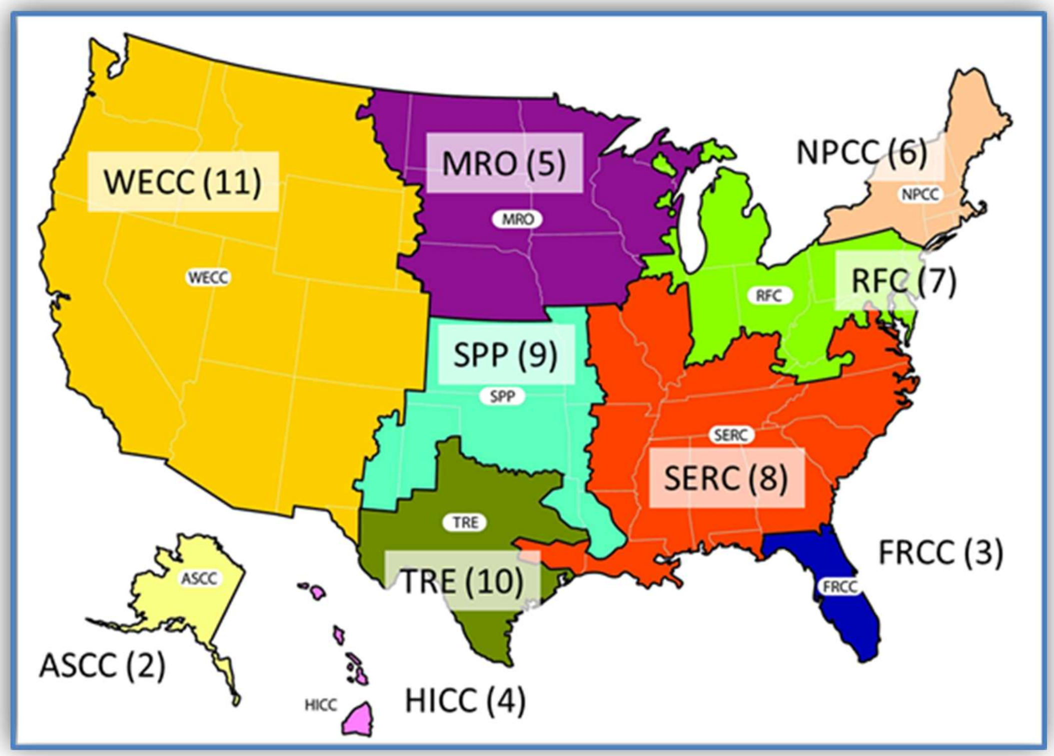

Figure 2. GREET electrical generation regions.

Table 6. GREET electricity emissions factors (grams/million BTU) for transportation end-users.

	NPCC Mix (CT, MA, ME, NY, RI, VT)	RFC Mix (DC, MD, NJ, PA)	SERC Mix (NC)	WECC Mix (CO, OR, WA)
NO_x	19.370	45.157	50.017	39.549
$PM_{2.5}$	2.180	5.985	5.147	3.988
CH_4	3.787	9.491	8.497	6.273
N_2O	0.177	1.510	1.325	0.936
CO_2	51233	106161	94078	68252

In addition, future state renewable energy projections were incorporated into the analyses for Colorado, the District of Columbia, Massachusetts, New Jersey, New York, Oregon, and Washington. Sonoma Technology used these projections to calculate the relative fractions of grid electricity that would be zero-emission in each calendar year, and then applied these fractions to the baseline GREET factors for 2020 to develop emissions rates for future years. (GREET information on the baseline mix of power sources in each region was used with the overall emissions rates above to calculate estimates of emissions rates for the power generated by fossil fuels only, and then these were factored by the state renewable power percentages by year to arrive at weighted rates for each year.)

