# Overview of EPA's MOtor Vehicle Emission Simulator (MOVES5)

United States Environmental Protection Agency

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Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

*NOTICE*

*This technical report does not necessarily represent final EPA decisions or positions. It is intended to present technical analysis of issues using data that are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments.*

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# 1. Introduction

EPA's MOtor Vehicle Emission Simulator (MOVES) is a state-of-the-science emissions modeling system that estimates air pollution emissions for criteria air pollutants, greenhouse gases and air toxics. MOVES covers onroad vehicles such as cars, trucks, and buses, and nonroad equipment such as bulldozers and lawnmowers. MOVES does not cover aircraft, locomotives, or commercial marine vessels. MOVES accounts for the phase-in of federal emissions standards, vehicle and equipment activity, fuels, temperatures, humidity, and emission control activities such as inspection and maintenance (I/M) programs.

MOVES models calendar year 1990 and 1999 through 2060. Emissions from onroad and nonroad sources can be modeled at the national or county scale using either model defaults or user-supplied inputs. Emissions from onroad sources can also be modeled at a more detailed "project" scale if the user supplies detailed inputs describing project parameters. The onroad module uses operating mode-specific emission rates to create a consistent approach across all three scales.

MOVES is a bottom-up emissions model that is designed to estimate emissions from separate physical emission processes depending on the source. MOVES models "fleet average" emissions, rather than emissions from individual vehicles or equipment types. And MOVES adjusts emission rates to represent real-world conditions.

This document provides a high-level overview of MOVES5, the latest official public version of the MOVES model. The model and supporting materials are available for free download on the EPA MOVES website, https://www.epa.gov/moves.

## 1.1 MOVES Scope

The functional scope of MOVES5 is detailed in Table 1-1 below.

*Table 1-1 MOVES Scope*

| | Onroad | Nonroad |
|---|---|---|
| Geographic Scope | U.S. including Puerto Rico and U.S. Virgin Islands with option to aggregate to county, state or nation[a] | Same |
| Scale | Default (national), county or project | National allocated to state and county |
| Mode | Inventory (grams) or Rates (grams per activity) | Inventory (although rates can be generated with integrated post-processing scripts) |

[a]Note, California uses the California Air Resources Board EMFAC and nonroad models for regulatory purposes.

| | Onroad | Nonroad |
|---|---|---|
| Time Span | MOVES estimates hourly emissions for weekdays and weekends by month and year for calendar years 1990 and 1999 through 2060, with options to run at more aggregate levels - day, month or year. | MOVES estimates daily emissions for weekdays and weekends by month and year for calendar years 1990 and 1999 through 2060. |
| Vehicles and Equipment | MOVES covers all highway vehicles, divided into 13 source use types (source types): motorcycles, passenger cars, passenger trucks, light commercial trucks, other buses, transit buses, school buses, refuse trucks, single-unit short-haul trucks, single-unit long-haul trucks, motorhomes, short-haul combination trucks and long-haul combination trucks. | MOVES covers nonroad equipment in 12 broad economic sectors: construction, agriculture, industrial, lawn & garden (commercial and residential), commercial, logging, railroad support (excluding locomotives), recreational vehicles, recreational marine (pleasure craft; excluding commercial marine vessels), airport service (excluding aircraft), oil field, and underground mining. |
| Regulatory Classes | MOVES covers all onroad regulatory classes (groups of vehicles with similar emission standards) ranging from motorcycles to heavy heavy-duty vehicles. | Most nonroad equipment is classified by horsepower bin and engine type—compression ignition (CI), 2-stroke spark ignition (SI) and 4-stroke SI. Small SI equipment is further classified by engine use (handheld and non-handheld) and engine displacement. |
| Fuels | MOVES models emissions from onroad vehicles using gasoline,[b] diesel, compressed natural gas (CNG), electricity[c] and ethanol (E85). Fuels are further characterized by fuel subtype and fuel formulation.[1,2] | MOVES models emissions from nonroad equipment using gasoline,[d] nonroad diesel, marine diesel, CNG, and liquid propane gas (LPG). MOVES does not model nonroad equipment powered by electricity. Fuels are further characterized by fuel subtype and fuel formulation.[3] |
| Road Type | MOVES models onroad vehicles on rural and urban restricted access and unrestricted access roads. MOVES also models vehicle emissions associated with non-driving operation as "off-network." | MOVES assigns nonroad emissions to the "nonroad" road type. |

[b] Including ethanol/gasoline blends of up to 15% ethanol.

[c] Electric vehicles modelled in MOVES include those powered by batteries and by fuel cells.

[d] Including ethanol/gasoline blends of up to 10% ethanol.

| | Onroad | Nonroad |
|---|---|---|
| Pollutants and Energy Outputs[e] | MOVES models a long list of criteria pollutants and their precursor emissions,[f] air toxics,[4] greenhouse gases, and energy use for onroad vehicles. These include total hydrocarbons (THC), volatile organic compounds (VOC), carbon monoxide (CO), nitrogen oxides ($NO_X$), particulate matter[g] ($PM_{2.5}$ & $PM_{10}$), elemental carbon (EC)[h], carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), sulfur dioxide ($SO_2$), ammonia, benzene, ethanol, 1,3 butadiene, formaldehyde, acetaldehyde, acrolein, polycyclic aromatic hydrocarbons, metals, dioxins, and furans. Organic gas emissions can be output in various aggregations (e.g., total organic gases and volatile organic compounds), but "chemical mechanism species" must be generated in post-processing. | MOVES models many criteria pollutants and precursors, air toxics and greenhouse gases, as well as energy use for nonroad equipment. These include fuel consumption, THC, VOC, CO, $NO_X$, $PM_{2.5}$, $PM_{10}$, $CO_2$, $CH_4$, $SO_2$, ammonia, benzene, ethanol, 1,3 butadiene, formaldehyde, acetaldehyde, acrolein, polycyclic aromatic hydrocarbons, metals, dioxins. and furans. Organic gas emissions can be output in various aggregations (e.g., total organic gases and volatile organic compounds), but "chemical mechanism species" and PM species such as elemental carbon from nonroad equipment must be generated in post-processing. Note, MOVES does not model $N_2O$ for nonroad equipment. |
| Emission Processes | MOVES calculates emissions for running, start, extended idle (e.g., heavy-duty truck hotelling), brake wear, tire wear, evaporative permeation, evaporative fuel vapor venting, evaporative fuel leaks, crankcase venting, and refueling vapor and spillage.[i] | MOVES calculates emissions from running exhaust, crankcase venting, refueling vapor and spillage, evaporative tank permeation, evaporative hose permeation, and fuel vapor venting from diurnal, hot soak and running activity. |

[e] A full list of MOVES pollutants is available in the MOVES "Cheat Sheets" found at https://github.com/USEPA/EPA_MOVES_Model/blob/master/docs

[f] The Clean Air Act identifies six criteria pollutants: ground-level ozone, particulate matter, carbon monoxide, lead, sulfur dioxide, and nitrogen dioxide.

[g] $PM_{2.5}$ refers to fine inhalable particles, with diameters that are generally 2.5 micrometers and smaller. $PM_{10}$ describes inhalable particles, with diameters that are generally 10 micrometers and smaller.

[h] While not exactly equivalent, elemental carbon is often used as a surrogate for black carbon in GHG estimates.

[i] MOVES does not include the capability to estimate emissions of re-entrained road dust. To estimate emissions from re-entrained road dust, practitioners should continue to use the latest approved methodologies.

| | Onroad | Nonroad |
|---|---|---|
| Activity Outputs | MOVES can output distance travelled, source hours, source hours operating, source hours parked, vehicle population, starts**,** extended idle hours, hotelling diesel auxiliary hours, hotelling battery or plug-in hours, and hours spent hotelling with all engines off. | MOVES can output equipment source hours, equipment population, average horsepower, and load factors. |

MOVES is intended to model the impact of regulatory standards on fleet-wide emissions. MOVES5 incorporates the regulations listed in Table 1-2 as well as many earlier regulations as explained in the MOVES technical reports.

*Table 1-2 Recent Mobile Source Regulations Covered by MOVES*

| | |
|---|---|
| **National Onroad Rules:** *All onroad control programs finalized as of the date of the MOVES5.0.0 release, including most recently:* | Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles (LMDV), March 2024 |
| | Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles – Phase 3 (HDP3), March 2024 |
| | Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards, January 2023 |
| | Revised 2023 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions Standards, December 2021 |
| | Safer Affordable Fuel Efficient (SAFE) Vehicles Rule: March 2020 |
| | Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles—Phase 2: October, 2016 |
| | Tier-3 Vehicle Emissions and Fuel Standards Program: March, 2014 |
| | 2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards: October, 2012 |
| | Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles: September, 2011 |
| | Regulation of Fuels and Fuel Additives: Modifications to Renewable Fuel Standard Program (RFS2): December, 2010 |
| **National Nonroad Rules:** *All nonroad control programs finalized as of the date of the MOVES4.0.0 release, including most recently:* | Emissions Standards for New Nonroad Spark-Ignition Engines, Equipment, and Vessels: October, 2008 |
| | Growth and control from Locomotives and Marine Compression-Ignition Engines Less than 30 Liters per Cylinder: March, 2008 |
| | Clean Air Nonroad Diesel Final Rule – Tier 4: May, 2004 |

| | |
|---|---|
| **Ozone Transport Commission (OTC) "National Low Emissions Vehicle" (NLEV) Program and California Regulations Adopted Under Clean Air Act Section 177** *These programs are not incorporated in MOVES defaults, but may be modelled by running MOVES input tools* | California Advanced Clean Trucks Rule[j] |
| | California Advanced Clean Car I Low Emissions Vehicle (LEV) Program |
| | OTC NLEV Program |
| | California Advanced Clean Car I Zero Emission Vehicle (ZEV) Program |
| **State and Local Programs:**[k] | Inspection and maintenance programs |
| | Fuel programs (also affect gasoline nonroad equipment) |
| | Stage II refueling control programs |

## 1.2 MOVES Versions

EPA's official public versions of MOVES are characterized as "major" releases when they include substantial changes to onroad criteria pollutant emissions. "Minor" releases include no substantial changes to onroad criteria emissions – for example, they may include updates to the user interface, changes to toxic or GHG emissions, or updates to nonroad emission rates.

EPA may also develop internal versions of the model for regulatory and analytic support. These versions typically lack some features required for a public release, but they are made available in relevant rulemaking dockets and their updates are generally incorporated into the next official public version.

Table 1-3 summarizes the public release history of MOVES.[l]

As of this writing, EPA provides support for MOVES versions 3.1 and later. The current list of supported MOVES versions is available at https://github.com/USEPA/EPA_MOVES_Model?tab=security-ov-file. We will provide security updates for these versions as needed.

[j] As explained in the Vehicle Population and Activity report, the ACT rule was also considered when estimating national default EV fractions for HD vehicles.

[k] As explained in the Technical Guidance, states and local areas should check and update default values for all local programs.

[l] MOVES was preceded by EPA's MOBILE and NONROAD series of models. Beginning in 1978, MOBILE estimated onroad emissions in gram per mile. Beginning in 1998, NONROAD estimated emissions for nonroad sources.

*Table 1-3: MOVES Version History*

| Public Releases | Release Date | Key Features |
|---|---|---|
| MOVES2010 | 2010 | • Onroad only<br>• Designed to model at project, county, and national scales |
| MOVES2010a | 2010 | • Modeled 2012+ LD GHG rule |
| MOVES2010b | 2012 | • Performance improvements<br>• Improved vapor venting calculations |
| MOVES2014 | 2014 | • Modeled Tier 3 and 2017+ LD GHG rules<br>• Updated gasoline fuel effects<br>• Improved evaporative emissions and air toxics<br>• Updated onroad activity, vehicle populations and fuels<br>• Incorporated NONROAD model |
| MOVES2014a | 2015 | • Added nonroad VOC and toxics<br>• Updated default nonroad fuels<br>• Added new options for user vehicle miles travelled (VMT) input |
| MOVES2014b | 2018 | • Improved emission estimates for nonroad mobile sources<br>• Updated outputs used in air quality modeling |
| MOVES3 | 2020 | • Updated onroad exhaust emission rates, including HD GHG Phase 2 and Safer Affordable Fuel Efficiency (SAFE) rules<br>• Updated onroad activity, vehicle populations and fuels<br>• Added gliders and off-network idle<br>• Revised inputs for hotelling and starts |
| MOVES3.0.1-MOVES3.0.4 | 2021-2022 | • Updated as detailed in the MOVES3 Update Log. |
| MOVES3.1 | 2022 | • Added an I/M benefit for Class 2b and 3 gasoline trucks with a gross vehicle weight rating between 8,500 and 14,000 pounds. |
| MOVES4 | 2023 | • Accounted for heavy-duty low NOx rule for model years 2027 and later and the light-duty greenhouse gas rule for model years 2023 and later<br>• Improved the modeling of light-duty electric vehicles and added heavy-duty battery-electric and fuel-cell vehicles, and CNG long-haul combination trucks<br>• Updated vehicle populations, fuel supply, travel activity, and emission rates |
| MOVES4.0.1 | 2024 | • Improved interface and repaired minor errors as detailed in the MOVES4 Update Log |
| MOVES5[m] | 2024 | • Updates as explained in Section 2 |

## 1.3 MOVES Uses

MOVES is used by the U.S. EPA to estimate emission impacts of mobile source regulations and policies, to generate inputs for other EPA tools, and to generate mobile sector information for national inventories of air pollutants such as the National Emissions Inventory and AirToxScreen.

U.S. state and local agencies outside of California use MOVES to develop emission inventories for a variety of regulatory purposes, including the development of state implementation plans (SIPs), transportation conformity determinations, general conformity determinations, and analyses required under the National Environmental Policy Act (NEPA), among others.[5] EPA provides training[6] and technical guidance on using MOVES for SIP and conformity modeling,[7] PM hot-spot analyses,[8] and CO hot-spot analyses,[9] including information on how to choose appropriate model inputs. MOVES is also used for state and local greenhouse gas emission planning.[10]

Others, including academics and interest groups, may also use MOVES to model the effects of policy choices and various mobile source scenarios.

When determining if MOVES is appropriate for a given use, modelers should be aware of both EPA guidance[5,7,10] and the limitations discussed in Section 8 below. Also see "Is MOVES the best tool for my work?" for suggestions of other resources that may be appropriate when estimating U.S. mobile source emissions for non-regulatory purposes.[11]

[m] If additional updates are made to MOVES, they will be documented in an update log available as a link from the MOVES page, https://www.epa.gov/moves/latest-version-motor-vehicle-emission-simulator-moves.

# 2. Updates for MOVES5

Updates to MOVES5 are detailed in the MOVES5 technical reports for onroad. The most important changes between MOVES4 and MOVES5 are summarized here. The only change made for nonroad was a change to fuel properties.[1]

## 2.1 New Regulations

MOVES5 accounts for EPA's *Light- and Medium-Duty Multi-Pollutant Rule*[12] (LMDV) with higher projected electric vehicle (EV) fractions and more stringent standards for carbon dioxide ($CO_2$), particulate matter (PM), non-methane organic gases (NMOG) and oxides of nitrogen ($NO_X$).

*MOVES5 also accounts for EPA's Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles—Phase 3[i] (HDP3*) with higher projected fractions for zero emission vehicles and updated energy consumption estimates for heavy-duty vehicles (both ICE and ZEV).[13]

## 2.2 New Features

We have expanded detailed calculations for a given analysis year to vehicles up to 40 years old, instead of 30. MOVES4 and earlier MOVES versions account for only 31 model years in any individual calendar year analysis (vehicle ages 0 through 30+). Vehicles older than 30 years are assigned characteristics of age 30 vehicles in these models.

MOVES5 has been updated to account for 41 model years (vehicle ages 0 through 40+). Adding model years better quantifies emissions from vehicles in the 31-40 age range and allows better modeling of vehicles without onboard diagnostic systems (OBD) and pre-OBD inspection and maintenance programs. Vehicles older than 40 years are modelled as 40-year-old vehicles, but the number of vehicles in this group, and their VMT, is much smaller. Because this change may lead to longer run-times, we provide improved guidance on constructing faster MOVES runs.[7]

## 2.3 Updates to Emission Rates

MOVES5 incorporates new data on brake wear from light- and heavy-duty vehicles[14] and new data on ammonia emissions from CNG vehicles.[15]

MOVES5 also updates future-year base emission rates[16] and fleet-averaging adjustments[17] for light- and medium-duty internal combustion engine $CO_2$, PM, hydrocarbons, and $NO_x$ associated with the more stringent standards under the LMDV.

For a more complete list, see Table 2-1.

## 2.4 Updates to Fuel Characteristics, Vehicle Populations and Activity

The gasoline fuel supply has been updated using data from an expanded nationwide retail survey program that was implemented following the 2020 Fuels Regulatory Streamlining rule. This program collects approximately 5,000 retail samples throughout the year distributed across the states proportional to their share of national gasoline sales, and within each state accounting for population density and transportation corridors. Starting with calendar year 2021, all the regional gasoline fuel properties have been redeveloped in MOVES5 based on this retail survey data, which has the benefit of more accurately representing fuel properties at the point of use. These new data indicate that sulfur levels are generally higher than in MOVES4, summer RVP values are generally lower, and winter RVP

values are generally higher. MOVES5 also accounts for recent changes to Reformulated Gasoline programs in Colorado and Maine, increased default E85 usage, updated default biodiesel blend levels, and reduced sulfur levels for marine diesel fuel.[1] MOVES5 does not change our modeling of how different fuel parameters affect emissions.[2]

Updates to national VMT and vehicle population inputs were based on newer historical data from the Federal Highway Administration (FHWA) and updated forecasts from the Department of Energy. Updates to national default source type, fuel type, regulatory class, and age distributions were based on newer vehicle registration data, as well as the EV sales forecasts mentioned in Section 2.2.[18]

For a more complete list, see Table 2-1.

*Table 2-1: Algorithm and Data Updates for MOVES5 and Emission Implications*

| Area | Description of Change and Emission Implications |
|---|---|
| Energy Consumption Rates | Updated LD and HD energy consumption rates based on recent data and new $CO_2$ emission standards.[13] [15] Account for fleet average emissions standards.[17] These changes lead to significant declines in future year $CO_2$. |
| Electric Vehicle Fractions | Updated LD and HD ZEV fractions based on recent data and projections that account for new EPA emission standards.[18] These lead to substantial reductions in exhaust and evaporative pollution after about 2040 |
| Brake Wear PM Rates | • Updated LD and HD brake wear emission rates for MY 2011 and later based on new test data. In general, the new PM2.5 brake wear rates are lower for light- and medium-duty vehicles, light-heavy-duty vehicles, and urban buses, but they are higher for other heavy-vehicle classes, most notably for heavy-heavy-duty vehicles.<br>• Account for regenerative braking in electric vehicles.<br>• Account for light-duty vehicle mass by fuel type.<br>• Particle size data allowed us to update the brake wear PM10/PM2.5 ratios in MOVES. The new data imply lower PM10 emission rates for all vehicle classes.[14][14] |
| Exhaust PM Rates | Updated LD exhaust PM rates that account for new PM standards. The lower PM rates for gasoline vehicles phase-in beginning in MY 2027.[16] |
| Exhaust HC and NOx Rates | Updated start and running rates and adjustments for LD and 2b3 vehicles to account for new emission standards[16] and new fleet averaging provisions.[17] The lower rates phase-in beginning in MY 2027. |
| Start HC, CO, and NOx Rates | Updated rates for LD start emissions to account for new emission standards.[16] The lower rates phase-in beginning in MY 2027. |
| Exhaust Ammonia Rates | Updated ammonia emission rates for all CNG vehicles based on new data.[15] The new rates are lower for MY 2009-and-earlier and higher for MY 2010-and-later. |

| Area | Description of Change and Emission Implications |
|---|---|
| Age Coverage | Extended MOVES onroad algorithm to allow detailed accounting for ages 0-40 vehicles, as compared to ages 0-30 in previous version. The improved modeling of older vehicles leads to increased emissions for most pollutants through about 2040. |
| Fuel Characteristics | Updated default fuel characteristics. New surveys of retail gasoline indicate that sulfur levels are generally higher than predicted in MOVES4, summer RVP values are generally lower, and winter RVP values are generally higher. Gasoline properties were updated to account for changes to Reformulated Gasoline programs in Maine and Colorado. The national average biodiesel blend level was updated from 3.6 to 3.5 percent. Marine diesel sulfur levels were updated. [1] |
| Default Vehicle Populations and Activity | Updated historical and forecast default VMT; vehicle populations; vehicle mix by source type, regulatory class, and fuel type; and age distributions.[18] This change generally increases emissions. No diesel passenger cars after MY 2019. |
| Inspection Maintenance Program Coverage | Updated descriptions of county-specific I/M programs based on new information received from states.[17] |
| Refueling HC Emissions | Updated to reflect end of Stage II refueling control programs in some states.[22] |
| $CO_2$ Equivalent Emissions | Updated Global Warming Potential (GWP) values used to convert $N_2O$ and $CH_4$ to $CO_2$ equivalent.[13] Additionally, MOVES now requires $CO_2$, $CH_4$, and $N_2O$ to be included in a run when $CO_2$ equivalent is requested. |
| Exhaust HC, $NO_x$, and $CO_2$. | Improved modeling of medium-duty truck fleet averaging provisions for vehicles subject to the Tier 3 and HD GHG Phase 2 rules.[17] |
| LD HC, CO, $NO_x$ and PM | Updated modeling of LEV III for Section 177 states. |

| Area | Description of Change and Emission Implications |
|---|---|
| Other Minor Fixes | We repaired problems including:<br>• an error in extended idle PM rates for gliders<br>• missing PM emissions for CNG long-haul combination trucks<br>• an issue when aggregating over dayID when using the summary reporter<br>• a problem when importing user-supplied start activity for only one day type<br>• an issue with reporting the correct units when using the EmissionRates.sql post-processing script<br>• an error in summary reporter when selecting certain pollutants<br>• a problem with starts when pre-aggregating emissions at default scale<br>• missing pollutants when running Project Scale with a linkID 0<br>• an error in EV energy rate adjustments for temperature and air conditioning at project scale |

### 2.5 Updates to User Interface and User Inputs

The MOVES5 interface is very similar to MOVES4. Users will see minor changes to the screens of the graphical user interface (GUI), but Run Specifications (RunSpecs) created with MOVES4 should work with MOVES5.[n]

Updates to MOVES databases and calculations mean that user input databases created for previous versions of MOVES will not work directly with MOVES5. Specifically, all user input tables that include vehicle age or cover all model years have changed because MOVES5 covers ages 0-40 and model years 1950-2060. For input databases that still contain the latest data, MOVES5 includes conversion tools and detailed instructions to update MOVES3 and MOVES4 input databases to work with MOVES5.