As part of the MOVES3 modeling, Sonoma Technology generated estimates of total energy consumption by vehicle class, in units of million BTUs. Sonoma Technology then used the EV fleet fractions calculated for the ACT program to determine what portion of that total energy consumption was attributable to EVs, and used the emissions factors described above to estimate the resulting grid emissions. Sonoma Technology also used a GREET-based petroleum well-to-pump factor (reflecting the CO_2 emissions associated with producing and distributing petroleum fuels) to estimate upstream well-to-pump emissions from conventional vehicles in each calendar year. The applicable GREET factors are included in the post-processing spreadsheet for each state.

3.5 Post-Processing Implementation Spreadsheet

Once all the necessary post-processing factors were developed, Sonoma Technology incorporated them into a template spreadsheet, which includes summary worksheets and individual results worksheets for each Scenario, the original MOVES3 output, and the post-processing adjustments. This spreadsheet is designed so that the MOVES3 output by calendar year, regulatory class, and pollutant can be copied into the spreadsheet, and the spreadsheet automatically applies the relevant post-processing factors.

MOVES3 County-scale (2017, 2030, 2040, and 2050) and Default-scale outputs (for all years estimated) are imported into the spreadsheet. The spreadsheet uses the MOVES3 Default-scale output to calculate interpolation trends[14], and interpolated County-scale estimates for 2020, 2025, 2035, and 2045 are generated. These final MOVES3 emissions tables are used in the various Scenario worksheets with the adjustment factors for the different programs to calculate emissions by Scenario for the ACT Scenarios, and EV electricity consumption is used to calculate grid emissions. In the Summary worksheets, the emissions totals for heavy-duty vehicles by year and Scenario are imported, and GREET factors are used to calculated net change in CO_2e. On another worksheet, EV population and sales estimates are calculated, and a separate table includes overall summary tables of emissions, population, and VMT for the heavy-duty fleet. Table 7 describes the contents of each of the worksheets in the post-processing spreadsheet.

Table 7. Contents of Summary Report post-processing spreadsheet.

Worksheet	Description of Contents
Key	Overview of Scenarios, programs evaluated, and information on vehicle types
Tables – ACT EVs	Tables of emissions, VMT, and population by year reflecting EVs sold under the ACT program
Tables – All EVs	Tables of emissions, VMT, and population by year reflecting EVs sold under either the ACT program or the GHG Phase 2 program
Emissions summary - ACT EVs	Emissions summary for all Scenarios; ACT Scenarios only reflect the incremental EVs sold under the ACT program
Emissions summary - All EVs	Emissions summary for all Scenarios; ACT Scenarios reflect all EVs sold under either the ACT program or the GHG Phase 2 program
ACT EV projections	Tables of in-use EV populations and EV sales by year
Scenario 1	Business-as-Usual Scenario
Scenario 2 – ACT EVs	ACT and Low-NO_x Omnibus programs; ACT EVs only
Scenario 2 - All EVs	ACT and Low-NO_x Omnibus programs; All EVs
Scenario 2a – ACT EVs	All CA programs (ACT, Low-NO_x, GHG Phase 2 trailers); ACT EVs only
Scenario 2a – All EVs	All CA programs (ACT, Low-NO_x, GHG Phase 2 trailers); All EVs

[14] The Default results are used to interpolate emissions for 2020 and 2025, when emissions rates are changing rapidly. For emissions in 2035 and 2045, when most federal control programs have been essentially fully implemented, straight-line interpolation is used. Straight-line interpolation is also used for VMT, the pollutants that are only dependent on VMT (brake wear and tire wear), and population.