In addition, we have improved the AVFT Tool to make it easier to develop user input fuel type distributions (including electric vehicle fractions). We also provide updated versions of the following external tools:

- Age Distribution Projection Tool
- AADVMT Converter Tool

Additional information on changing to MOVES5 from older versions is included in the MOVES5 Technical Guidance[7] and the MOVES5 code documentation at https://github.com/USEPA/EPA_MOVES_Model.

[n] The only exception to this is if a MOVES4 RunSpec includes $CO_2$ equivalent and one or two (but not all) of $CO_2$, $CH_4$, or $N_2O$. Since MOVES5 requires all three to be selected to run $CO_2$ equivalent, opening such a RunSpec in the MOVES GUI will show a red X on the Pollutants and Processes panel. This issue can be resolved by clicking the "Select Prerequisites" button and saving the RunSpec.

Inputs for nonroad runs have not changed. Nonroad RunSpecs developed for MOVES4 should generally work with MOVES5.

The most important interface and user input changes are summarized in Table 2-2.

*Table 2-2: Changes in MOVES interface from MOVES4 to MOVES5*

| Description | | Notes |
|---|---|---|
| *RunSpec Selections* | | |
| | Onroad Vehicles Panel | Source type IDs are now included in the source type description. |
| | Road Type Panel | The Road Type Panel now appears after the Pollutants and Processes Panel.<br>• In Default Scale and County Scale, the selections on this panel will be made for you automatically based on your selections on the Pollutants and Processes Panel.<br>• In Project Scale, all on-network road types will be automatically selected for you if you select a running process. However, not all road types are necessary in Project Scale, and you may delete unnecessary types if applicable. |
| *User Tools* | | |
| | AVFT Tool | • Replaced the "fill with 0s" gap-filling option with "automatic". This option fills missing values with 0s if possible. However, if a model year is entirely missing from the input data, this method fills with default values instead.<br>• Added the "use defaults, preserve inputs" gap-filling option, which could be useful if you have inputs for only one fuel type, for example.<br>• Gap-filling is run back to model year 1950, allowing easier use of the outputs with multiple analysis years.<br>• Improved error checking and handling. |
| | Age Distribution Projection Tool | • Added an option to automatically insert default age distributions for long-haul source types.<br>• Requires input age distributions to cover ages 0-40. |
| | User input DB Converters | Conversion scripts for databases created with MOVES3 and MOVES4. |
| *User Input Tables* | | |
| | HotellingActivityDistribution | If this optional table is included in a user input database, it must cover all model years 1950-2060, whereas previous versions only covered 1960-2060. The database conversion tools can update the data in this table from MOVES3 or MOVES4 databases for use with MOVES5. |
| | HotellingAgeFraction | If this optional table is included in a user input database, it must cover all ages 0-40, whereas previous versions only covered 0-30. The database conversion tools cannot update the data in this table from older databases for use with MOVES5. |

| Description | | Notes |
|---|---|---|
| | IdleModelYearGrouping | If this optional table is included in a user input database, it must cover all model years 1950-2060. The database conversion tools can update the data in this table from MOVES3 or MOVES4 databases for use with MOVES5. |
| | SourceTypeAgeDistribution | This required table in County Scale and Project Scale input databases must cover all ages 0-40. The database conversion tools can update the data in this table from MOVES3 or MOVES4 databases for use with MOVES5. |
| | Starts<br>StartsAgeAdjustment<br>StartsOpModeDistribution | If these optional tables are included in a user input database, it must cover all ages 0-40. The database conversion tools cannot update the data in this table from older databases for use with MOVES5. |
| | TotalIdleFraction | If this optional table is included in a user input database, it must cover all model years 1950-2060. The database conversion tools can update the data in this table from MOVES3 or MOVES4 databases for use with MOVES5. |
| *Output Changes* | | |
| | Output Databases | MOVES includes no diesel passenger cars after MY 2019, so these rows no longer appear in correlated MOVES output. |
| *Changes in GUI* | | |
| | AVFT Tool | • Source types can be included/excluded from the AVFT Tool output by checking a box.<br>• Clicking "Create Template" for the Known Fractions input file now provides a dialog for you to select the source type / fuel type combinations for which you have known fractions. |
| | Data Manager | • Improved the description of the user option for automatically assigning worksheets to MOVES input tables<br>• Added the "Export Defaults" button to the Hotelling tab for Project Scale |
| | Miscellaneous | • GUI windows now include the MOVES version in their titles<br>• Improved description of the sources covered by the Nonroad model |
| *Software Changes* | | |
| | Version updates | MOVES5 is distributed with updated versions of MariaDB, Go, Java, and Ant. |
| *Command Line Changes* | | |
| | AVFT Tool | The AVFT Tool is now available for use on the command line using the ant avftTool command. |
| *Default Database Schema* | | |
| | Added new tables | • FleetAvgGroup: describes the fleetAvgGroupID field<br>• FleetAvgAdjustment: adjusts ICE emission rates based on EV sales where fleet averaging is allowed |
| | Removed tables | • EVPopIceAdjustLD: this table has been replaced by the new FleetAvgAdjustment table. |

| Description | | Notes |
|---|---|---|
| | Changed schema for existing tables | • All tables now use UTF-8 encoding, which supports international use of MOVES as well as changes in Java libraries used by MOVES.<br>• RegulatoryClass: added the column fleetAvgGroupID.<br>• TemperatureAdjustment: added the column regClassID. |

# 3. MOVES Onroad Algorithms

The way MOVES calculates emissions varies depending on the processes and pollutants being modeled, and the vehicle or equipment type. This section provides a brief general overview of the algorithms used to model emissions from cars, trucks and other onroad sources. The MOVES onroad technical reports, available at https://www.epa.gov/moves/moves-onroad-technical-reports, provide detailed information on algorithms and default inputs for all onroad source types and pollutant process combinations.

For all onroad processes, the emissions of detailed organic gas and PM species are calculated by applying appropriate speciation factors.[19]

For electric vehicles, the only relevant processes in MOVES are brake wear and tire wear, as well as running and hotelling (for energy consumption).

## 3.1 Running Exhaust and Energy

Running emissions are the archetypal mobile source emissions—exhaust emissions from a running vehicle. "Running emissions" also covers energy consumption while running. For internal-combustion engines, running operation is defined as operation of internal-combustion engines after the engine and emission control systems have stabilized at operating temperature, i.e., "hot-stabilized" operation.[16]

The general flow of information to calculate running emissions for onroad sources is summarized in Figure 3-1, below. The model uses vehicle population information to sort the vehicle population into source bins defined by vehicle source type, fuel type (gas, diesel, etc.), regulatory class, model year and age. Regulatory classes define vehicles with similar emission standards, such as heavy heavy-duty regulatory classes, which may occur in vehicles classified in several different source types, such as long-haul combination, short-haul single-unit and refuse trucks.[18]

For each source bin, the model uses vehicle characteristics and activity data (vehicle miles traveled (VMT), speed, idle fractions and driving cycles) to estimate the source hours in each running operating mode. The running operating modes are defined by the vehicle's instantaneous vehicle speed, acceleration and estimated vehicle power.[15] [16] [20]

Each source bin and operating mode is associated with an emission rate, and these are multiplied by source hours, adjusted as needed, and summed to estimate the total running emissions. Depending on the pollutant and vehicle characteristics, MOVES may adjust the running emissions to account for local fuel parameters,[2] heating and air conditioning effects, ambient temperature, humidity, electrical charging losses, fleet averaging, LD inspection and maintenance programs[17] and fuel economy adjustments.[13]

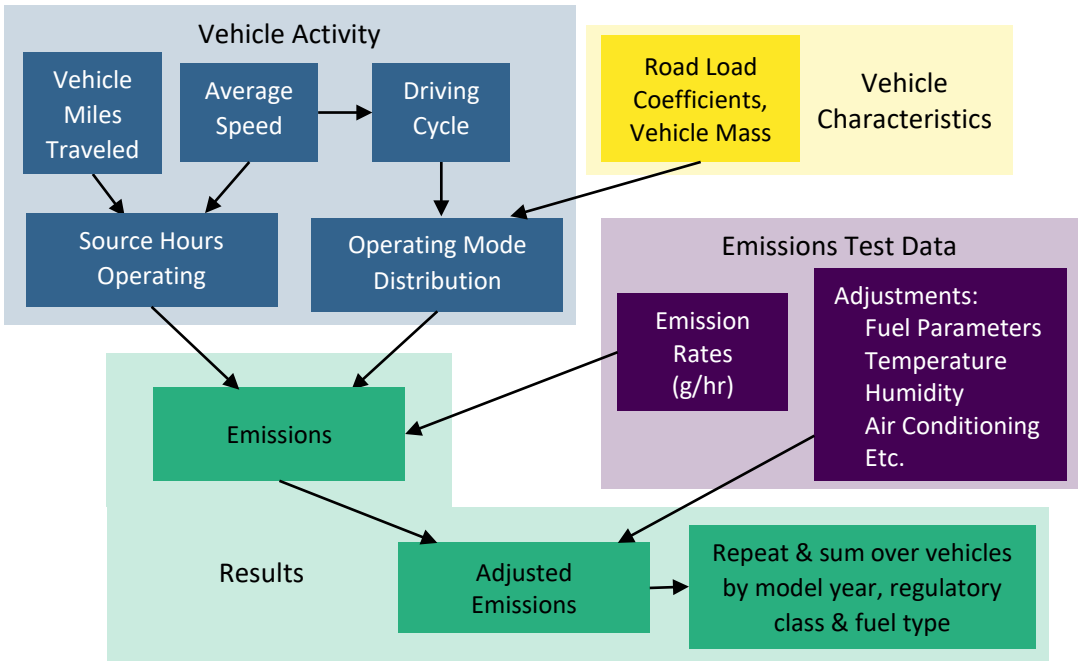


*Figure 3-1: Calculating Running Emissions for Onroad Vehicles*

## 3.2 Start Exhaust

Onroad "start" emissions are the instantaneous exhaust emissions occur at the engine start (e.g., due to the fuel rich conditions in the cylinder to initiate combustion) as well as the additional running exhaust emissions that occur because the engine and emission control systems have not yet stabilized at the running operating temperature. Operationally, start emissions are defined as the difference in emissions between an exhaust emissions test with an ambient temperature start and the same test with the engine and emission control systems already at operating temperature. As such, the units for start emission rates are instantaneous grams/start.

The model uses vehicle population information to sort the vehicle population into source bins defined by vehicle source type, fuel type (gas, diesel, etc.), regulatory class, model year and age. The model uses default data from instrumented vehicles (or user-provided values) to estimate the number of starts for each source bin and to allocate them among eight operating mode bins defined by the amount of time parked ("soak time") prior to the start. Thus, the model accounts for different amounts of cooling of the engine and emission control systems. Each source bin and operating mode has an associated g/start emission rate. Start emissions are also adjusted to account for fuel characteristics, LD inspection and maintenance programs, fleet averaging, and ambient temperatures. [15] [16]

## 3.3 Hotelling Emissions (Extended Idle Exhaust and Auxiliary Power Exhaust)

MOVES defines "hotelling" as any long period of time (e.g., > 1 hour) that drivers spend in their long-haul combination truck vehicles (source type 62) during mandated rest times. Hotelling is differentiated from off-network idling because the exhaust temperatures and engine load may differ, causing different emissions.

The default MOVES hotelling hours are computed as a fixed ratio to the miles these trucks travel on restricted access roads.[18]

The hotelling algorithm applies only to long-haul combination trucks. Hotelling activity is allocated among four operating modes: engine idle ("extended idle"), diesel auxiliary power unit (APU) use, "Shore Power," i.e., plugged-in, and "Battery or All Engines and Accessories Off." This allocation varies by model year and fuel type.[18] MOVES computes emissions for extended idle and APU use based on the hours and source-bin specific emission rates. Hotelling $NO_X$ emissions are adjusted for ambient humidity. In MOVES output, extended idle, APU, and shore power are assigned separate emission processes.[15]

### 3.4 Crankcase (Running, Start & Extended Idle)

Crankcase emissions include combustion products that pass by the piston rings of a compression ignition engine as well as oil droplets from the engine components and engine crankcase that are vented to the atmosphere.[21]

In MOVES, onroad crankcase emissions are computed as a ratio to the exhaust emissions, with separate values for running, start and hotelling (extended idle mode only). The crankcase ratio varies by pollutant, sourcetype, regulatory class, fuel type, model year and exhaust process.[15]

### 3.5 Brake Wear

Brake pads lose material during braking. A portion of this lost material becomes airborne particulate matter. This "brake wear" differs from exhaust PM in its size and chemical composition.

MOVES estimates brake wear from onroad vehicles using weighted average g/hour rates. The emission rates vary by vehicle regulatory class and fuel type.[o] They were developed using emissions test data that included brake pad composition, number and type of brakes, and braking intensity. The rates account for average vehicle weight and for regenerative braking by electric vehicles.[14]

Braking activity is modeled as a portion of running activity. In MOVES, the running operating modes for braking, idling and coasting (opModes IDs 0, 1, 11, 21, 33) are all modeled as including some amount of braking. The operating mode "brakewear; stopped" (opMode 501) can be used at the project scale to model emissions of an idling vehicle with no braking.[14]

### 3.6 Tire Wear

Contact between tires and the road surface causes tires to wear, and a portion of this material becomes airborne. This "tire wear" differs from exhaust PM in its size and chemical composition.

MOVES tire wear rates in g/hr are based on analysis of LD tire wear rates as a function of vehicle speed, extrapolated to other vehicles based on the number and size of tires. The analysis also considers the

[o] For heavy-duty vehicles, all fuel types within a regulatory class are modeled with the same mass. For example, we assume that the electric HD fleet has the same vehicle characteristics (weight, wheel configuration, number of axles, etc.) as its non-EV counterpart, because we lacked data on the weight of HD EVs and assume that heavy-duty truck weights depend less on powertrain weight and more on payload and GVWR.

fraction of tire wear that becomes airborne. The tire wear operating mode bins differ from those used for running emissions and brake wear because they account only for speed and not for acceleration.[14]

### 3.7 Evaporative Permeation

Permeation is the migration of hydrocarbons through materials in the fuel system. Permeation emissions are strongly influenced by the materials used for fuel tank walls, hoses, and seals, and by the temperature, vapor pressure and ethanol content of the fuel.

In MOVES, permeation is estimated only for vehicles using gasoline-based fuels (including E-85). Permeation is estimated for every hour of the day, regardless of activity. Permeation rates in g/hour vary by model year to account for the phase-in of tighter standards. Permeation emissions are adjusted to account for gasoline fuel properties and ambient temperatures. [22]

### 3.8 Evaporative Fuel Vapor Venting

When gasoline fuel tank temperatures rise due to vehicle operation or increased ambient temperatures, hydrocarbon vapors are generated within the fuel tank. The escape of these vapors is called Tank Vapor Venting (TVV) or Evaporative Fuel Vapor Venting. This vapor venting may be eliminated with a fully sealed metal fuel tank. More commonly, venting is reduced by using an activated charcoal canister to adsorb the vapors as they are generated; vapors from the canister are later consumed during vehicle operation. However, to prevent pressure build-up, canisters are open to the atmosphere, and after several days without operating, fuel vapors can diffuse through the charcoal or pass freely through a completely saturated canister. Tampering, mal-maintenance, vapor leaks and system failure can also result in excess vapor venting.

MOVES calculates vapor venting only for vehicles using gasoline-based fuels (including E-85). The tank vapor generated depends on the rise in fuel tank temperature, fuel vapor pressure, ethanol content and altitude. Fuel tank temperature changes are modeled as a function of 24-hour temperature patterns and default vehicle activity, with different vapor generation rates for vehicles that are operating, “hot soaking” (parked, but still warm) and “cold soaking” (parked at ambient temperature). MOVES evaporative emission calculations have not been updated for off-network idle and thus model this idle time as hours parked. Vapor venting is modeled as a function of vapor generated, days cold soaking, model-year specific vehicle fuel system characteristics, and age and model year related vapor leak rates. Inspection and maintenance (I/M) programs can also impact leak prevalence rates.[22]

### 3.9 Evaporative Fuel Leaks (Liquid Leaks)

Liquid leaks are fuels escaping the gasoline fuel system in a non-vapor form. In MOVES, they are referred to as evaporative fuel leaks because they subsequently evaporate into the atmosphere after escaping the vehicle. These leaks may occur due to failures with fuel system materials, or due to tampering or mal-maintenance. Liquid spillage during refueling is modeled separately as part of the refueling process.

In MOVES, fuel leak frequency is estimated as a function of vehicle age and vehicle emission standards. Fuel leak size (g/hour) is a function of age and vehicle operating mode (cold soaking, hot soaking or operating).[22]

### 3.10 Refueling Displacement Vapor and Spillage Loss

Refueling emissions are the displaced fuel vapors when liquid fuel is added to the vehicle tank. Refueling spillage is the vapor emissions from any liquid fuel that is spilled during refueling and subsequently evaporates. Diesel vehicles are assumed to have negligible vapor displacement, but MOVES does compute emissions for onroad diesel fuel spillage.

Refueling vapor and spillage emissions are estimated from the total volume of fuel dispensed (gallons). This volume is based on previously calculated fuel consumption. In addition, refueling emissions are a function of gasoline vapor pressure, ambient temperatures, the presence of an on-board refueling vapor recovery system (ORVR) on the vehicles, and the use of Stage II vapor recovery controls at the refueling pump. The effectiveness of ORVR systems decline with age.[22]

### 3.11 Preaggregation

MOVES is designed to calculate emissions for each selected county and hour, and then to aggregate emissions to the level of output detail selected in the RunSpec. However, modelers may sometimes choose to simplify MOVES calculations by preaggregating MOVES inputs to cover larger geographic or temporal scales. For example, modelers may run MOVES for the nation as a whole or for an entire year.

When a user selects preaggregation, average values for MOVES inputs are calculated as activity-weighted distributions or averages. For geographical preaggregation, the StartAllocFactor column in the Zone table is used as a weighting factor. StartAllocFactor contains the ratio of each county's VMT to the total national VMT, based on data from the NEI. Temporal preaggregation from Hour to Day is based upon the values in the HourVMTFraction table; the weighting used for the Month aggregation is based upon the values in the DayVMTFraction table; and the activity weighting used for the Year aggregation is based upon the values in the MonthVMTFraction table.

Runs with geographic or temporal preaggregation lack important detail and tend to underestimate emissions; they do not meet the regulatory requirements for SIPs and conformity determinations.[7]

# 4. MOVES Nonroad Algorithms

This section provides a brief general overview of the algorithms used to model emissions from nonroad equipment types. These calculations vary depending on the processes and pollutants being modeled and the equipment type. They also depend on whether the equipment uses a spark-ignition (SI) or compression-ignition (CI) engine, and the engine horsepower (hp) size class. The MOVES nonroad technical reports at https://www.epa.gov/moves/nonroad-technical-reports provide detailed information on algorithms and inputs for the nonroad calculations.