Worksheet	Description of Contents
Scenario 3	ACT program; ACT EVs only
Scenario 3 - All EVs	ACT program; All EVs
Scenario 4	Low-NO_x Omnibus program only
Scenario 5	Implementation of GHG Phase 2 trailer program in 2025
Combined MOVES output	County-scale MOVES3 output for 2017, 2030, 2040, and 2050; interpolated MOVES3 output for 2020, 2025, 2035, and 2045 (source data for Scenario worksheets)
County-scale output 2017-2050	Imported MOVES3 County-scale output
Default output 2017-2050	Imported MOVES3 Default-scale output
Output interpolation	Factors derived for using MOVES3 default output to interpolate County values for 2020, 2025, 2035, and 2045
New vehicle fractions	MOVES3 default output of population by model year used to derive new model year vehicle fractions (for use in calculating EV sales)
ACT	ACT fleet penetration, sales, and emissions adjustment fractions (derived in a separate spreadsheet)
Low-NO_x	Derivation of Low-NO_x Omnibus program reduction factors
Trailers	GHG Phase 2 trailer emissions adjustments (derived in a separate spreadsheet)
GREET factors	GREET electricity and petroleum production emissions rates used in the ACT Scenarios
Grid data	State renewable energy projections (if provided)
All GREET factors	GREET electricity factors for all 14 areas analyzed as part of the project

4. Results

Emission reductions for the California programs vary by calendar year, program Scenario, and state. Reductions ranged from 1%-53% for NO_x, 3%-23% for $PM_{2.5}$, and 1%-55% for well-to-wheels CO_2e. There are several reasons for differences in emissions trends among these states. First, use of NEI 2017 data as a starting point means that the individual states have different vehicle age distributions (which influence the rate of fleet turnover), and different mixes of VPOP by vehicle class (some states may have more or fewer large heavy-duty vehicles than others). A few states provided state-specific estimates of VMT and VPOP growth, which drive overall emissions levels. For the states that did not, MOVES3 default growth rates were used.

CO_2e emissions are reported on a "well-to-wheels" basis, which includes vehicle exhaust emissions along with the upstream emissions associated with producing and delivering fuel for vehicles (liquid and gaseous fuels for internal combustion vehicles, and/or electricity for electric vehicles). Unlike NO_x and $PM_{2.5}$, greenhouse gases accumulate in the atmosphere over time, and contribute to climate change regardless of where or when they are emitted. Maryland, North Carolina, and Pennsylvania had low net reductions of CO_2e on a well-to-wheels basis compared to the other eleven areas. This is due in large part to the very high CO_2 emissions rates associated with the electrical grid in those states. The CO_2 rates in the GREET RFC and SERC regions, where these states are located, are nearly twice as high as those for the NPCC region (the far northeast states) and the WECC region (which includes Colorado, Oregon, and Washington). Conversely, the analyses for Colorado, the District of Columbia, Massachusetts, New Jersey, New York, Oregon, and Washington reflect future grid power source projections that Sonoma Technology used in place of the default GREET assumptions. Since these areas plan to progressively decarbonize their electrical supply, future electricity will be "cleaner" than that reflected in the calendar year 2020 rates in GREET, and these areas thus have higher net reductions in CO_2e.

Upstream utility emissions were also calculated for NO_x and $PM_{2.5}$. For NO_x, the increase in emissions from electrical generation needed to charge EVs was always smaller than the reduction in tailpipe emissions (0% to 60% of the NO_x emissions reduction), meaning the electrification scenarios still provided a net benefit to NO_x emissions even with electrical generation considered. For $PM_{2.5}$ however, the reduction in vehicle emissions was not usually large enough to offset the increase in utility emissions. In most cases, the increase in utility $PM_{2.5}$ emissions is several times larger than the reduction in vehicle $PM_{2.5}$ emissions. This is partly because brake wear and tire wear emissions are a large source of $PM_{2.5}$, and EVs still have these emissions even when tailpipe $PM_{2.5}$ emissions are eliminated. (By 2040, brake wear and tire wear emissions combined exceed tailpipe emissions in most states.) The exceptions to this outcome were the analyses for areas with renewable energy projections, which result in a much cleaner electrical supply. None of these areas saw the emissions reductions from vehicle electrification offset by increased emissions from electrical generation.