The MOVES nonroad module estimates emissions as the product of an adjusted emission factor multiplied by rated power, load factor, engine population and activity. Starting with base-year equipment populations by technology type and model year, the model uses growth factors to estimate the population in the analysis year. Estimates of median life at full load, load factors, activity and age distributions are then combined to generate estimates of nonroad emissions by equipment type, fuel type and age. Equipment populations are also allocated to county and season; national equipment populations are allocated to the county level using surrogate data.

The nonroad module has importers for user information on meteorology and fuels, and a "generic" importer that can be used to enter data on retrofit programs. We recommend accounting for custom population and activity using post-processing scripts as explained in the MOVES training and technical guidance.

For all nonroad processes, toxics are estimated in the nonroad portion of the model, but detailed TOG speciation and speciation of $PM_{2.5}$ must be post-processed.[23]

## 4.1 Running Exhaust

For nonroad, "running exhaust" emissions include exhaust emissions both at start and during running operation.

The MOVES nonroad module calculates an emission factor for THC, CO, $NO_X$, PM and brake-specific fuel consumption (BSFC)[p] as the product of a steady-state emission factor for new ("zero-hour") engines, a transient adjustment factor if needed to represent typical operation, and a deterioration factor to account for wear and aging. Gasoline THC, CO and $NO_X$ emissions are adjusted to account for gasoline oxygenate content. $SO_2$ emissions from all nonroad equipment is a function of BSFC and fuel sulfur level. Diesel PM emissions are adjusted to account for diesel fuel sulfur levels.[24] Temperature effects are applied to THC, CO and $NO_X$ exhaust emissions from 4-stroke SI engines.[25]

## 4.2 Crankcase Exhaust

Crankcase emissions are those emissions that escape from the combustion chamber past the piston rings into the crankcase and out to the atmosphere. The MOVES nonroad module models THC crankcase

[p] When BSFC is selected as a "pollutant" in the MOVES RunSpec, MOVES will output fuel consumption. Although it is labeled "brake-specific fuel consumption," the output is total mass of fuel. The units depend on the units selected on the "General Output" panel.

emissions for four-stroke spark-ignition engines that have open crankcases[26] and for all compression-ignition engines prior to implementation of the Tier 4 NR diesel standard.[27]

### 4.3 Refueling Displacement Vapor and Spillage Loss

Refueling emissions are the displaced fuel vapors when liquid fuel is added to the equipment fuel tank. Refueling spillage is the vapor emissions from any liquid fuel that is spilled during refueling and subsequently evaporates.[28]

For both spillage and vapor displacement, the MOVES nonroad module initially calculates an THC emission factor in terms of grams of emissions per gallon of gasoline fuel consumed. Fuel consumption is then used to calculate total emissions. The g/gal emission factor varies as a function of fuel tank volume, gasoline RVP, ambient and dispensed fuel temperatures, and whether the equipment is more likely fueled using a portable container or at the pump, and the use of Stage II vapor recovery controls at the refueling pump.

No refueling emissions are reported for diesel, CNG or LPG nonroad equipment.

### 4.4 Fuel Vapor Venting (Diurnal, Hot Soak and Running Loss)

Fuel vapor venting emissions for nonroad equipment are analogous to the evaporative vapor venting emissions for onroad vehicles. Diurnal emissions are vapors generated due to temperature changes throughout the day; running emissions are generated by heating caused by engine operation, and hot soak emissions are generated from residual heat from the equipment just after the engine is shut off.

In general, diurnal emissions are calculated based on equipment standards, percent tank fill, percent headspace, tank size, vapor pressure of the fuel, and the minimum and maximum ambient temperature. Diurnal emissions for recreational marine emissions are calculated slightly differently. Running loss emissions are calculated as a function of operating time and are not affected by ambient temperatures. Hot soak emissions are a function of default equipment starts/hour and gram/start rates.

No fuel vapor venting emissions are reported for diesel, CNG or LPG nonroad equipment.[29]

### 4.5 Permeation: Tank, Hose, Neck, Supply/Return and Vent Hose

Permeation is the migration of hydrocarbons through materials in the fuel system. Permeation emissions are strongly influenced by the materials used for fuel tank walls, hoses, and seals—and are also affected by the temperature, vapor pressure and ethanol content of the fuel.

The MOVES nonroad module calculates various types of permeation. No permeation is calculated for spark-ignition engines larger than 25 hp because they usually have impermeable metal fuel tanks and lines.

Fuel tank permeation is calculated as the product of the inside area of the fuel tank, a tank permeation emission factor that varies with equipment emission standard and a temperature adjustment. The permeation is also adjusted to account for the market share of ethanol blend gasolines.

Fuel hose permeation is calculated as the product of the surface area of non-metal hoses, a hose permeation emission factor that varies with equipment size category and emission standard, and a temperature adjustment. For recreational marine equipment, separate fuel hose emissions are calculated for the supply/return, fill neck, and vent lines.

No permeation emissions are reported for diesel, CNG or LPG nonroad equipment.[29]

# 5. MOVES Software Structure

MOVES is written in Java (compiled with Microsoft's build of OpenJDK), MariaDB, and the Go programming language. The MOVES Nonroad module is written in Fortran. The principal user inputs, outputs and most of the model's internal working storage are held in MariaDB databases. The model includes a default database with emission rates, adjustment factors, and relevant information for all U.S. counties. The default database supports model runs for calendar years 1990 and 1999–2060.

The MOVES architecture was originally designed to model only onroad vehicles. In 2014, the existing NONROAD2008 model was integrated into MOVES as the "MOVES nonroad module". The nonroad module uses the same interface as the rest of MOVES, but the calculations are handled by a separate Fortran program.

MOVES uses a main-process/worker-process program architecture that enables multiple computers to work together on a single model run. However, a single computer can be used to execute MOVES runs by running both the main and worker components on the same computer.

The following diagram illustrates the overall flow of processing in MOVES highlighting the division of work between the MOVES Main and Worker programs.

In general, modelers use the GUI to create a RunSpec that specifies the scope and options for a given run. It can be started via the GUI or the command line. Based on the contents of the RunSpec, MOVES Main selects relevant data from the Default Database and any user-provided input databases (e.g., county and project databases) and performs any internal pre-processes needed to generate an Execution Database with all the data needed for the run. Then MOVES Main runs the calculators for the run. MOVES Main creates bundles of work (TODO files) to be performed by MOVES Workers. After the Workers finish processing the bundles, they send them back to MOVES Main as DONE files. Finally, MOVES Main retrieves the DONE files and completes any final aggregation before saving the results in the MOVES Output Database indicated in the RunSpec.

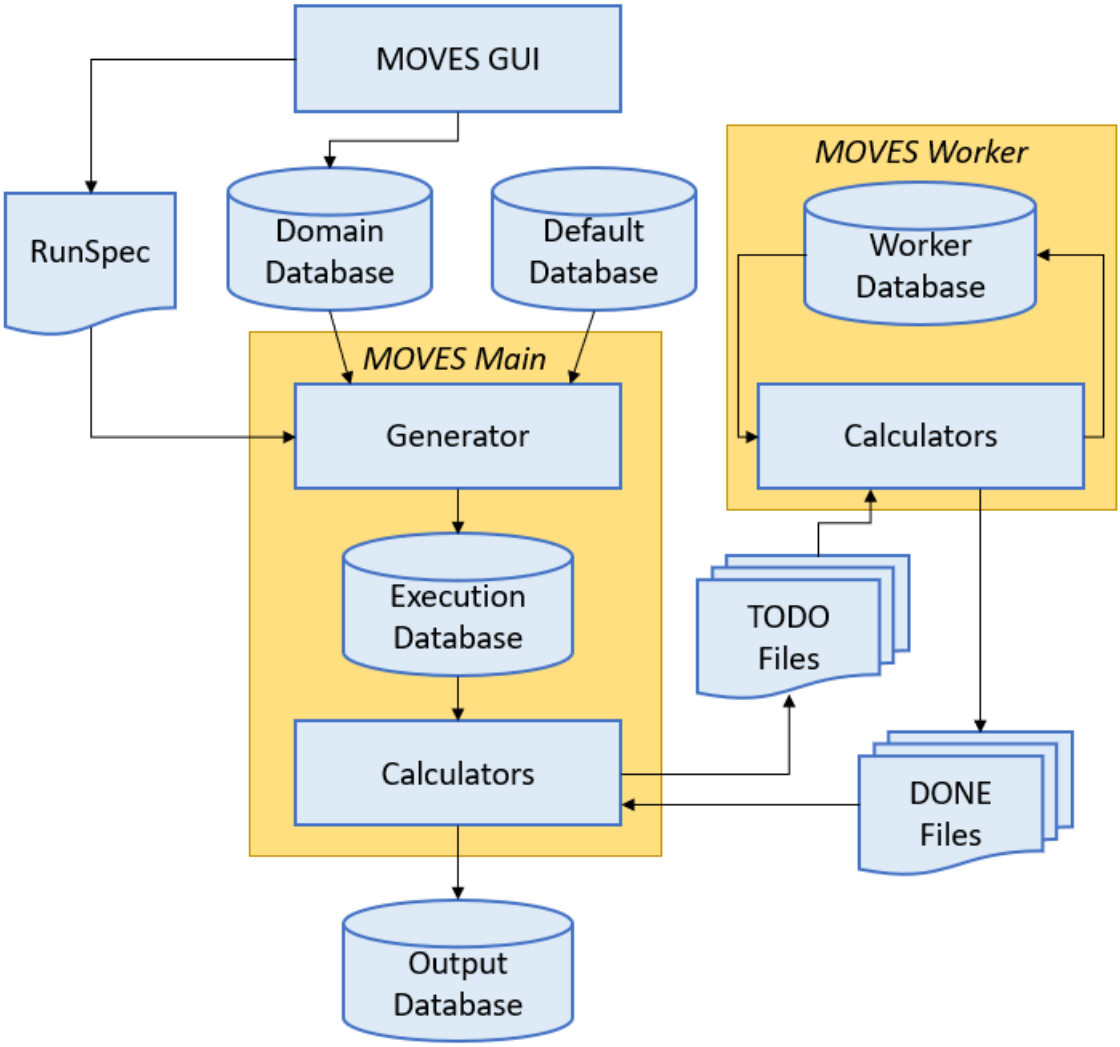


*Figure 5-1-- Diagram of MOVES information flow*

## 5.1 MOVES Software Components

Looking at this architecture in greater detail, the MOVES software application consists of several components, introduced briefly in this chapter. More information is available in the documentation at the MOVES GitHub site, https://github.com/USEPA/EPA_MOVES_Model/tree/master/docs.

### *RunSpec*

Users create a RunSpec file to define the place and time period of the analysis as well as the vehicle types, road types, fuel types, emission processes, and pollutants that will be included in the analysis. The RunSpec also specifies the input and output databases that will be used for the run. The RunSpec is a text file in XML format that can be edited and executed directly, or that can be accessed, changed, and run through the MOVES GUI. For more information, see the MOVES training.

### *MOVES Graphical User Interface (GUI)*

The MOVES GUI is a Java program that may be used to create, save, load, and modify a RunSpec, and to initiate and monitor the status of a model run. The MOVES GUI also includes data managers that assist users in building the input databases required for county and project scale runs and includes error-checking code to ensure that the RunSpec and inputs are consistent with MOVES algorithms and capabilities.

### *MOVES Main Program*

When the run is started, MOVES Main uses information in the RunSpec, the default database, and the user input domain database to generate the execution database specific to the MOVES run. This is done using "Generator" modules. The Main program then bundles data and calculation instructions into ToDo files to be processed by MOVES Workers. The MOVES Main also compiles the results returned from the MOVES Workers via Done files into the MOVES output database and performs final aggregation steps. During the MOVES run, both the ToDo and Done files are stored in the SharedWork directory which must be accessible to both the Main and Worker programs.

Note that only one executing MOVES Main program can be used during a MOVES run. That is, a single computer can run only one RunSpec at a time.

### *MOVES Worker Program*

The MOVES Worker program processes the ToDo files created by the MOVES Main program and returns the results as Done files. This processing is done by various "Calculator" modules.

At least one executing copy of this program is needed to complete a MOVES run. Running multiple MOVES Worker programs during a MOVES run enables ToDo files to be processed in parallel. While this capability may reduce the duration of a MOVES run, the improvement in performance strongly depends on the contents of the RunSpec and the computing environment. The MOVES Worker program may be executed on the same computer as the MOVES Main program, or on other computer(s) having access to the SharedWork file directory.[q]

### *MOVES Nonroad Module*

The code used to model nonroad emissions in MOVES predates the MOVES model. Beginning with MOVES2014, the standalone NONROAD model was incorporated into MOVES such that the NONROAD Fortran program is called by the MOVES Worker program. MOVES supplies the Fortran program with the appropriate flat file inputs based on values from the MOVES default database and any optional user input databases. Note that nonroad and onroad share the same default meteorology and fuel inputs. After the MOVES Worker executes the NONROAD Fortran program, it post-processes the Fortran output flat files and saves the results in the MOVES output database.

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[q] See additional information on configuring MOVES for faster runs at https://github.com/USEPA/EPA_MOVES_Model/blob/master/docs/TipsForFasterMOVESRuns.pdf

Later minor releases of MOVES2014 improved nonroad population growth estimates and diesel emission factors, in addition to new features including Go-based calculators that compute nonroad fuel subtype splits, some nonroad THC species, and nonroad air toxics.

## 5.2 MOVES Databases

The MOVES model stores and accesses data for its calculations in a series of MariaDB databases. This section introduces the different types of MOVES databases, and how they are used by the program. A detailed description of each MOVES input and output table is available at MOVES Database Tables.

### *Default Database*

The default database is included in the MOVES Installation Package and is required for MOVES to run. This database contains the required emission factors, adjustment factors, fuel data, and default vehicle population and activity data for all U.S. counties to support model runs for calendar years 1990 and 1999–2060.

### *User Input Databases*

User databases may contain any of the tables that are in the default input database and are used to add or replace records as input by the user; EPA's MOVES Technical Guidance[7] describes which data inputs must be updated by the user for SIP and conformity purposes. These databases typically contain region-specific fuels, vehicle populations, age distributions, activity, and where applicable, I/M program characteristics. These databases are optional for a default run, but user input is required for runs at the County or Project Scale. The MOVES GUI includes a County Data Manager and a Project Data Manager that assist the user in creating an input database that contains all the necessary data for a MOVES run.

### *The MOVESExecution Database*

The MOVESExecution database is created by the MOVES Main program. It is used for temporary working storage during the MOVES run. Users do not interact with this database.

### *MOVES Output Databases*

These databases are the final outputs of MOVES runs. The output database name is specified by the user in the RunSpec. Output for Emission Inventory mode runs is contained in the movesOutput table. Emission Rates mode produces output in multiple tables.

The output databases also include tables that describe each run in the output, activity data, translation tables for the codes used in the output, information on errors during the run, and other tables used for diagnostics and troubleshooting.

### *MOVESWorker Database*

This temporary database is used as working storage by the MOVES Worker Program. When running with multiple MOVES Workers, each Worker program creates its own MOVESWorker database. The user does not interact directly with this database.

# 6. MOVES5.0 Results

Vehicle and equipment emissions vary by location and time. This section shows MOVES5 results for the United States as a whole, based on national defaults. For brevity, the graphs here show only a few of the pollutants calculated by MOVES and are aggregated by fuel type and calendar year.

However, for the most accurate results for a given time and location, it is important to run MOVES for the specific case using accurate local inputs. In contrast, the national results shared in this document are calculated based on average inputs that do not fully capture the variation in emissions from time to time and place to place. For selected pollutants, we also show onroad results for two sample urban counties as modeled at County Scale with county-specific inputs. While the two counties shown here differ in their traffic mix, fuels, and meteorology, they are not intended to represent the full range of local trends. To understand mobile source emissions in a particular county, one must model that county.

These caveats are also true for the average emission rates EPA provides to the Bureau of Transportation Statistics (https://www.bts.gov/content/estimated-national-average-vehicle-emissions-rates-vehicle-vehicle-type-using-gasoline-and).

Additional emission summaries for selected past years are available from the National Emissions Inventory (https://www.epa.gov/air-emissions-inventories/national-emissions-inventory-nei). The NEI emissions are calculated with county-level inputs; NEI mobile source inventories prior to the 2023 NEI were generated with previous versions of MOVES and thus lack MOVES5 updates.

## 6.1 Onroad

The following plots summarize key results for onroad vehicles from running MOVES5 at the national, annual level using default inputs as compared to runs using the previous model, MOVES4.0.1.[30] Because results for specific times and locations will vary, for some pollutants, we also show results for two sample urban counties with county-specific fleet, fuel, and meteorological conditions.

Compared to MOVES4, MOVES5 generally predicts higher national emissions for years prior to about 2040. This reflects the change to better account for older vehicles as well as other changes detailed in Section 2. The exception is $CO_2$, which is generally lower in MOVES5 starting in the early 2020s.

Figure 6-1 shows a shift in MOVES5 defaults to more E-85, CNG and EV VMT and a decrease in VMT from gasoline and diesel vehicles. There is a slight decrease in total vehicle miles travelled starting in 2022.

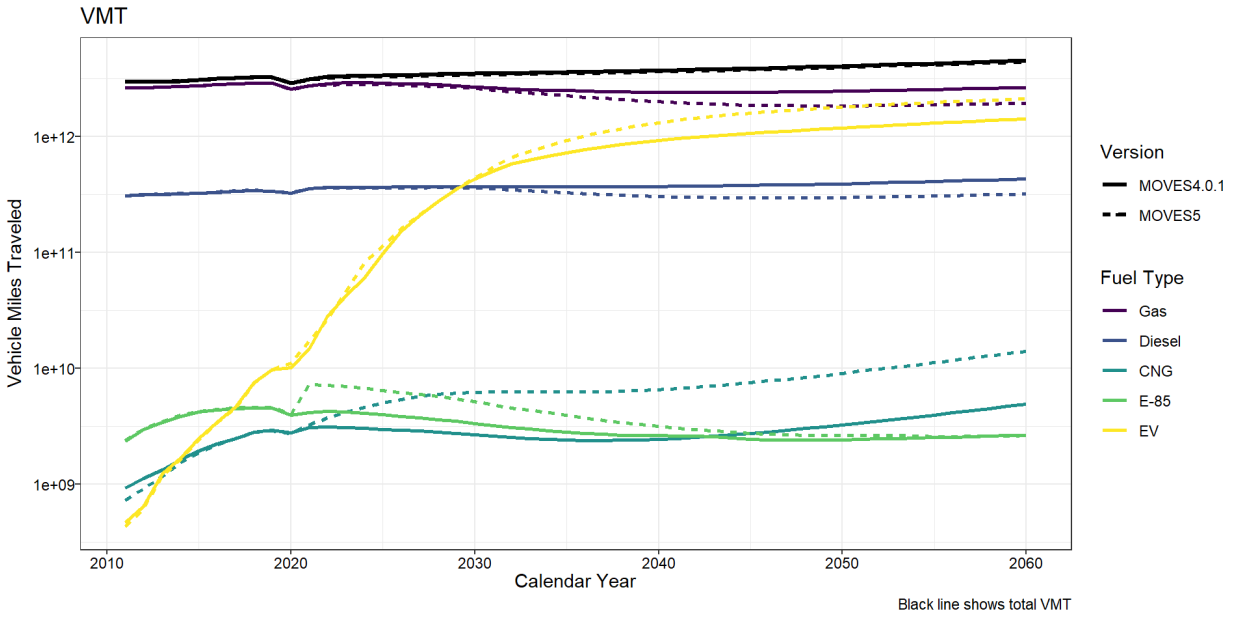


*Figure 6-1—National onroad vehicle miles travelled (VMT) by fuel type in MOVES5 as compared to MOVES4.0.1. Note the y-axis is in log space. The black lines are totals across all fuel types.*

For county level runs, modelers must enter county-specific VMT and fuel mix. Figure 6-2 illustrates VMT for two example counties. In these county runs, total VMT and most other inputs are the same for the MOVES4 and MOVES5 runs. However, the MOVES5 inputs include EV fractions consistent with the new EPA GHG rules and the 41-year age distributions. For both MOVES4 and MOVES5, County A includes future year electric vehicle population fractions that are proportional to the county's historic share of national EVs. In contrast, County B includes future year electric vehicle population fractions that reflect adoption of California's Advanced Clean Car I (2012) and Advanced Clean Trucks (2020) rules requiring electric vehicle sales for light- and heavy-duty vehicles. In both counties, the expected effect of the new EPA GHG rules is visible in the MOVES5 EV VMT starting in the early 2030s. The VMT values shown here are used as inputs in the sample county illustrations below.

*Figure 6-2—Sample county-specific onroad vehicle miles travelled (VMT) in MOVES4.0.1 and MOVES5. Percentage values indicate change compared to calendar year 2021. The values shown here are used in the sample county illustrations below.*

### *Greenhouse Gases*

While total VMT is quite similar in both models, for exhaust $CO_2$ (Figure 6-3), MOVES5 projects substantially greater decreases over time than MOVES4. This reflects the shift to more EVs as well as more efficient vehicles with internal combustion engines.

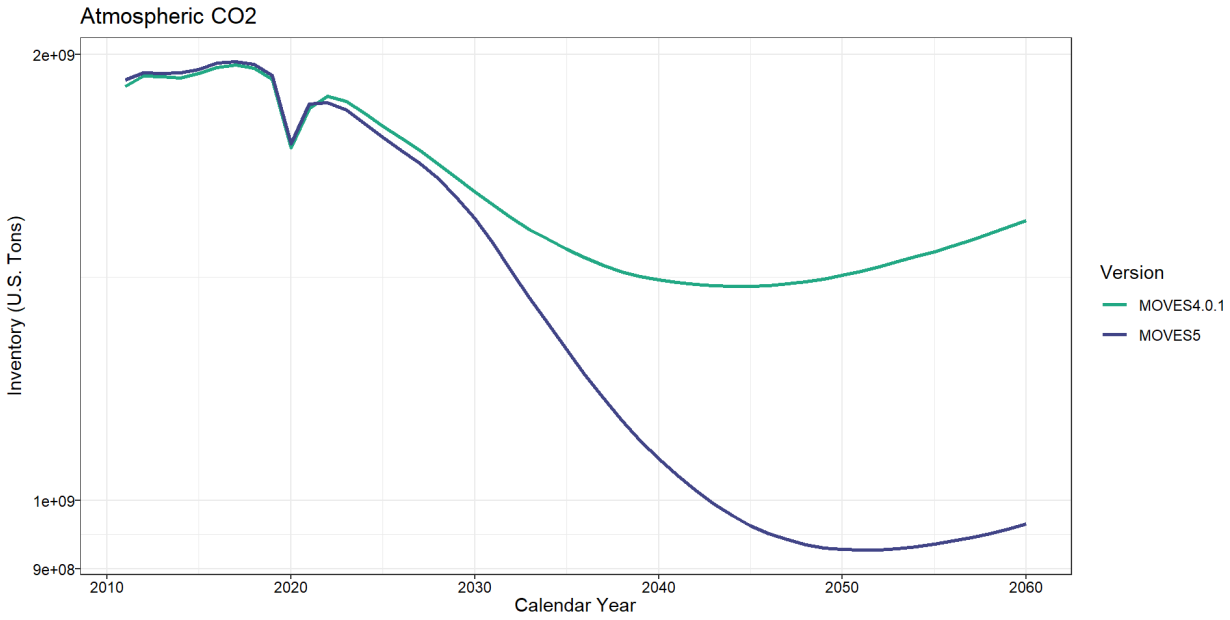


*Figure 6-3—National onroad carbon dioxide in MOVES5 as compared to MOVES4.0.1. Note the y-axis is in log space.*

Similar $CO_2$ reductions are seen at the county level (Figure 6-4). As noted above, County A is modeled with EPA rules only. County B is modeled with California's Advanced Clean Car I (2012) and Advanced Clean Trucks (2020) rules requiring electric vehicle sales for light- and heavy-duty vehicles.

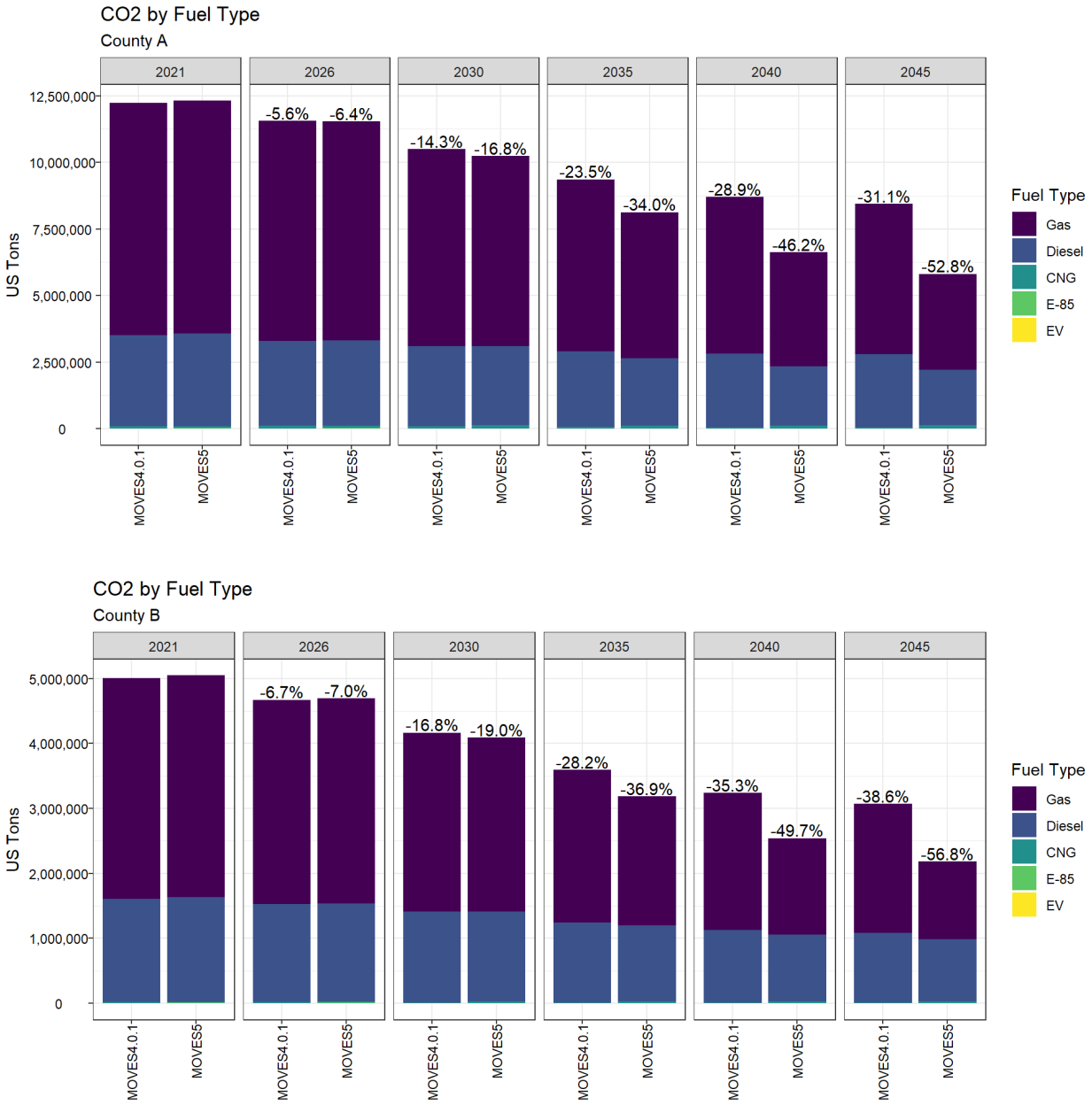


*Figure 6-4—Sample county-specific onroad carbon dioxide in MOVES4.0.1 and MOVES5. Percentage values indicate change compared to calendar year 2021.*

As shown in Figure 6-5, both models predict a pre-2020 decline in methane emissions from onroad vehicles, followed by an increase in later years; however, MOVES5 emissions are higher than MOVES4 in all years. In later years, this reflects the shift in MOVES defaults to include more activity from CNG vehicles, which have high methane emissions.

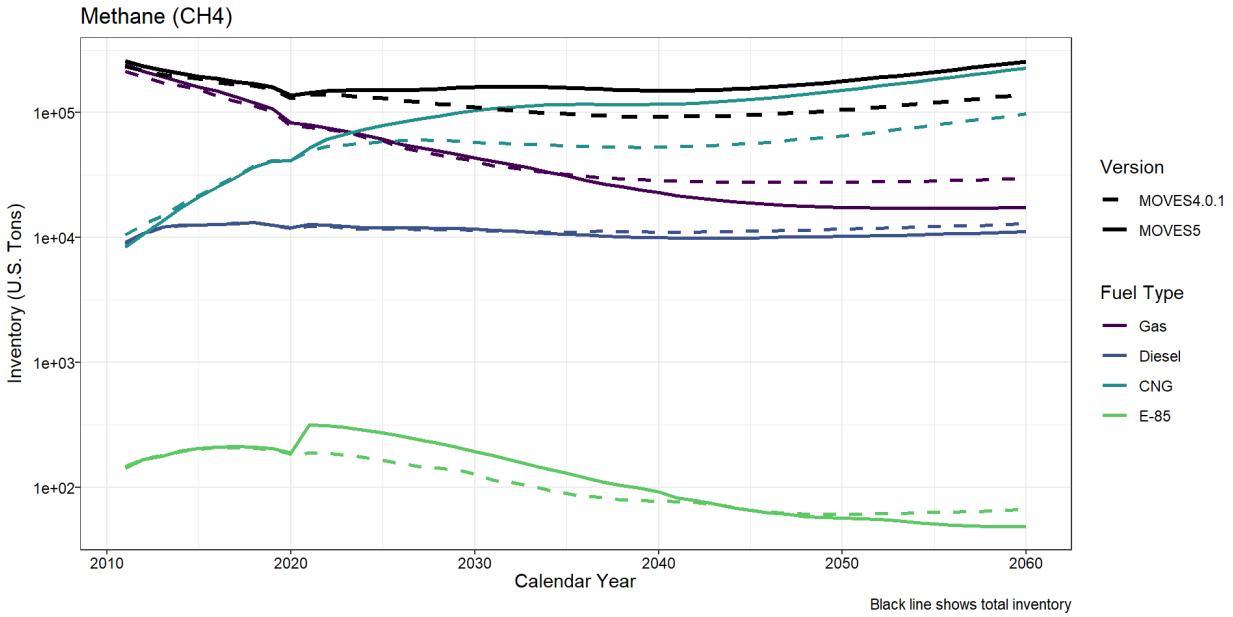


*Figure 6-5—National onroad methane in MOVES5 as compared to MOVES4.0.1. Note the y-axis is in log space. The black lines are totals across all fuel types.*

MOVES inputs for nitrous oxide emission rates have not changed since MOVES4, but, as shown in Figure 6-6, MOVES5 $N_2O$ emission results track changes in the vehicle fuel mix. At the national scale, MOVES5 net $N_2O$ is higher before 2020 and lower afterwards.

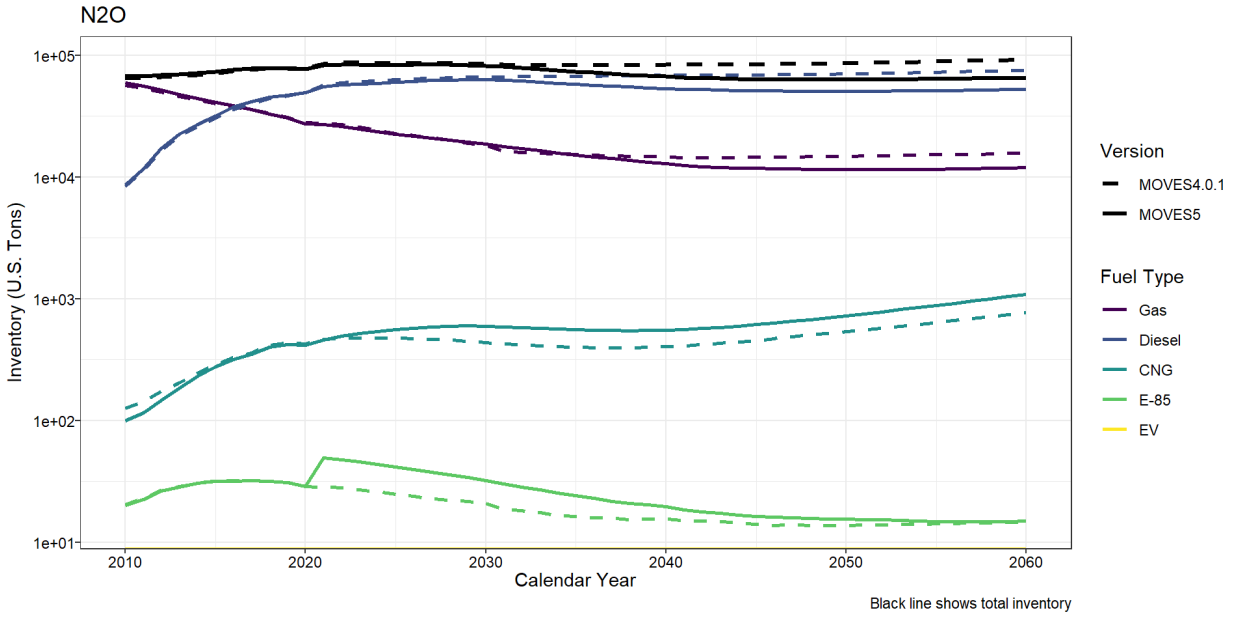


*Figure 6-6—National onroad $N_2O$ in MOVES5 as compared to MOVES4.0.1. Note the y-axis is in log space. The black lines are totals across all fuel types.*

The net $CO_2$ equivalent emissions are shown in Figure 6-7. These are based on the emissions of $CO_2$, $CH_4$ and $N_2O$ as weighted by their global warming potentials (GWPs). The GWPs were updated for

MOVES5.[13] In total, the MOVES5 projects lower $CO_2$ equivalent emissions with decreases in $CO_2$ and $N_2O$ outweighing the increase in $CH_4$.

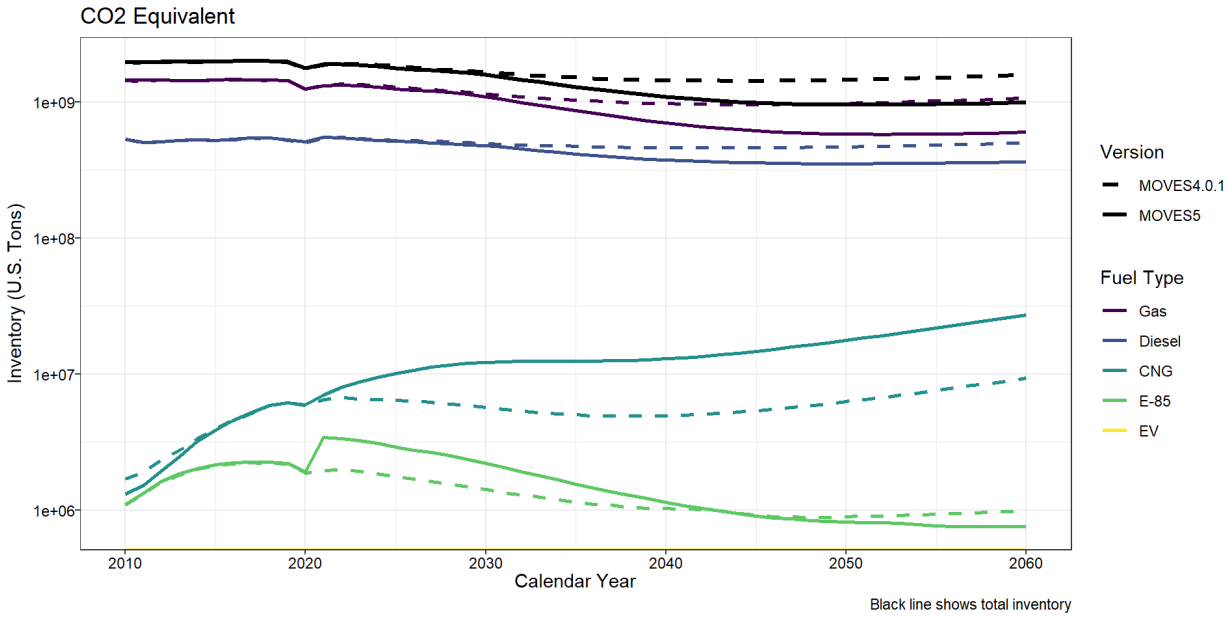


*Figure 6-7—National onroad $CO_2$ equivalent in MOVES5 as compared to MOVES4.0.1. Note the y-axis is in log space. The black lines are totals across all fuel types.*

### *Criteria Pollutants and Precursors*

#### Oxides of Nitrogen

Figure 6-8 shows national $NO_X$ emissions decline through about 2040 with the phase-in of light-duty and heavy-duty rules already accounted for in MOVES4. MOVES5 shows additional declines in later years due to tighter emission standards under the LMDV and a higher fraction of EVs under both the LMDV and HDP3 rules. At the national scale, $NO_x$ emissions in MOVES5 are higher than MOVES4 until about 2040. This is due to more detailed accounting of vehicles age 30-40 and changes in the fleet mix.

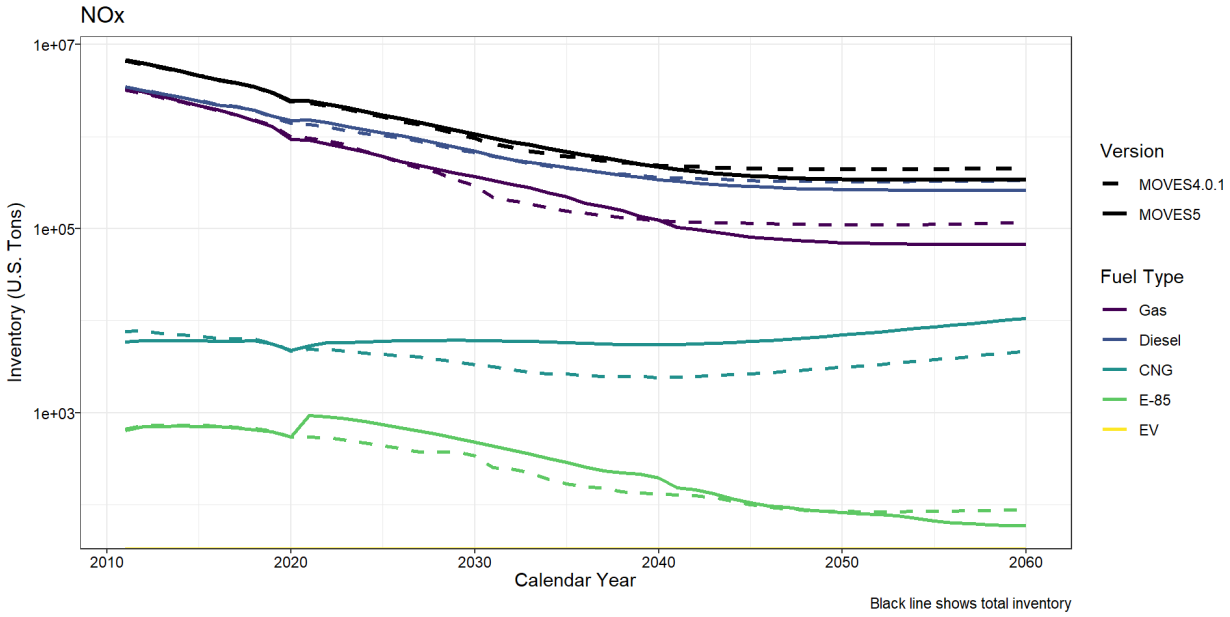


*Figure 6-8— National onroad $NO_x$ in MOVES5 as compared to MOVES4.0.1. Note the y-axis is in log space. The black lines are totals across all fuel types.*

Figure 6-9 illustrates $NO_x$ for two example counties with the VMT shown in Figure 6-2. As noted above, County A includes future year electric vehicle population fractions that are proportional to the county's historic share of national EVs. In contrast, County B includes future year electric vehicle population fractions that reflect adoption of California's Advanced Clean Car (2012) and Advanced Clean Trucks (2020) rules requiring electric vehicle sales for light- and heavy-duty vehicles.

As in the national runs, MOVES5 $NO_x$ is higher than MOVES4 until about 2040 due to changes in fleet mix and the modeling of older vehicles. After about 2040, MOVES5 $NO_x$ is lower due to more stringent LD standards and a greater fraction of EVs. Note that until about 2040, the percent reduction in emissions from 2021 is similar in the two versions.