Table 8 provides estimates of both total heavy-duty vehicle population and the number of electric vehicles expected under the ACT and GHG Phase 2 programs. In some cases, the HDV population estimates decline over part of the analysis timeframe. Sonoma Technology used the states' 2017 NEI population estimates as a starting point in developing inputs for the MOVES3 County-scale modeling. They were then projected into the future to create estimates for 2030, 2040, and 2050 using the trend in MOVES3 default population. (The exceptions to this were Massachusetts and New Jersey, which provided us with projections of VPOP by year.) The MOVES3 population inputs are in the form of sourcetype population (the 13 MOVES3 vehicle types), because MOVES3 does not accept inputs by regulatory class. For generating interpolated results in 2020, 2025, 2035, and 2045, Sonoma Technology used straight-line interpolation between the years that were modeled at the County scale.

Since the MOVES3 emissions rates are organized by regulatory class, MOVES3 takes the population inputs by sourcetype and internally converts them to population by regulatory class. While the VPOP totals in Sonoma Technology's MOVES3 inputs and outputs are consistent (within the limits of MOVES3' internal rounding), there are significant shifts among the vehicle types. EPA's MOVES3 technical report on VPOP and activity[15] sheds some light on this. On page 30 of this report, EPA provides projections of population by sourcetype, which Sonoma Technology used to calculate the County input values for future years. EPA is projecting a decline in the population of passenger trucks and light commercial trucks. These categories are dominated by vehicles in regulatory classes 30 and 41. In Sonoma Technology's outputs, there is a large decline in the population of regulatory class 41 vehicles in 2030 relative to 2017, and a small decline in the regulatory class 42 vehicle population. EPA's technical report describes the sources of data for these projections, but it does not provide an explanation of any of the resulting trends.

However, as a result of the trend in default populations, Sonoma Technology's projections of population by regulatory class also show a decline in HDV population, driven almost entirely by the trend in regulatory class 41 vehicle population. The effects vary by state; states with relatively large fractions of sourcetype 31 and 32 vehicles in their 2017 NEI inputs will show the largest decline in total HDV populations, and vice versa.

[15] "Population and Activity of Onroad Vehicles in MOVES3," April 2021. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1011TF8.pdf

Table 8. Projected heavy-duty electrical VPOP and sales.

Colorado

	Total HDV Fleet Pop	ACT EVs	GHG Phase 2 EVs	Total In-Use EVs	New EV Sales
2020	374917	N/A	N/A	N/A	N/A
2025	354271	0	1842	1842	1842
2030	333624	3939	16125	20064	6154
2035	337906	25003	34212	59215	10562
2040	343654	51731	52948	104678	10945
2045	357305	76323	69006	145329	11445
2050	374325	97048	81286	178334	11733

Connecticut

	Total HDV Fleet Pop	ACT EVs	GHG Phase 2 EVs	Total In-Use EVs	New EV Sales
2020	181806	N/A	N/A	N/A	N/A
2025	186488	0	1003	1003	1445
2030	191169	2449	9376	11825	3679
2035	204205	15580	21106	36686	6565
2040	218477	33694	34215	67909	7136
2045	231195	50467	45302	95769	7589
2050	246202	65025	54188	119213	7897

District of Columbia

	Total HDV Fleet Pop	ACT EVs	GHG Phase 2 EVs	Total In-Use EVs	New EV Sales
2020	10646	N/A	N/A	N/A	N/A
2025	10735	0	49	49	72
2030	10824	107	458	565	170
2035	11208	723	974	1697	302
2040	11644	1547	1508	3054	318
2045	12001	2245	1928	4173	327
2050	12463	2813	2242	5056	330

Maryland

	Total HDV Fleet Pop	ACT EVs	GHG Phase 2 EVs	Total In-Use EVs	New EV Sales
2020	317445	N/A	N/A	N/A	N/A
2025	311100	0	1625	1625	2391
2030	304754	3700	14654	18354	5739
2035	319025	23441	32661	56101	10029
2040	335007	49855	52499	102354	10711
2045	352814	74405	69423	143828	11338
2050	373910	95587	82669	178256	11748