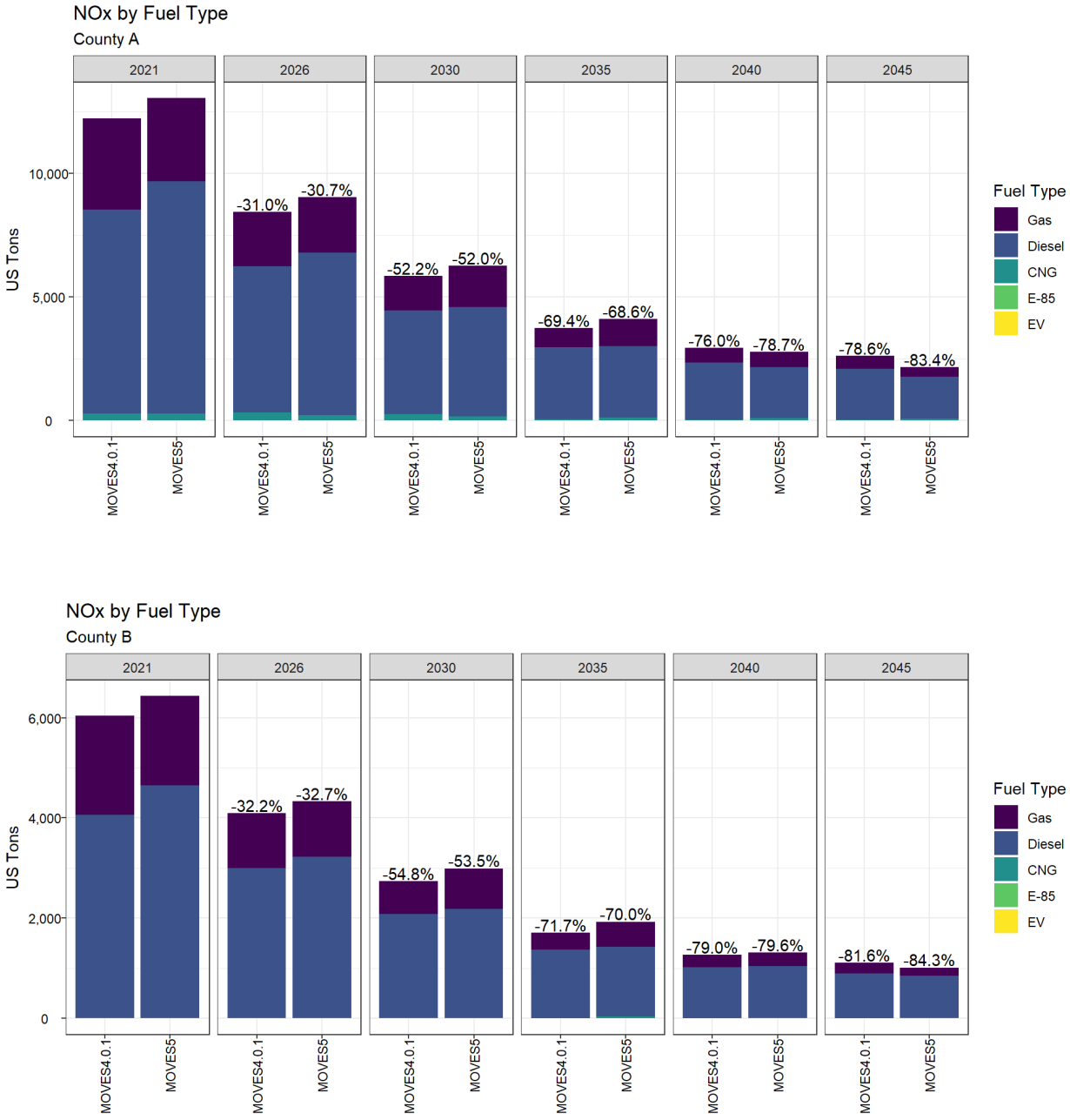


*Figure 6-9—Onroad $NO_X$ from two sample urban counties in MOVES5 as compared to MOVES4.0.1. Percentage values indicate change compared to 2021.*

## Particulate Matter

MOVES PM emissions include exhaust PM, tire wear and brake wear. Figure 6-10 shows national $PM_{2.5}$ inventory declining with the phase-in of light-duty and heavy-duty PM regulations already in place. MOVES5 shows additional declines in later years due to tighter emission standards under the LMDV and a higher fraction of EVs under both the LMDV and HDP3 rules. At the national scale, PM emissions in MOVES5 are higher than MOVES4 until about 2040. The higher emissions are due to data on brake wear

that shows higher brake wear emissions from HD vehicles, plus changes due to detailed accounting of vehicles age 30-40 and changes in the fleet mix. In MOVES5, brake wear emission rates for electric vehicles are lower than for internal combustion engine vehicles after accounting for both increased vehicle mass and regenerative braking.

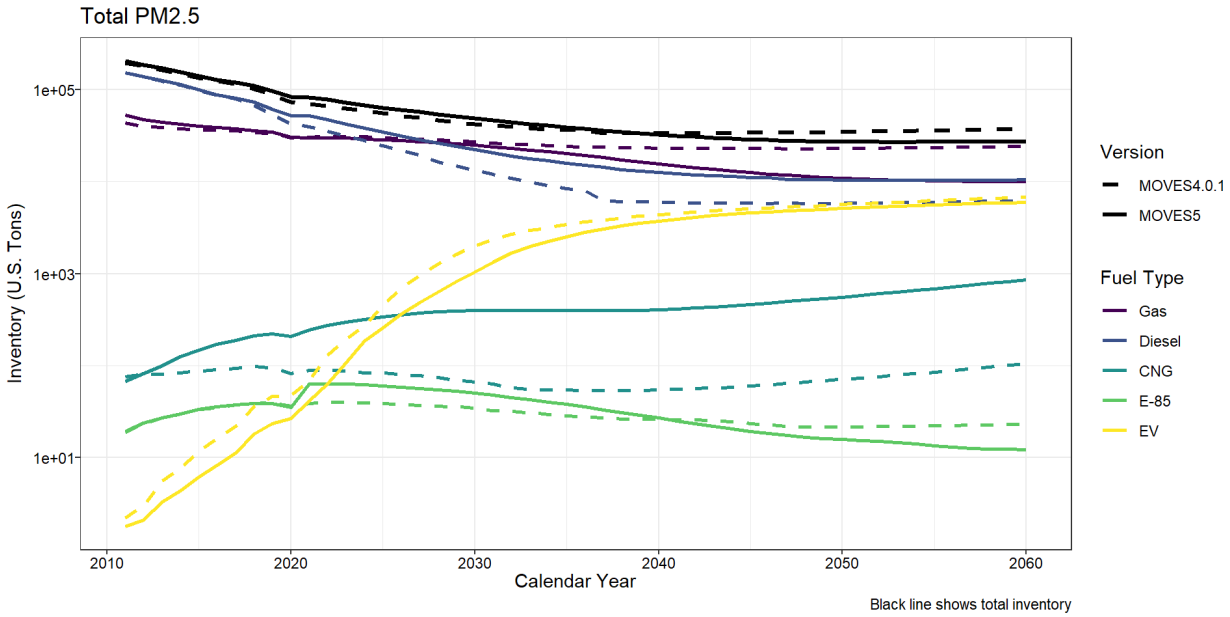


*Figure 6-10—National $PM_{2.5}$ in MOVES5 as compared to MOVES4.0.1. Note the y-axis is in log space. The yellow line graphs brake and tire wear emissions from EVs. The black lines are totals across all fuel types..*

Figure 6-11 depicts total $PM_{2.5}$ emissions by fuel type in two sample counties. The gasoline and diesel emissions include exhaust, brake, and tire wear. The EV emissions are from brake and tire wear only. The trends resemble the trends for national $PM_{2.5}$. Note that until about 2035, the percent reduction in emissions from 2021 is similar in the two versions.

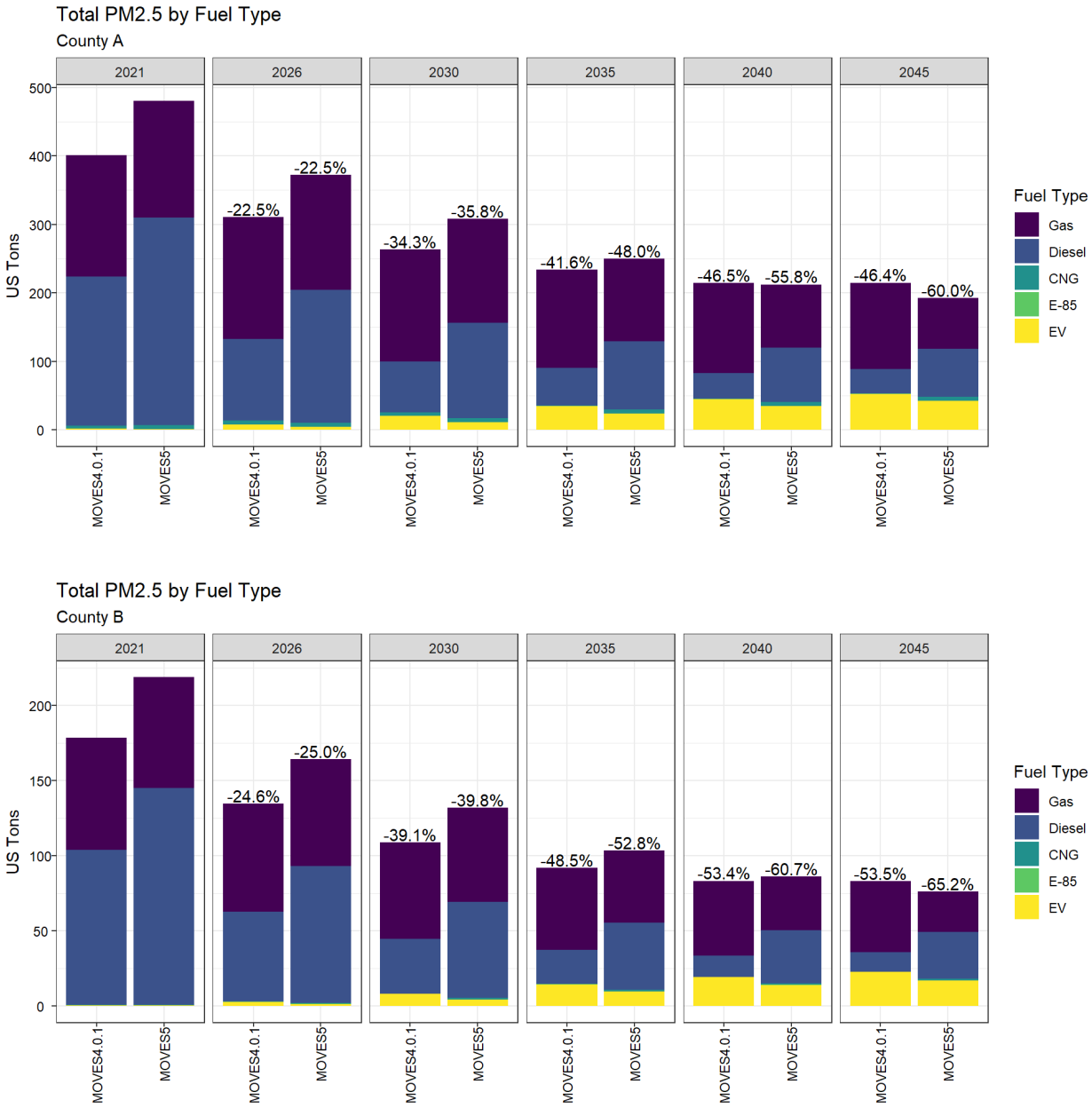


*Figure 6-11—Onroad $PM_{2.5}$ by fuel type from two sample urban counties in MOVES5 as compared to MOVES4.0.1. Percentage values indicate change compared to 2021.*

Figure 6-12 shows the same county results distinguished by grouped emission processes (e.g., with crankcase emissions summed with corresponding exhaust emissions). These graphs clearly illustrate the reductions in start and running PM emissions, and the enduring contribution of brake and tire wear.

*Figure 6-12—Onroad $PM_{2.5}$ by grouped emission process from two sample urban counties in MOVES5 as compared to MOVES4.0.1. Percentage values indicate change compared to 2021.*

MOVES5 updates the factors used to compute $PM_{10}$ brake wear from $PM_{2.5}$ brake wear.[14] Because brake wear dominates $PM_{10}$ emissions, this change results in a notably different trend for $PM_{10}$ as compared to $PM_{2.5}$. MOVES5 estimates much less $PM_{10}$. Figure 6-13 illustrates the $PM_{10}$ trend for County A. Trends are similar in other counties and at the national scale.

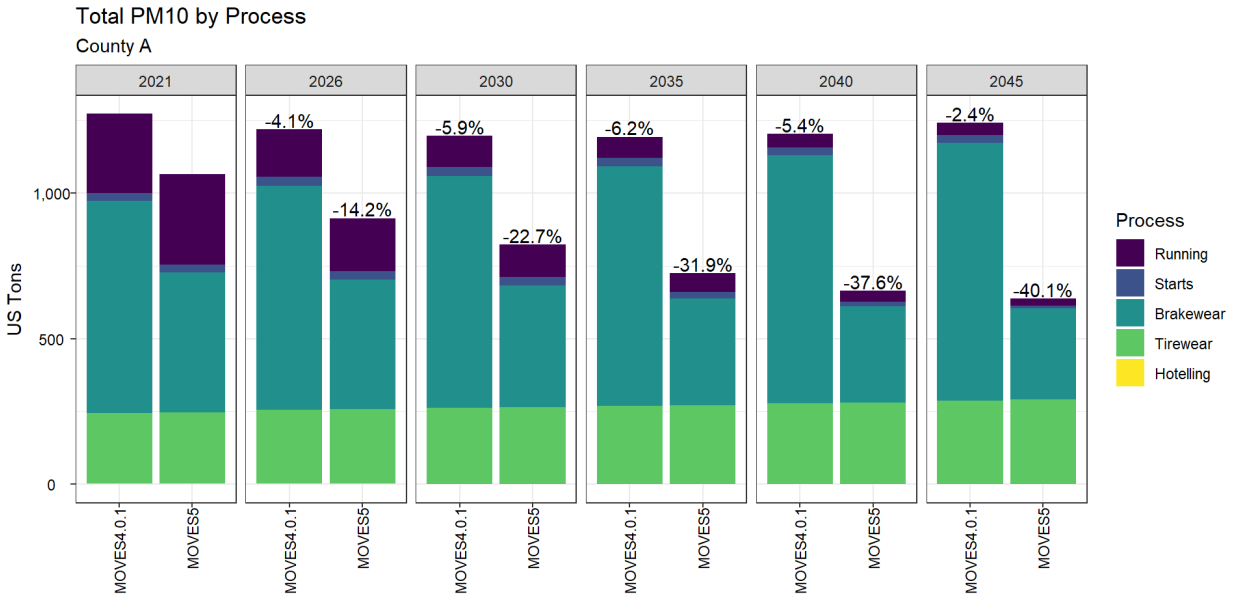


*Figure 6-13—Onroad $PM_{10}$ by grouped emission process from a sample urban county in MOVES5 as compared to MOVES4.0.1. Percentage values indicate change compared to 2021.*

## Volatile Organic Compounds

As shown in Figure 6-14, onroad VOC emissions are dominated by emissions from gasoline vehicles, which decline with the phase-in of Tier 3 standards, the increased fraction of electric vehicles, and tighter standards under the LMDV rule. Like other pollutants, VOC emissions in MOVES5 are higher than MOVES4 until about 2040 due to more detailed accounting of vehicles age 30-40 and changes in the fleet mix.

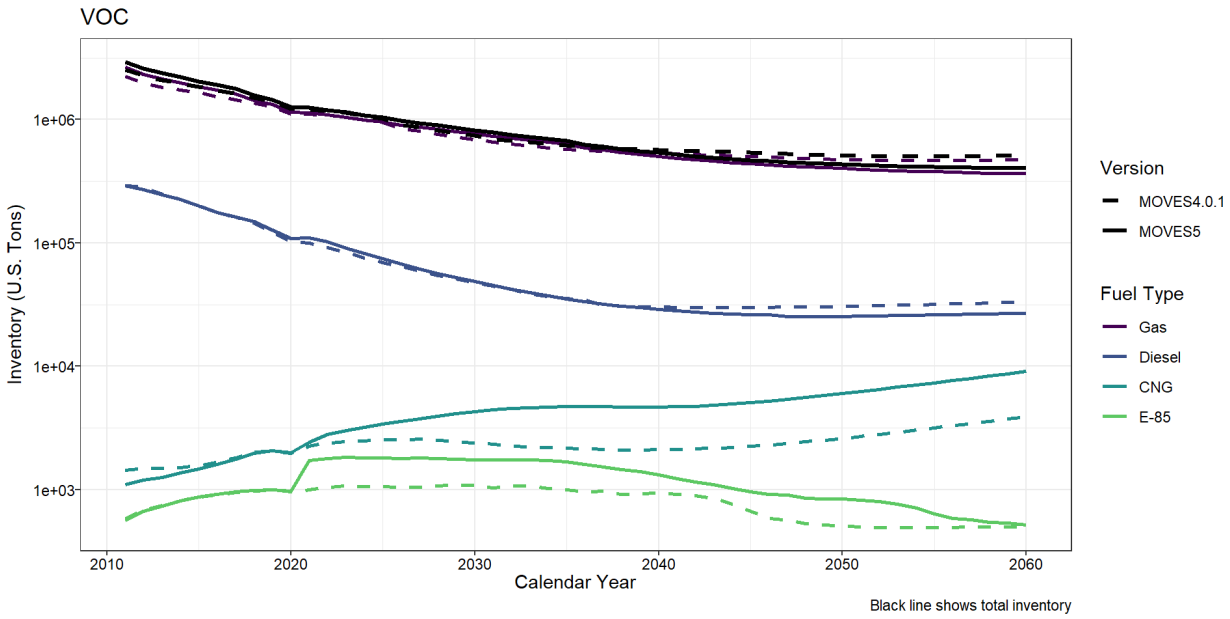


*Figure 6-14—National onroad VOC by fuel type in MOVES5 as compared to MOVES4.0.1. Note the y-axis is in log space. The black lines are totals across all fuel types.*

The graphs for sample urban counties shown in Figure 6-15 illustrate the decrease in VOC over time, as well as higher MOVES5 emissions pre-2040. In both versions of MOVES, onroad VOC is dominated by emissions from refueling and other evaporative emissions.

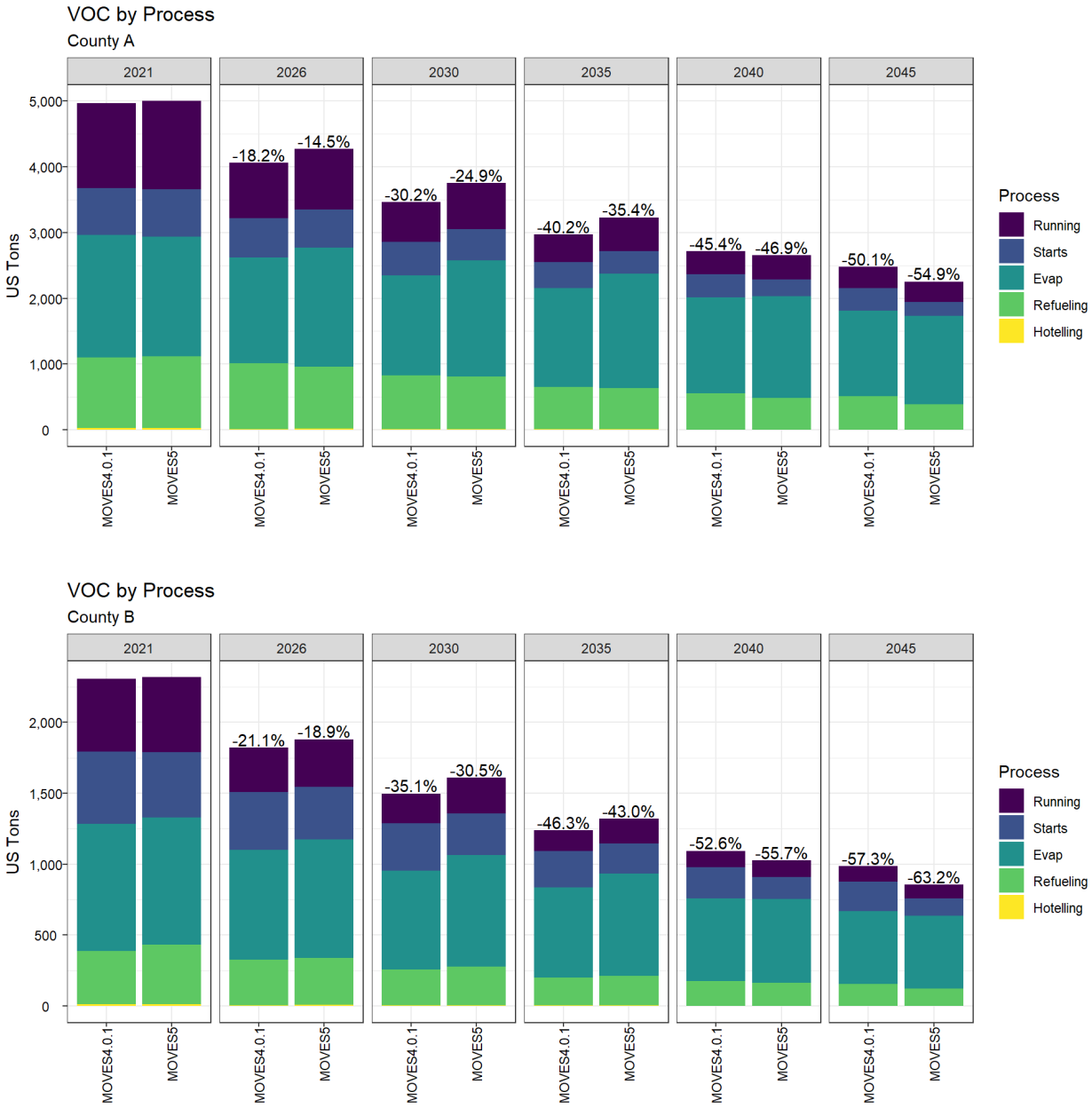


*Figure 6-15—Sample county onroad VOC by grouped emission process in MOVES5 as compared to MOVES4.0.1. Percentage values indicate change compared to 2021.*

## Carbon Monoxide

Like VOC, onroad CO emissions (Figure 6-16) are heavily dominated by emissions from gasoline vehicles. The CO emissions decline over time with the phase-in of Tier 3 standards, improved technology and EVs. Carbon monoxide emissions in MOVES5 are higher than MOVES4 until about 2040 due to more detailed accounting of vehicles age 30-40 and changes in the fleet mix.

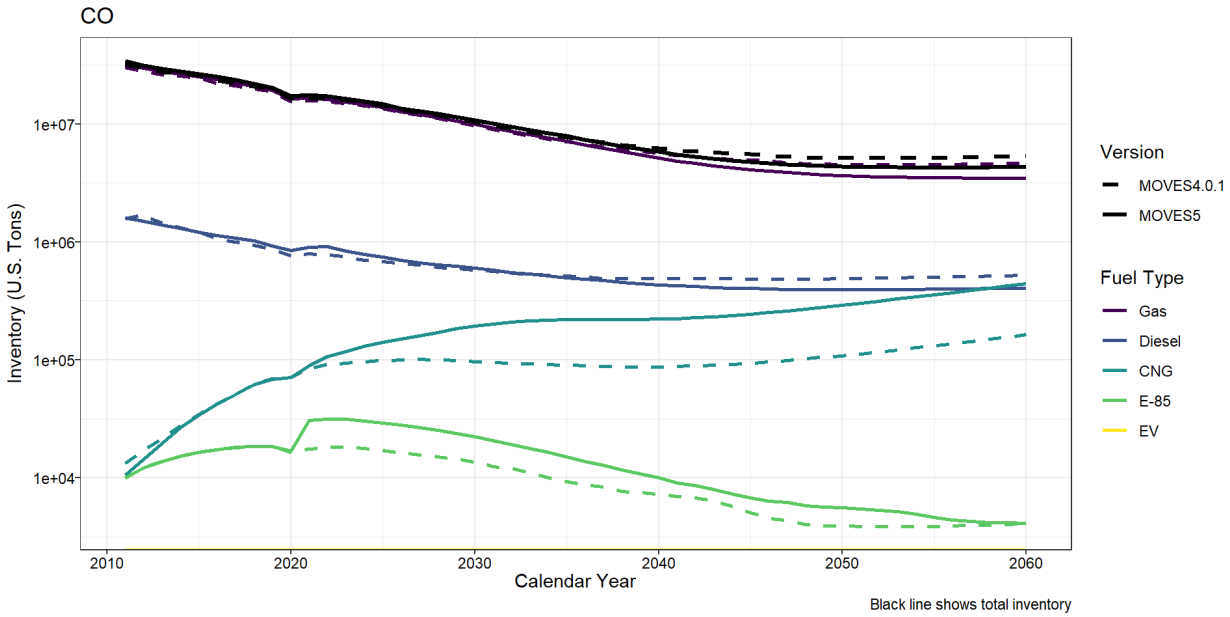


*Figure 6-16—National onroad VOC by fuel type in MOVES5 as compared to MOVES4.0.1. Note the y-axis is in log space. The black lines are totals across all fuel types.*

Figure 6-17 illustrates these trends in two sample urban counties.

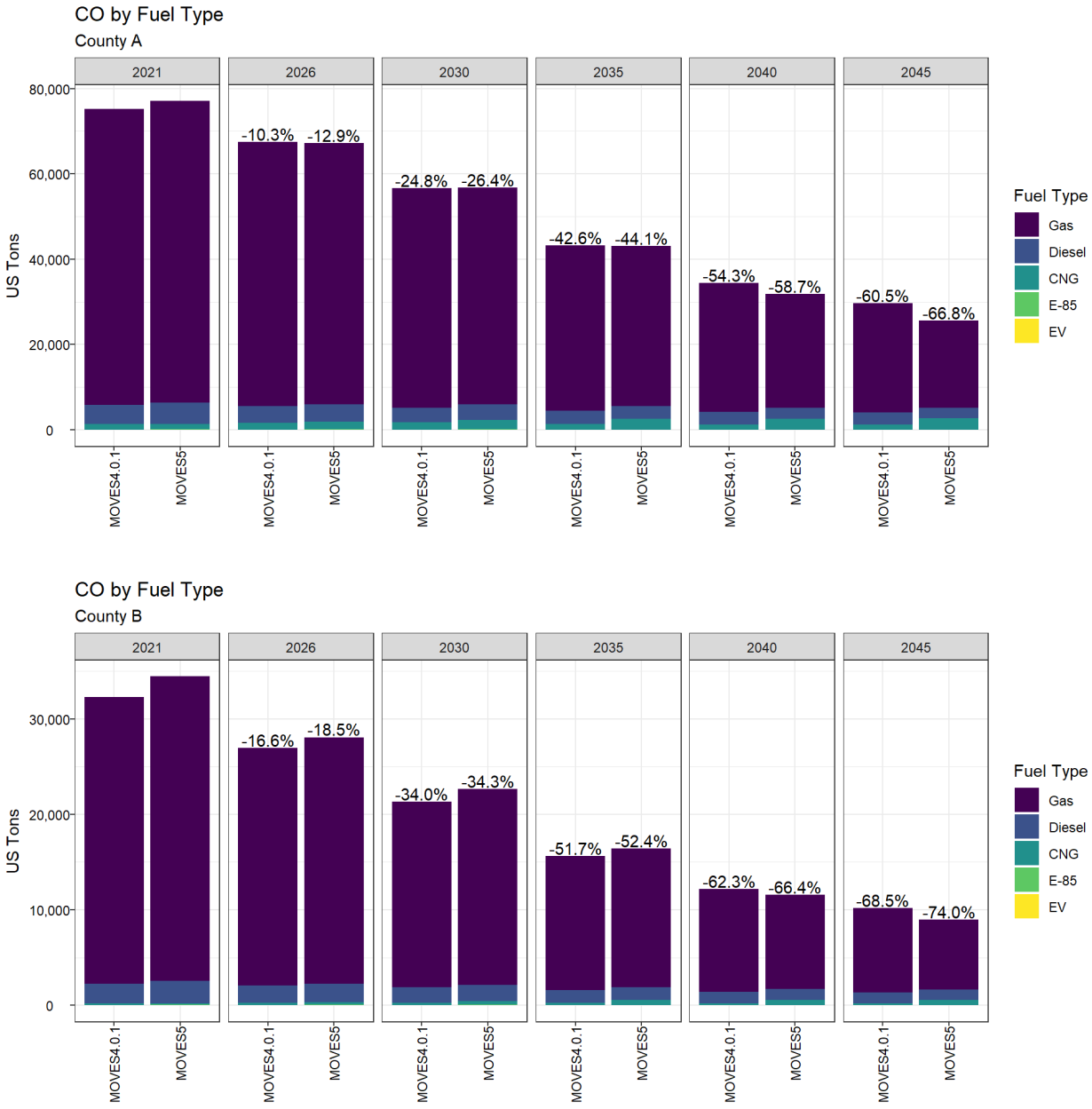


*Figure 6-17—Onroad CO by emission process for two sample counties in MOVES5 as compared to MOVES4.0.1. Percentage values indicate change compared to 2021.*

## Ammonia

Ammonia (NH3) emissions in MOVES5 are similar to MOVES4, except for an update to the $NH_3$ rates from CNG vehicles. Net emissions in the two MOVES versions are similar in early years, but lower in MOVES5 after about 2030 due to the phase-in of more EVs.

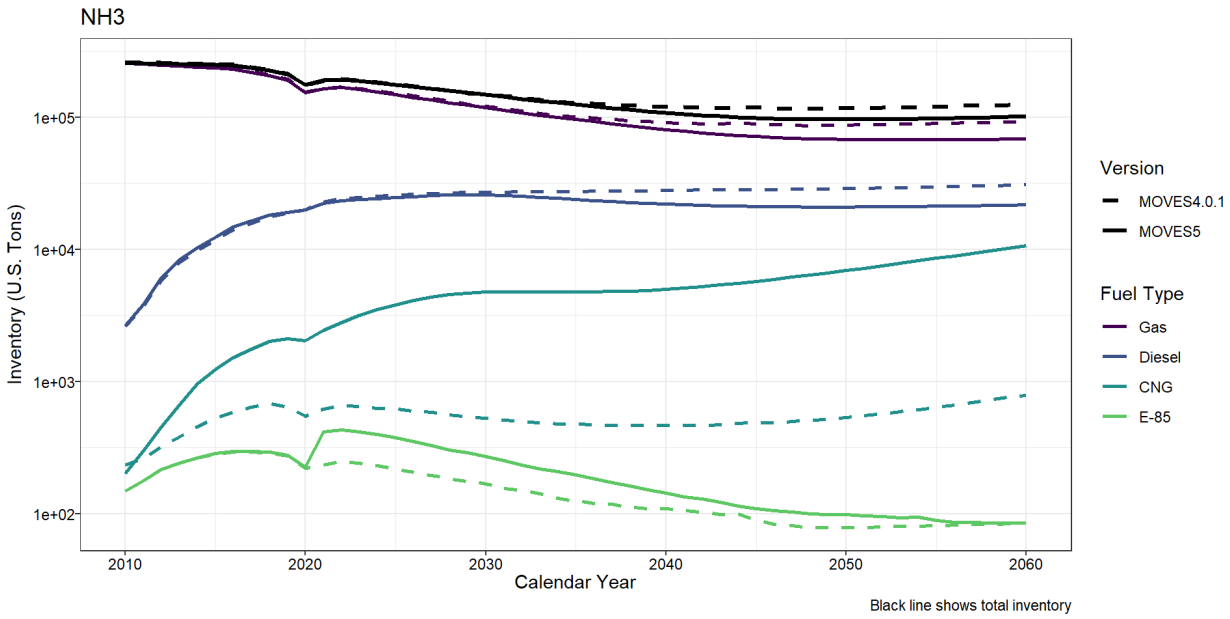


*Figure 6-18—National onroad $NH_3$ by fuel type in MOVES5 as compared to MOVES4.0.1. Note the y-axis is in log space. The black lines are totals across all fuel types.*

## Sulfur Dioxide

As illustrated in Figure 6-19, $SO_2$ emissions are dominated by emissions from gasoline vehicles. From 2021 to about 2040, MOVES5 estimates higher $SO_2$ emissions as compared to MOVES4, primarily due to updated information on gasoline sulfur content. After about 2040, $SO_2$ emissions are lower in MOVES5 due to the shift to EVs and more efficient vehicles.

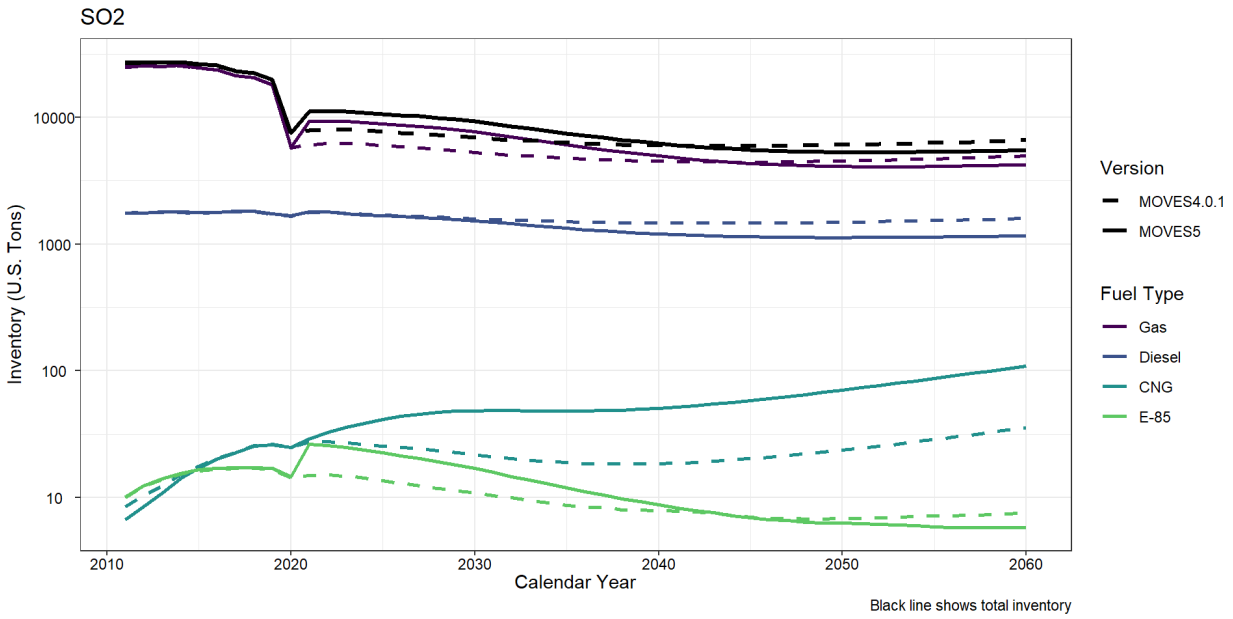


*Figure 6-19—National onroad $SO_2$ by fuel type in MOVES5 as compared to MOVES4.0.1. Note the y-axis is in log space. The black lines are totals across all fuel types.*

## 6.2 Nonroad

The only nonroad inputs that were changed for MOVE5 were the sulfur levels for nonroad gasoline and marine diesel fuels, resulting in a net increase in $SO_2$ emissions from nonroad vehicles as shown in Figure 6-20.

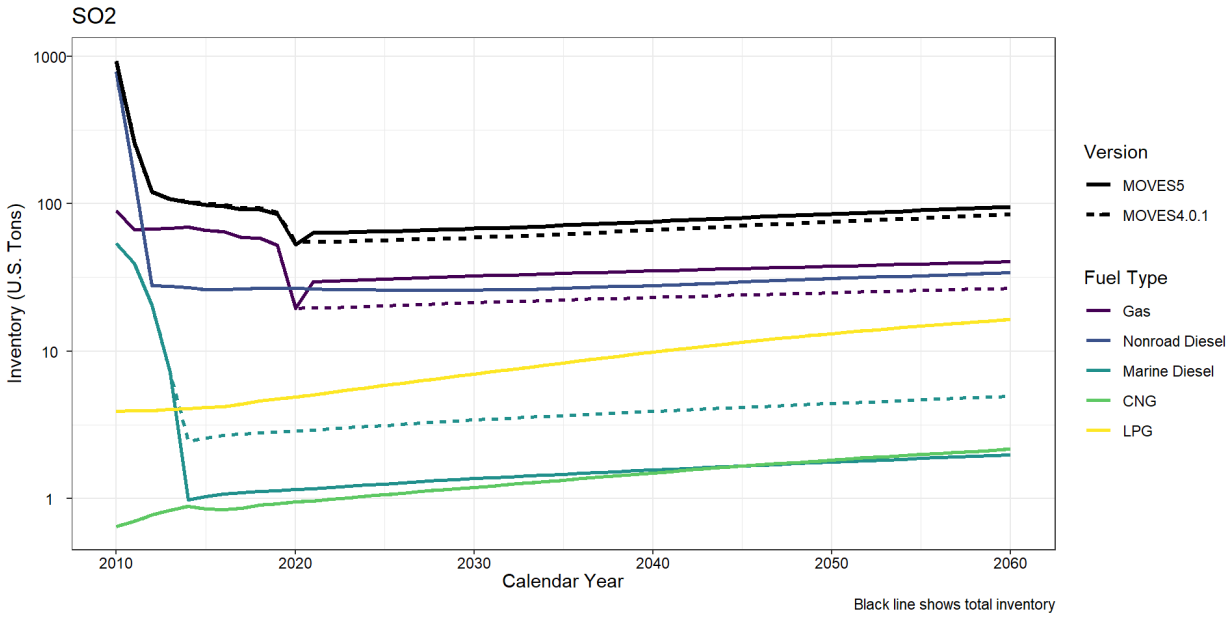


*Figure 6-20 Nonroad $SO_2$ in MOVES5 as compared to MOVES4.0.1. Note the y-axis is in log space. The black lines are totals across all fuel types.*

Emissions of other nonroad pollutants are the same in MOVES5 as in MOVES4. Figure 6-21 summarizes annual nonroad emissions for key pollutants from running MOVES5 at the national level using default inputs. Because nonroad activity varies substantially with season and geography, results for specific times and locations will differ from these national results. As noted previously, MOVES does not cover aircraft, locomotives, and commercial marine vessels.

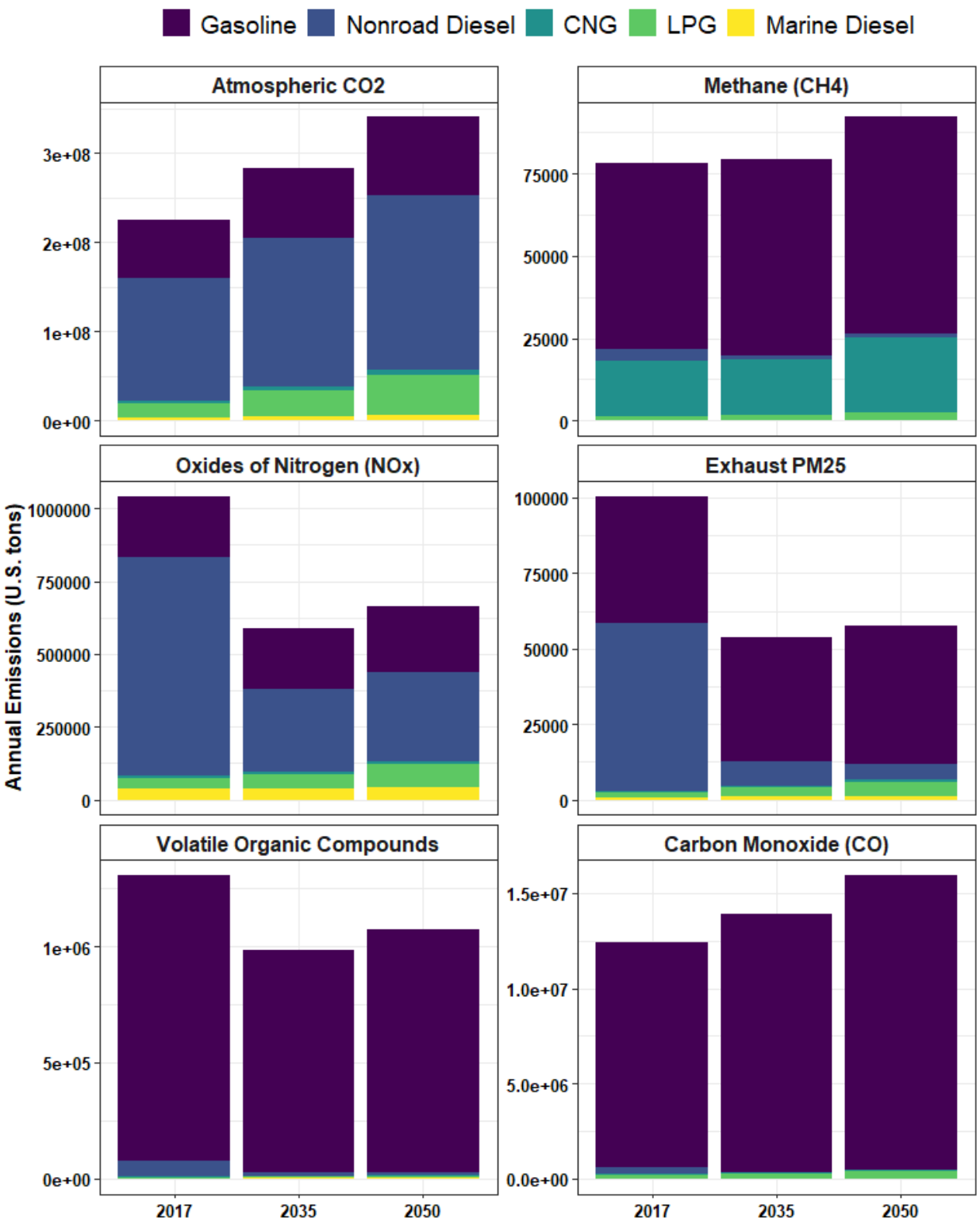


*Figure 6-21 MOVES5 Nonroad emissions by calendar year*

# 7. MOVES Testing and Evaluation

To ensure that the MOVES model contains the state-of-the-science when estimating emissions from mobile sources and that it is usable by a variety of modelers, MOVES is subject to review and evaluation in several different ways. Because the MOVES model is developed incrementally, reviews and evaluations of earlier versions of MOVES are often relevant even for later versions.

## 7.1 Peer Review

Since MOVES2014b, we have conducted five rounds of peer review for the updates to MOVES data and algorithms, following EPA's peer review policies and procedures.[31] Reviewer comments and EPA's responses are documented in EPA's Science Inventory, online at https://cfpub.epa.gov/si/index.cfm with the Record IDs listed below.