Maine

	Total HDV Fleet Pop	ACT EVs	GHG Phase 2 EVs	Total In-Use EVs	New EV Sales
2020	105764	N/A	N/A	N/A	N/A
2025	108427	0	583	583	850
2030	111090	1442	5416	6858	2171
2035	118629	8932	12408	21339	3826
2040	126955	19190	20373	39563	4157
2045	135113	28843	27248	56091	4443
2050	144564	37263	32766	70029	4642

Massachusetts

	Total HDV Fleet Pop	ACT EVs	GHG Phase 2 EVs	Total In-Use EVs	New EV Sales
2020	260286	N/A	N/A	N/A	N/A
2025	301252	0	1525	1525	2269
2030	322514	3557	15549	19106	5653
2035	329525	24373	31990	56362	9994
2040	337427	51742	48075	99817	10391
2045	341875	74741	59972	134713	10547
2050	349835	93440	68432	161872	10529

New Jersey

	Total HDV Fleet Pop	ACT EVs	GHG Phase 2 EVs	Total In-Use EVs	New EV Sales
2020	357886	N/A	N/A	N/A	N/A
2025	363439	0	1916	1916	2832
2030	385543	4765	18495	23261	7348
2035	408129	29949	42108	72057	12904
2040	430716	63690	68343	132034	13837
2045	453302	94898	90039	184936	14598
2050	475889	120485	105882	226367	14940

New York

	Total HDV Fleet Pop	ACT EVs	GHG Phase 2 EVs	Total In-Use EVs	New EV Sales
2020	630858	N/A	N/A	N/A	N/A
2025	670603	0	3589	3589	5166
2030	710349	9039	34505	43543	13551
2035	756331	57310	77684	134994	24174
2040	802313	122539	125403	247942	26086
2045	848295	183316	165531	348847	27672
2050	894277	233459	195698	429157	28456

North Carolina

	Total HDV Fleet Pop	ACT EVs	GHG Phase 2 EVs	Total In-Use EVs	New EV Sales
2020	521848	N/A	N/A	N/A	N/A
2025	512320	0	2642	2642	3918
2030	501328	6114	23729	29843	9450
2035	521541	37356	52966	90322	16169
2040	544680	78131	85110	163241	17075
2045	570097	115287	112089	227376	17898
2050	600366	146490	132613	279102	18375

Oregon

	Total HDV Fleet Pop	ACT EVs	GHG Phase 2 EVs	Total In-Use EVs	New EV Sales
2020	460715	N/A	N/A	N/A	N/A
2025	454017	0	2440	2440	3566
2030	447319	5884	21760	27643	8830
2035	456737	34176	48336	82512	14825
2040	469406	69606	77710	147316	15498
2045	502236	105229	104719	209948	16652
2050	539523	136500	126204	262704	17470

Pennsylvania					
	Total HDV Fleet Pop	ACT EVs	GHG Phase 2 EVs	Total In-Use EVs	New EV Sales
2020	803348	N/A	N/A	N/A	N/A
2025	814160	0	4301	4301	6332
2030	823804	10644	39295	49939	16065
2035	873923	63716	90791	154508	27749
2040	930131	134887	149865	284752	29900
2045	991149	202968	200945	403913	31963
2050	1060868	262334	241209	503544	33389

Rhode Island					
	Total HDV Fleet Pop	ACT EVs	GHG Phase 2 EVs	Total In-Use EVs	New EV Sales
2020	49129	N/A	N/A	N/A	N/A
2025	49394	0	262	262	385
2030	49659	626	2403	3029	957
2035	52770	3909	5476	9385	1681
2040	56193	8378	8951	17329	1816
2045	59400	12542	11891	24434	1929
2050	63149	16149	14201	30349	2005

Vermont					
	Total HDV Fleet Pop	ACT EVs	GHG Phase 2 EVs	Total In-Use EVs	New EV Sales
2020	36785	N/A	N/A	N/A	N/A
2025	37674	0	197	197	289
2030	38562	472	1843	2315	725
2035	40403	2969	4113	7081	1267
2040	42467	6310	6613	12923	1355
2045	44494	9349	8700	18049	1426
2050	46935	11926	10319	22245	1470

Washington					
	Total HDV Fleet Pop	ACT EVs	GHG Phase 2 EVs	Total In-Use EVs	New EV Sales
2020	638472	N/A	N/A	N/A	N/A
2025	626354	0	3410	3410	4874
2030	614236	8169	30310	38479	12078
2035	633995	48928	66740	115668	20756
2040	658155	101461	106690	208151	21952
2045	703831	153326	143018	296344	23581
2050	756325	198908	172423	371330	24747

5. Appendix

Table A-1. ARB EV Sales Projections, Percentage of New Vehicle Sales.

	ARB Vehicle Types T4 and T5		ARB Vehicle Type T6 - Heavy Tractor		ARB Vehicle Type T6 - Non-Tractor and T6 - Small		ARB Vehicle Type T7 - Tractor		ARB Vehicle Type T7 - Non-Tractor	
Model Year	Mandated ACT Sales	Percentage Assumed For GHG Phase 2	Mandated ACT Sales	Percentage Assumed For GHG Phase 2	Mandated ACT Sales	Percentage Assumed For GHG Phase 2	Mandated ACT Sales	Percentage Assumed For GHG Phase 2	Mandated ACT Sales	Percentage Assumed For GHG Phase 2
2024	5%	10%	5%	16%	9%	16%	5%	16%	9%	16%
2025	7%	13%	7%	16%	11%	16%	7%	16%	11%	16%
2026	10%	15%	10%	16%	13%	16%	10%	16%	13%	16%
2027	15%	18%	15%	19%	20%	20%	15%	19%	20%	20%
2028	20%	18%	20%	19%	30%	20%	20%	19%	30%	20%
2029	25%	18%	25%	19%	40%	20%	25%	19%	40%	20%
2030	30%	18%	30%	19%	50%	20%	30%	19%	50%	20%
2031	35%	18%	35%	19%	55%	20%	35%	19%	55%	20%
2032	40%	18%	40%	19%	60%	20%	40%	19%	60%	20%
2033	45%	18%	40%	19%	65%	20%	40%	19%	65%	20%
2034	50%	18%	40%	19%	70%	20%	40%	19%	70%	20%
2035+	55%	18%	40%	19%	75%	20%	40%	19%	75%	20%

Table A-2. ARB Fleet Assumptions – In-State Sales and Out-of-State Migration, Percentage of All Vehicles.

	ARB Vehicle Types T4 and T5		ARB Vehicle Type T6 - Heavy Tractor		ARB Vehicle Type T6 - Heavy Non-Tractor		ARB Vehicle Type T6 - Small		ARB Vehicle Type T7 - Tractor		ARB Vehicle Type T7 - Non-Tractor	
Vehicle Age (Years)	First Sold in CA	Remaining in CA	First Sold in CA	Remaining in CA	First Sold in CA	Remaining in CA	First Sold in CA	Remaining in CA	First Sold in CA	Remaining in CA	First Sold in CA	Remaining in CA
New (0)	100%		84%		85%		91%		87%		90%	
1		100%		82%		80%		88%		79%		86%
2		100%		77%		76%		86%		69%		82%
3		100%		70%		73%		83%		57%		78%
4		100%		62%		70%		81%		46%		76%
5		100%		55%		68%		79%		38%		74%
6		100%		50%		67%		78%		34%		74%
7+		100%		48%		67%		77%		34%		74%