- In 2017, we conducted peer review of updates to onroad vehicle population and activity, heavy-duty exhaust emission rates, fuel supply defaults, speciation and toxic emissions from on-road vehicles, and particulate matter emissions from light-duty gasoline vehicles. (Record IDs 328810 and 328830)
- In 2019, we conducted a peer review of additional updates to the modeling of heavy-duty vehicles, including updates to heavy-duty exhaust emission rates, incorporation of glider trucks to MOVES, and updated start, hotelling and idling activity data from instrumented vehicle studies. (Record IDs 347135 and 347136)
- In 2020, we conducted peer review of updates to the light-duty exhaust emission rates, updates to heavy-duty crankcase emission rates, and updated fuel supply and fuel wizard factors. (Record ID 347138)
- In 2022 and 2023, we conducted peer review of updates to the modeling of electric vehicles and updates to refueling and ammonia emissions. (Record IDs 356887 and 356914)
- In 2024, we conducted peer review of updates to the MOVES fuel supply, updates to brake wear emissions, and updates to ammonia emission rates from CNG vehicles. (Record IDs 361938, 361941, and 361938)

Peer review documents for previous versions of MOVES are also available at the Science Inventory page.

## 7.2 MOVES Review Work Group

To provide expert feedback and advice on development of the first three versions of MOVES, the Mobile Sources Technical Review Subcommittee (MSTRS) chartered a series of MOVES Review Work Groups focused on sharing technical expertise. Members of the work group represented a variety of stakeholders, including vehicle and engine manufacturers, fuel producers, state and local emission modelers, academic researchers, environmental advocates, and affected federal agencies. The first work group was chartered in April 2007 and met through April 2010 to provide feedback on MOVES initial development, culminating with the release of MOVES2010 in December 2009. A second work group met from July 2012 through July 2013 during the development of MOVES2014, released in October 2014. A third work group met from September 2016 through September 2021 to provide feedback on the development of MOVES3, released in November 2020.[32]

Each work group was charged with reviewing information about MOVES development and providing recommendations to the MSTRS. In turn, the MSTRS evaluated the work group recommendations and

decided how these issues should be reported to the Clean Air Act Advisory Committee (CAAAC), which, under the Federal Advisory Committee Act (FACA), may formally give EPA collective advice. Notes and presentations from the MOVES3 workgroup meetings are available at https://www.epa.gov/moves/moves-model-review-work-group.

### 7.3 Internal Testing

The MOVES development team performs rigorous testing throughout the model development life cycle. This includes unit testing to ensure that every change to MOVES affects emissions and activity as expected, and systematic integrated testing to ensure changes do not have unintended side effects. We also test to ensure that Rates Mode and Inventory Mode generate the consistent outputs if used with same inputs.

### 7.4 Beta Testing and Shared Release Candidate

Prior to public release, draft versions of MOVES are tested by a small group of experienced MOVES users outside of EPA. This beta testing has helped to identify errors and to improve the MOVES interface and documentation.

Immediately prior to the official release, we also posted a draft, release candidate version to the MOVES GitHub site (https://github.com/USEPA/EPA_MOVES_Model/releases/tag/MOVES5-RC2). This posting allowed additional user testing of a near-final version of the model and allows modelers to become familiar with functional changes prior to the official public release.

### 7.5 Accessibility Testing

The MOVES3 graphical user interface was reviewed for accessibility under the Web Content Accessibility Guidelines 2.0 and the Revised Section 508 standards published January 18, 2017 and corrected January 22, 2018. The MOVES interface partially supports Section 508 accessibility requirements.[33] Interface changes for MOVES4 and MOVES5 were minimal and the MOVES3 assessment is still applicable. We plan to improve MOVES accessibility in future versions.

### 7.6 MOVES Sensitivity Analysis

A number of studies have been conducted to identify the input factors that are most important in influencing MOVES results.[34,35,36,37] In general, model year--and thus calendar year and age distribution--is important because it captures the decline in emissions as emission standards become more stringent over time. Other factors such as vehicle speed and driving pattern, fuel parameters, humidity and ambient temperature may also be important for specific vehicle categories, emission processes, and pollutants. However, changes to MOVES emission factors, emission adjustments, and the relative activity and vehicle population across MOVES versions can affect the model's sensitivity greatly. This means that one should not assume that sensitivity determinations developed for one version of MOVES are accurate for other versions.

### 7.7 Evaluation by Industry-Funded Research Group

The MOVES2014 model was reviewed by the Coordinating Research Council, a non-profit corporation supported by the energy and mobility industries. The review (CRC project E-101) included three distinct task elements: (1) a critical evaluation of modeling methods, (2) inventory analyses applied to three locations, and (3) a validation of the fuel methodology using independent data sources.[38] The report

provided detailed recommendations in 10 areas. EPA used these recommendations to help prioritize efforts for MOVES3 and published a detailed response.[39]

An additional review (CRC project E-116) investigated MOVES2014 evaporative inputs.[40] While the feedback was valuable, most of the issues pointed out in this CRC report were expected to have very little impact on the magnitude of the evaporative emissions computed by MOVES.

### 7.8 Comparisons to Independent Data

Evaluating the performance of the MOVES model in comparison to other measures is useful for assessing the model's performance in accurately estimating current emission inventories and forecasting emission trends. It also helps to identify areas in need of improvement, and guide future work and research. However, it is not appropriate to evaluate MOVES by comparing against measurements based only on a few vehicles, or without sufficiently customizing MOVES inputs to account for the measurement conditions (e.g., fleet composition, vehicle activity, meteorology).

In our efforts to evaluate MOVES, we have prioritized comparisons for the major sources of emissions (e.g., onroad light-duty gasoline, heavy-duty diesel) and areas where significant independent data is available. In assessing our results, we consider systematic bias observed across multiple data sources as indicative of model underperformance. On the other hand, if the model predictions are generally within the variability of independent measurements, it gives confidence that the model is predicting real-world emissions reasonably well.

Evaluating vehicle emissions is complex. Lyu and coauthors summarized potential evaluation methods in a 2021 review study and concluded that "selecting different measurements will significantly impact the assessment of the vehicle emission results and the applicable scope of the measurements. Considering the different influencing factors of the operating vehicle emissions will have an impact on the model application of the vehicle emission evaluation."[41] In addition, some aspects of emissions, such as start and evaporative emissions, are particularly challenging to measure in the real world, and, thus, to evaluate.

Evaluating MOVES emission rates may include comparisons to data from sources such as dynamometer tests, remote sensing devices (RSD) and portable emission monitoring systems (PEMS). To capture rare (but influential) high emitters, it is important that the data samples are large and diverse. Likewise, we prefer comparison data that represent known operating conditions (e.g., a pre-conditioned IM240 drive cycle). Such comparisons are particularly valuable because the emission rates from the study can be compared with MOVES emission rates using the same activity and fleet variables such as vehicle mix, vehicle age, and vehicle operating mode. For example, a broad-based study was used to evaluate MOVES2014b and subsequently to update high-power emission rates in MOVES3.[42]

Another study compared light-duty gasoline vehicle emissions measured with remote sensing to emission rates from MOVES3. The study was intended to evaluate a new RSD methodology rather than to judge the accuracy of MOVES. The authors noted differences in the time scale of measured emissions and the resulting complication in determining emissions by VSP bin. However, they found that their measured emission rates were in the same range as MOVES3 input rates for $CO_2$, CO, and NO. Hydrocarbon emission rates were high compared to MOVES values. They suspected an error or noise in

their THC measurements. The relative effects of vehicle age were similar between the observed values and those incorporated into MOVES3.[43]

For heavy-duty vehicles, Allen et al. used RSD to measure heavy-duty truck emissions in Utah and compared measured NOx emissions to MOVES4 emission rates. Unlike MOVES predictions, they found that winter NOx emissions were twice as high as summer emissions. They also saw much more emission deterioration with age than MOVES predicts.[44]

Other studies compare "localized composite" emissions, using composite emission measurements from many vehicles by tunnel[45] or roadside emission monitors[46] where vehicle emissions are predominant and vehicle activity and fleet mix can be accounted for to some degree. A strength of tunnel and roadside measurements is that they can capture the large sample sizes of vehicles operating in real-world conditions needed to measure 'fleet-average' emission rates. However, such comparisons may not include all pollutants, and they only assess the operating conditions represented at the specific location. And, as Simon, et al. demonstrated, the inferred emissions depend on the observation method and the distance from the roadway.[47] The heavy-duty exhaust technical report includes comparisons of MOVES heavy-duty emission rates to tunnel and roadside measurements and examples of using such data to update ammonia and $N_2O$ emissions.[15] A near-road study that suggests increases in heavy-duty diesel emissions with decreasing ambient temperature[48] is discussed in more detail in the MOVES adjustment report.[17]

While tunnel studies and remote sensing can measure real-world emissions from many vehicles in a few locations, portable emission monitors can measure emissions from a smaller number of vehicles throughout a real-world driving route. Frey and coauthors instrumented light-duty gasoline vehicles driven on prescribed routes and compared their emissions to MOVES model projections, concluding that the MOVES operating mode approach has good accuracy and moderate-to-high precision, explaining a wide range of variability in emission rates,[49] and that MOVES is highly accurate in locating measured emission "hotspots," that is, segments of a driving route with emissions in the 80$^{th}$ and 90$^{th}$ percentiles.[50] Similarly for HD diesel vehicles, Farzaneh et al. compared draft MOVES3 $NO_x$ emission factors to emissions measured using PEMS on three trucks of model year 2005, 2009 and 2014 with different load weights and sizes. However, they comment, "The current MOVES opMode equations do not appear to capture the impact of weight on the emission rates of HDDVs." In addition, while the emision rates in their comparison are not corrected for fuels or ambient conditions, the pattern of relative emissions by operating mode can be compared with MOVES base rates. The results for the MY 2005 truck and the MY 2009 tested with a normal load show a much flatter curve than predicted by MOVES based on heavy-duty in-use testing data. The results for the MY 2014 truck tested with a normal load show a curve with much higher emissions for the lower-speed coasting bins (11 & 21) than predicted by MOVES based on heavy-duty in-use testing data.[51])

At a more general level, some MOVES evaluations compare regional air quality model results from models such as the Community Multiscale Air Quality Modeling System (CMAQ) with air quality monitor and deposition data and satellite data. These "top-down studies" are useful to assess the overall emissions contribution from all relevant emission sources to air quality measurements. Discrepancies between air quality modeling predictions and measurements can point to deficiencies in the emissions inventory but may be confounded with deficiencies in the air quality model (e.g., modeling transport,

boundary layer, deposition, transformation, and other physical and chemical processes). In addition, top-down studies on their own cannot identify the individual sources in the emissions inventory that are responsible for the modeling discrepancy.[52,53] Newer studies[54] have focused on efforts to minimize influence of parameters other than emissions, providing valuable insights into differences between MOVES and other methods to estimate onroad inventories; however the use of MOVES in air quality model studies necessarily involves using support tools that facilitate the use of local activity inputs as well as gridding of emissions spatially and temporally, which can add uncertainty to the identification of specific sources contributing to discrepancies.

Like air quality studies, "macro-scale" fuel consumption studies are also useful, comparing "bottom-up" fuel consumption as estimated by MOVES to "top-down" fuel tax data. These studies can help assess MOVES large-scale vehicle activity estimates and fuel economy values.

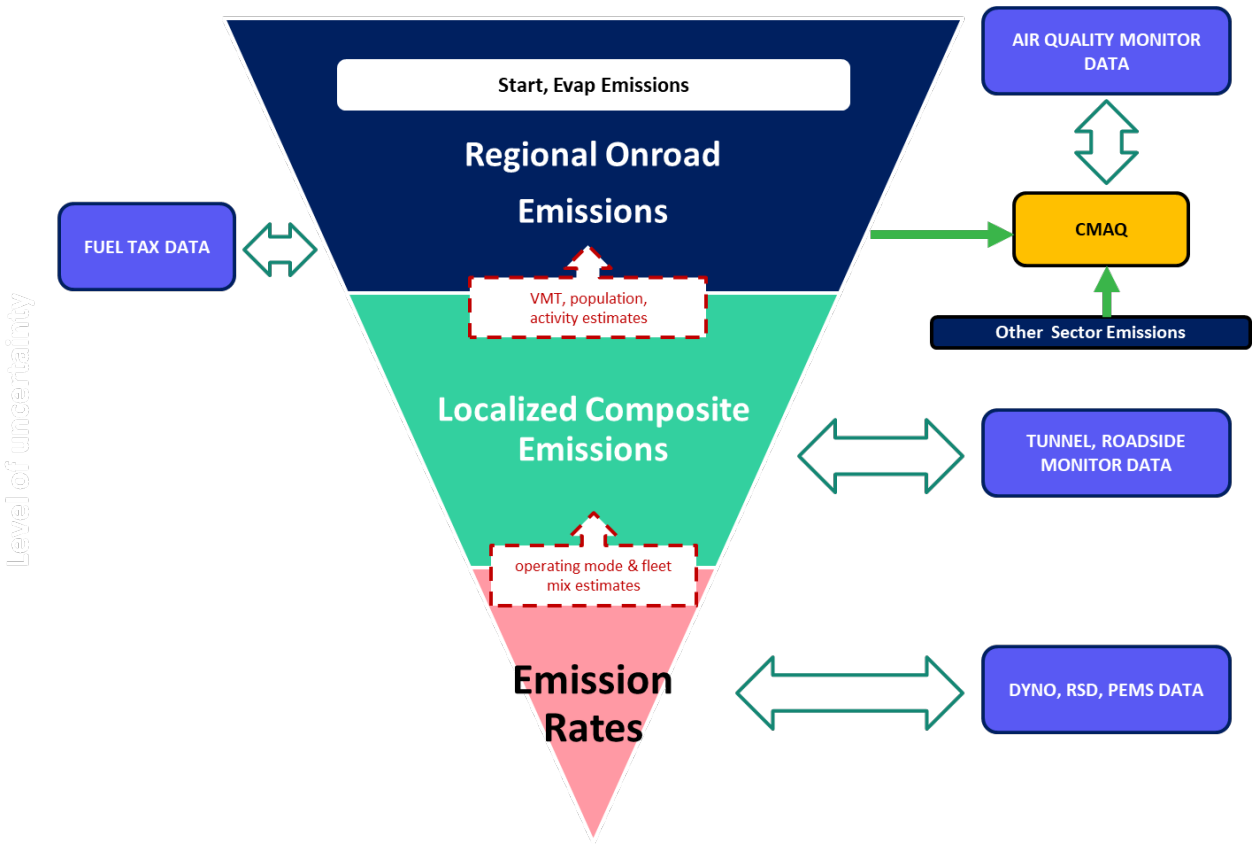


*Figure 7-1--MOVES evaluation opportunities at rising levels of generalization and uncertainty.*

### *Fuel Consumption Comparisons*

Beginning with MOVES3, we have conducted a detailed comparison of the gasoline and diesel fuel consumption estimated by MOVES and estimated by FHWA based on fuel tax data. For our MOVES5 analysis, we used MOVES5 release candidate 2 (MOVES5RC2), a near-final version of that captures all the major activity and energy consumption updates to the model.

As show in Figure 7-2 and Figure 7-3, MOVES5 and MOVES4 both overestimate gasoline and diesel consumption when compared to FHWA estimates. The comparisons should note a number of caveats, such as uncertainties in the MOVES activity inputs, potential inaccuracies in the state-provided fuel tax data, and difficulties in matching the vehicle categories covered by the two estimates--including accounting for public vehicles excluded from the FHWA analysis and uncertainties in the methodology used by FHWA to allocate between highway and off-road fuel use.

Also, note that certain inputs to MOVES do not capture changes over time, such as relative mileage accumulation rates and fuel energy consumption. Given the important use of MOVES in forecasting future emissions, we have chosen updates for these values such that MOVES better represents current and future conditions rather than past. This may partially explain the better agreement seen in Figure 7-2 for years after 2020, and in Figure 7-3 for years after 2018.

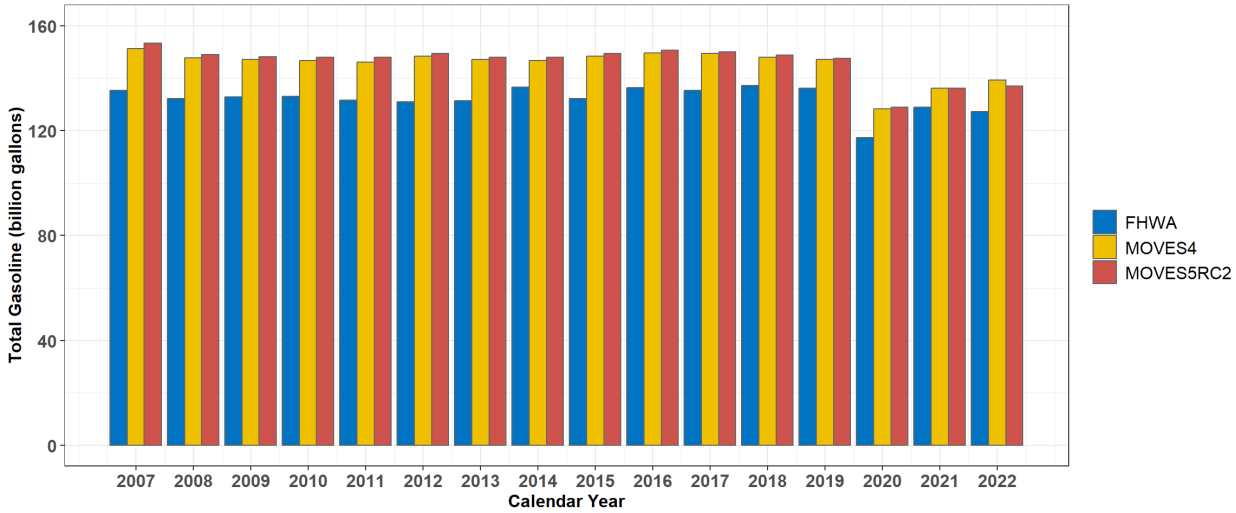


*Figure 7-2—National gasoline consumption (in billion gallons) by calendar year estimated by MOVES4, a near-final version of MOVES5, and FHWA.*

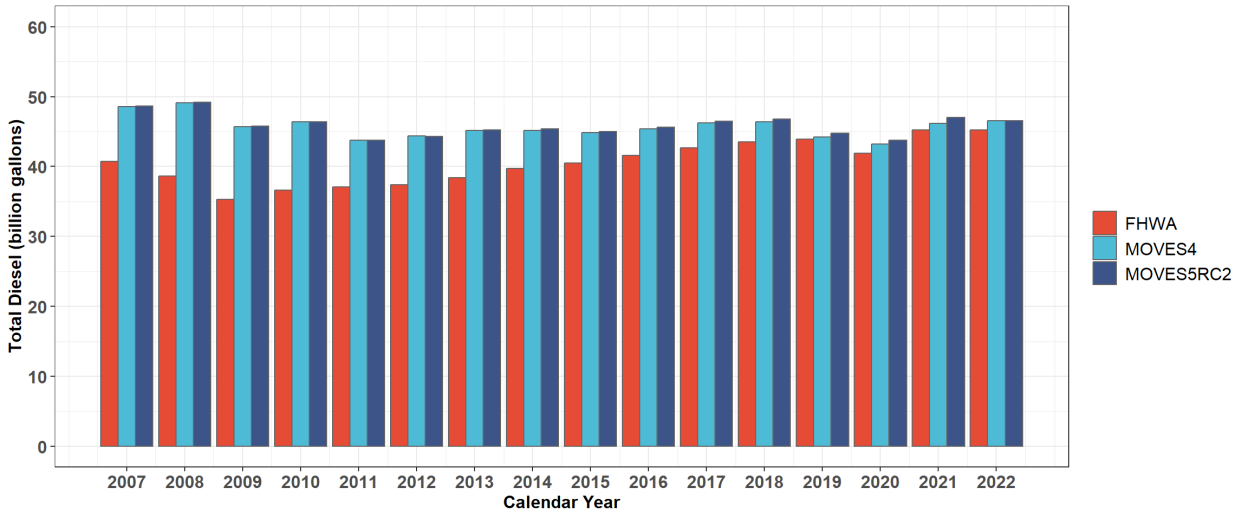


*Figure 7-3—National diesel consumption (in billion gallons) by calendar year estimated by MOVES4, a near-final version of MOVES5, and FHWA.*

### *$NO_X$ Evaluation Work*

Several studies using emissions generated with versions of MOVES2014 have shown differences between air quality model estimates and monitored values for nitrogen oxides. Researchers suggested that air quality models appear to overestimate $NO_X$ ambient values due to an overestimate in $NO_X$ emissions[55,56,57] particularly from LD gasoline vehicles.[58]

In response, as part of MOVES3 development efforts, we evaluated the MOVES2014 light-duty emission rates against in-use measurements and, based on the comparisons,[4242,] we updated the emission rates in MOVES3, generally decreasing light-duty $NO_X$ emissions.

We also formed a cross-EPA workgroup to coordinate efforts to evaluate $NO_x$ emissions and modeling. This effort concluded that:

> *Model over-predictions were likely due to multiple compounding factors that each contributed to a portion of the bias. Based on our review of the evidence, the most important contributing factor to the summer NOx bias was:*
>
> • *Planetary boundary layer (PBL) and vertical mixing algorithms in the Community Multiscale Air Quality (CMAQ) model (version 5.0.2 and earlier) led to too little vertical mixing at certain times and in some locations. These algorithms have been improved in CMAQv5.1 and later versions of CMAQ. These changes substantially reduced the NOx bias, as well as the NOx diurnal bias pattern in simulations run with more recent CMAQ versions.*
>
> *We also demonstrated that there is important uncertainty in the model bias caused by $NO_x$ and $NO_y$ measurement uncertainty, as well as chemical mechanism used. Caution should be taken in using modeled $NO_x$ bias to constrain $NO_x$ emissions or processes incorporated into air quality modeling.*

*Through this effort, we identified aspects of the mobile source $NO_x$ emissions that were overestimated in the evaluated air quality platforms, but based on our analysis so far, mobile source $NO_x$ only had a modest impact on the magnitude and pattern of the bias in modeled $NO_x$ concentrations.*[59]

The workgroup is no longer formally active, but EPA offices continue to work together to understand and improve our emission and air quality models.

# 8. Considerations When Using MOVES

The task of keeping MOVES current with manufacturers' ever-changing vehicle and equipment products, activity data that reflect how these vehicles and equipment are used, and the evolving scientific understanding of emissions can be daunting. We must prioritize our efforts on updates that will affect emissions results the most, are of the most value for our users, and have the largest impact on the overall accuracy of the model.

So, while the functional scope of MOVES is large, the model is not designed to answer every possible question about mobile source emissions. While there are areas of the model that rely on assumptions or limited data, in many cases, these areas either have a small contribution to the total emissions inventory or represent cases where no data was available (e.g., emission deterioration of MY 2027+ heavy-duty diesel emissions).

When deciding whether to use MOVES for a given purpose, it is important to note the following features of the MOVES design:

- MOVES algorithms calculate emissions based on physical and chemical principles, statistical relationships, and use of good engineering judgement. We develop MOVES algorithms based on the best available knowledge at the time, and emission relationships inferred from present emission databases. MOVES algorithms have and will continue to be updated in future MOVES versions as our knowledge of technologies and emission processes is updated.
- MOVES is designed to model fleet-average emissions rather than the emissions of any specific vehicle or piece of equipment.
- MOVES models the emissions from vehicles and equipment designed to meet emission standards in the United States. There are considerable challenges to adapting the MOVES framework to other nations, primarily related to the need for specific information about the emission performance and activity of vehicles.[60] [61] [62] [63] [64]
- While MOVES models onroad and nonroad emissions in California, the MOVES defaults do not capture all the details of California emission standards and control programs. Instead, California uses California-specific models for modeling mobile sources.[65]
- MOVES allows users to "pre-aggregate" location and time-specific input data when modeling emissions at the national and state level and over time periods longer than one hour. Pre-aggregating inputs to these larger scales is faster but reduces the model accuracy and precision compared to modeling at a more detailed level and aggregating the results at the end.
- MOVES defaults generally characterize fleet characteristics and activity at the national level. To accurately model emissions in a specific location, accurate local inputs must be used. For example, MOVES national default information on vehicle fleet mix, including the fraction of electric vehicles, does not capture the substantial variation by location.
- MOVES allows user input of many parameters, and therefore, the quality of model output will depend on the quality of these inputs, as well as the appropriateness of the model defaults relied on. When inputs are generated by other models, it is important to understand the limitations of those models as well.[66]
- MOVES does not separately model hybrids or plug-in hybrids with a conventional gas or diesel engine. Onroad hybrid vehicles meet the same emissions standards as conventional gasoline or

diesel vehicles and are incorporated into the fleet average criteria pollutant, energy, and $CO_2$ emissions for each model year in MOVES.

- MOVES uses the same estimates of vehicle activity regardless of fuel type, i.e., activity for vehicles fueled by electricity and compressed natural gas are the same for vehicles fueled by gasoline and diesel.
- MOVES includes default tampering and mal-maintenance rates that are used to derive heavy-duty diesel emission rates, which cannot be updated by users. These rates were last updated for MOVES2014 with many of the data and assumptions from studies conducted between 1988 and 2007.[15] MOVES does not explicitly account for tampering and mal-maintenance of light-duty onroad vehicles or nonroad equipment.
- MOVES is not designed to model the impact of grade at national or county levels. MOVES does allow grade to be included at the project scale. The project scale allows modeling of a wide variety of onroad drive cycles and grades; users should assess whether the modeled drive cycle is realistic at a given grade for the project-scale analysis.

In addition, it is useful to understand the sources and process used to update the MOVES default data. MOVES5 and MOVES4 updates were limited in scope as described in Section 2.3 above and in the MOVES4 Overview Report,[67] so most emission rates have not been updated since MOVES3. While the MOVES3 updates were based on millions of emission test results, coverage varies depending on data availability. MOVES forecasts emissions up to calendar year 2060; these estimates are necessarily based on forecasts and extrapolation from data available at the time of analysis, generally 2021 or earlier. Consistent with MOVES purpose and design, MOVES relies on multiple datasets and analysis methods to estimate emissions across model years, fuel types, vehicle and engine types, and emission processes. Thus, fleet-average emission estimates and overall trends are generally more robust than emission rates from individual vehicle types, model years, fuel types and emission processes that may be based on a single data set or analysis.

Furthermore, due to MOVES priorities and data availability, some onroad inputs have not been updated recently or have other notable limitations. For example, due to the small number of light-duty diesel vehicles in the U.S. fleet, MOVES uses the same exhaust emission rates for light-duty diesel vehicles as for light-duty gasoline vehicles.[16] MOVES motorcycle emissions rates were last analyzed in 2010.[68] Light-duty gasoline running emission rates were updated for MOVES3 based on millions of test results,[16] but differences between "with I/M" and "non I/M" rates for THC, CO and NOx emission rates are based on previous analysis, and the emissions effects of different I/M program designs were generated using MOBILE6.[16 17] Light-duty gasoline start deterioration with age is derived from information on running emissions.[16] Evaporative emissions other than refueling have not been updated since MOVES2014, and the refueling updates are based on a limited range of ambient temperatures, gasoline RVPs and model years. Also, while MOVES3 updated the vehicle activity patterns used to estimate start and ONI exhaust emissions, MOVES evaporative emission calculations rely on older, more limited, trip pattern data.[18]

MOVES3 emission rate updates included updates to HD diesel running emissions rates based on analysis of a substantial database of running emissions data from well-maintained heavy-duty diesel trucks,[69] but the values used to estimate heavy-duty emission deterioration with age were last updated for MOVES2014. We also have fewer data on start and crankcase emissions. Forecasts of HD diesel start emission rates for MY 2027 and later are based on tests of a single prototype engine. MOVES4 crankcase

changes are due to an updated algorithm but continue to use MOVES3 data. In addition, while we also updated rates for heavy-duty gasoline and heavy-duty CNG vehicles, data are sparse for these vehicles. In particular, peer reviewers have suggested that we may be underestimating crankcase emissions from CNG vehicles.[15]

MOVES tire wear emission rates are based primarily on a literature review from 2006 and 2007[14] and do not account for technology and market changes such as the increasing number of electric vehicles. Fuel effects and some other MOVES adjustment factors are based on testing of older vehicle technologies.[2 17]

Nonroad emissions estimates are generally based on more limited data than onroad emissions for both emission factors and population and activity. Many of the onroad emissions factors are applied to nonroad engines due to a lack of nonroad data; therefore, several of the previously mentioned limitations for onroad also apply to nonroad, with the added uncertainty of applying onroad factors to nonroad engines. Since many of the source data and algorithms used to model nonroad equipment date from the first release of EPA's NONROAD model in 1998, some recent industry trends, such as the increased adoption of electric- or battery-powered equipment (e.g., lawn and garden equipment) and transition from 2-stroke to 4-stroke engines, are not reflected in the model. We are currently working on acquiring nonroad emissions and activity data to improve the emissions characterization of the nonroad sector.

# 9. MOVES5 Documentation

There is extensive documentation for MOVES, including guidance documents to help explain regulatory requirements, user instructions, training materials, and technical reports.

MOVES documentation is available on the web at https://www.epa.gov/moves. In addition, user help is built into the MOVES GUI. Information on installing and using MOVES is available at https://www.epa.gov/moves/latest-version-motor-vehicle-emission-simulator-moves.

The MOVES source code is available at https://github.com/USEPA/EPA_MOVES_Model and documentation relating to the code and the computer technology aspects of using MOVES are at https://github.com/USEPA/EPA_MOVES_Model/tree/master/docs.

To cite MOVES5.0.0 in general:

USEPA (2024) *Motor Vehicle Emission Simulator: MOVES5.0.0.* Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2024. https://www.epa.gov/moves

Table 9-1 lists the various documentation currently available for MOVES5 and provides information on accessing each document.

*Table 9-1 MOVES Documentation*

| General: | | | |
|---|---|---|---|
| | EPA Releases MOVES5 Mobile Source Emissions Model: Questions and Answers | Highlights the difference between MOVES5 and earlier versions of MOVES and explains EPA policy on using MOVES5 in state implementation plans and transportation conformity analyses | https://www.epa.gov/moves/latest-version-motor-vehicle-emission-simulator-moves#background |
| | Frequently Asked Questions | Answers to frequently asked questions on MOVES installation, use, terminology and output | https://www.epa.gov/moves/frequent-questions-about-moves-and-related-models |
| | MOVES Webinars | Webinars describing MOVES versions and their use | https://www.epa.gov/moves/moves-training |

| Using MOVES for Regulatory and Other Purposes: | | | |
|---|---|---|---|
| | Federal Register Notice of Availability | Announces the official release of MOVES5 for use in SIP development and transportation conformity purposes in states other than California. | https://www.epa.gov/state-and-local-transportation/policy-and-technical-guidance-state-and-local-transportation#emission |
| | MOVES5 Technical Guidance: Using MOVES to Prepare Emission Inventories for State Implementation Plans and Transportation Conformity | Guidance on appropriate input assumptions and sources of data for the use of MOVES5 in SIP submissions and regional emissions analyses for transportation conformity purposes. | https://www.epa.gov/state-and-local-transportation/policy-and-technical-guidance-state-and-local-transportation#emission |
| | MOVES5 Policy Guidance: Use of MOVES for State Implementation Plan Development, Transportation Conformity, General Conformity, and Other Purposes | How and when to use the MOVES5 for SIP development, transportation conformity, general conformity, and other purposes. | https://www.epa.gov/state-and-local-transportation/policy-and-technical-guidance-state-and-local-transportation#emission |
| | Additional Guidance | Other guidance covers MOVES at the Project Scale (used for hot-spot analyses), using MOVES to model specific control programs (e.g., replacing or retrofitting older diesel vehicles and equipment with cleaner technologies), using MOVES to conduct I/M performance standard modeling analyses for I/M SIPs, using MOVES to develop port-related emissions inventories, and using MOVES to estimate GHGs | Until updated, existing guidance is generally applicable to MOVES5<br>See https://www.epa.gov/state-and-local-transportation |

| Training & Cheat Sheets: | | | |
|---|---|---|---|
| | Onroad Cheat Sheet | Summarizes common tables and values used to create onroad MOVES runs and interpret their outputs. | https://github.com/USEPA/EPA_MOVES_Model/blob/master/docs/MOVES5CheatsheetOnroad.pdf<br><br>Also available in the MOVES GUI Help menu. |
| | Nonroad Cheat Sheet | Summarizes common tables and values used to create nonroad MOVES runs and interpret their outputs. | https://github.com/USEPA/EPA_MOVES_Model/blob/master/docs/MOVES5CheatsheetNonroad.pdf<br><br>Also available in the MOVES GUI Help menu. |
| | MOVES Hands-on Training | A detailed hands-on course for state and local agency staff who will use MOVES for developing emissions inventories for SIP and conformity analyses. The course is designed to be self-taught in periods where no classes are scheduled, or constraints prevent attending an in-person course. Users can work through the modules and hands-on exercises at their convenience. | https://www.epa.gov/moves/moves-training#hands-on-training |

| | | | |
|---|---|---|---|
| | Project-Level Training for Quantitative PM Hot-Spot Analyses | EPA's training course on implementing EPA's PM Hot-Spot Guidance is a technical, hands-on course geared toward state and local agency staff. The course focuses on using EPA's emission model MOVES and EPA's dispersion model AERMOD to complete quantitative PM hot-spot analyses. The course can be self-reviewed when training sessions are not available.<br><br>The course is based on MOVES2014b and still largely applicable to MOVES5. | https://www.epa.gov/moves/moves-training-sessions#hotspot |

| Installation and Computer-Related Aspects of Using MOVES | | | |
|---|---|---|---|
| | Installation Suite | Executable program to install MOVES5 and all required software. Instructions are embedded in the installer | https://www.epa.gov/moves/latest-version-motor-vehicle-emission-simulator-moves#download |
| | MOVES Installation Troubleshooting | How to resolve common installation issues | https://github.com/USEPA/EPA_MOVES_Model/blob/master/docs/InstallationTroubleshooting.pdf |
| | Quick Start Guide to Accessing MariaDB Data | Hints on how to access data in new MariaDB installation | https://github.com/USEPA/EPA_MOVES_Model/blob/master/docs/QuickStartGuideToAccessingMariaDBData.pdf |
| | MOVES5 Database Conversion Tool Help | Explains use of tool to convert MOVES3 and MOVES4 databases for use with MOVES5 | https://github.com/USEPA/EPA_MOVES_Model/blob/master/database/ConversionScripts/InputDatabaseConversionHelp.pdf |
| | Speciation Profile Scripts Tool Help | Instructions for how to speciate MOVES output for air quality modeling as a post-processing step | https://github.com/USEPA/EPA_MOVES_Model/blob/master/database/ProfileWeightScripts/profileScriptHelp.pdf |
| | AVFT Tool Help | Instructions on how to use the AVFT Tool for building the AVFT input table | https://github.com/USEPA/EPA_MOVES_Model/blob/master/gov/epa/otaq/moves/master/gui/avfttool/AVFTToolHelp.pdf |
| | Building LEV and NLEV Input Databases Help | Instructions on how to use the LEV/NLEV Tool in the MOVES GUI | https://github.com/USEPA/EPA_MOVES_Model/blob/master/database/LEV_NLEVScripts/InstructionsForLEV_NLEV_Tool.pdf |
| | ONI Tool Help | Instructions on how to use the ONI Tool when running MOVES in rates mode with default off-network idling activity | https://github.com/USEPA/EPA_MOVES_Model/blob/master/database/ONITool/InstructionsForONITool.pdf |

| | | | |
|---|---|---|---|
| | Anatomy of a RunSpec | An overview of all of the fields contained in a MOVES RunSpec | https://github.com/USEPA/EPA_MOVES_Model/blob/master/docs/AnatomyOfARunspec.md |
| | Command Line MOVES | A brief guide on how to run MOVES and MOVES tools from the command line | https://github.com/USEPA/EPA_MOVES_Model/blob/master/docs/CommandLineMOVES.md |
| | Debugging MOVES | Tips for troubleshooting and debugging unexpected behavior in MOVES runs | https://github.com/USEPA/EPA_MOVES_Model/blob/master/docs/DebuggingMOVES.md |
| | MOVES Code: Folder by Folder | Descriptions of the contents within the folders in the MOVES source code directory | https://github.com/USEPA/EPA_MOVES_Model/blob/master/docs/FolderByFolder.md |
| | MOVES Input/Output Database Changes | Description of the schema changes to MOVES County Scale and Project Scale input databases | https://github.com/USEPA/EPA_MOVES_Model/blob/master/docs/InputOutputDBChanges.md |
| | MOVES Database Glossary | Glossary of the column names used in the MOVES default database | https://github.com/USEPA/EPA_MOVES_Model/blob/master/docs/MOVESGlossary.md |
| | MOVES Database Tables | Schema descriptions for each table in the MOVES default database | https://github.com/USEPA/EPA_MOVES_Model/blob/master/docs/MOVESDatabaseTables.md |
| | Tips for faster MOVES runs | Suggestions for how to structure MOVES runs to be as efficient as possible | https://github.com/USEPA/EPA_MOVES_Model/blob/master/docs/TipsForFasterMOVESRuns.pdf |
| | MOVES5 Update Log | Chronological listing of updates to MOVES5 | https://www.epa.gov/moves/moves5-update-log |

| MOVES Algorithms and Default Inputs | | | |
|---|---|---|---|
| | Onroad Technical Reports | Link to MOVES technical reports describing the default inputs and algorithms for the onroad functions of MOVES5 and earlier MOVES versions | https://www.epa.gov/moves/moves-onroad-technical-reports |
| | Nonroad Technical Reports | Link to MOVES technical reports describing the default inputs and algorithms for the nonroad functions of MOVES5 and earlier versions Although the stand-alone NONROAD model is now incorporated into MOVES, many of the NONROAD technical reports still apply to the nonroad inputs and algorithms used in MOVES. | https://www.epa.gov/moves/nonroad-technical-reports |

# 10. Acronyms

| Acronym | Meaning |
|---|---|
| 2b3 | Class 2b and 3 Trucks (8,500 lbs < GVWR <= 14,000 lbs) |
| AERMOD | Atmospheric dispersion modeling system |
| APU | Auxiliary power unit |
| AVFT | Alternative vehicle fuels and technologies |
| BSFC | Brake-specific fuel consumption |
| $CH_4$ | Methane |
| CI | Compression ignition |
| CMAQ | Community Multiscale Air Quality Modeling System |
| CNG | Compressed natural gas |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| CRC | Coordinating Research Council |
| EC | Elemental carbon |
| EMFAC | California onroad vehicle emission factor model |
| EPA | Environmental Protection Agency |
| EV | Electric vehicle |
| FHWA | Federal Highway Administration |
| GHG | Greenhouse gases |
| GUI | Graphical user interface |
| GVWR | Gross vehicle weight rating |
| GWP | Global warming potential |
| HD | Heavy duty |
| HD2027 | Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards |
| HDGHG2 | Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles—Phase 2 |
| HDP3 | Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles—Phase 3 |
| I/M | Inspection and maintenance |
| LEV | Low-emission vehicle |
| LD | Light duty |
| LHD | Light Heavy-Duty |
| LMDV | Light- and Medium-Duty Multi-Pollutant Rule |
| LPG | Liquified petroleum gas |
| MOVES | Motor Vehicle Emission Simulator |
| MY | Model year |
| NEI | National Emissions Inventory |
| NEPA | National Environmental Policy Act |
| NLEV | National low-emissions vehicle |
| NMHC | Non-methane hydrocarbons |
| NMOG | Non-methane organic gases |
| NonEC | PM other than elemental carbon |
| NonHAPTOG | Residual total organic gases |
| $NO_X$ | Oxides of nitrogen |

| | |
|---|---|
| NR | Nonroad |
| NREL | National Renewable Energy Laboratory |
| ONI | Off-network idling |
| ORVR | Onboard refueling vapor recovery system |
| PEMS | Portable emission measurement systems |
| $PM_{10}$ | Particulate matter <= 10 µm |
| $PM_{2.5}$ | Particulate matter <= 2.5 µm |
| RSD | Remote sensing device |
| RVP | Reid vapor pressure |
| SAFE | Safer Affordable Fuel Efficient Vehicles rule |
| SI | Spark ignition |
| SIP | State implementation plan |
| THC | Total hydrocarbons |
| TOG | Total organic gases |
| TVV | Tank vapor venting |
| VMT | Vehicle miles travelled |
| VPAT | Voluntary Product Accessibility Template |
| VSP | Vehicle specific power |
| VOC | Volatile organic compounds |
| ZEV | Zero emissions vehicle (battery electric and fuel cell vehicles) |

# 11. References


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[3] USEPA (2005). *Exhaust Emission Effects of Fuel Sulfur and Oxygen on Gasoline Nonroad Engines.* NR-003c EPA-420-R-05-016. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. December, 2005. https://www.epa.gov/moves/nonroad-technical-reports.

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[6] https://www.epa.gov/moves/moves-training

[7] USEPA (2024). *MOVES5 Technical Guidance: Using MOVES to Prepare Emission Inventories for State Implementation Plans and Transportation Conformity*. EPA-420-B-24-043. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2024. https://www.epa.gov/state-and-local-transportation/policy-and-technical-guidance-state-and-local-transportation

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[11] USEPA (2023), *Is MOVES the best Tool for my work?* Frequently Asked Question at https://www.epa.gov/moves/moves-best-tool-my-work

[12] *Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles,* 89 Fed. Reg. 27842, April 18, 2024.

[i] *Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles—Phase 3,* 89 Fed. Reg. 29440., April 22, 2024.

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