Overview of EPA's MOtor Vehicle Emission Simulator (MOVES4)

United States Environmental Protection Agency

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

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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, and 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 MOVES4, the latest official 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 MOVES4 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 ($PM_{2.5}$ & PM_{10}), elemental carbon (EC)[g], 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" and PM species such as elemental carbon from nonroad equipment 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.[h]	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] While not exactly equivalent, elemental carbon is often used as a surrogate for black carbon in GHG estimates.

[h] 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. MOVES4 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 MOVES4.0.0 release, including most recently:*	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
	Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule for Model-Year 2012-2016: May, 2010
	Final Mobile Source Air Toxics Rule (MSAT2): February, 2007
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
	California Low Emissions Vehicle (LEV) Program
	OTC NLEV Program
	California Zero Emission Vehicle (ZEV) Sales Mandate
State and Local Onroad Programs:[i]	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 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 and its predecessors, MOBILE and NONROAD.

Table 1-3: MOVES Version History

Public Releases	Release Date	Key Features
MOBILE1-MOBILE6.2	1978-2004	• Predecessor to MOVES • Estimated g/mi onroad emissions • Increased scope and complexity over time
NONROAD	1998-2010	• Predecessor to MOVES • Estimated emissions for nonroad sources
MOVES2010	2010	• New structure for onroad only • Incorporated vehicle activity • Designed to model at project, county, and national scales
MOVES2010a	2010	• Modeled 2012+ LD GHG rule
MOVES2010b	2012	• Performance improvements • Improved vapor venting calculations
MOVES2014	2014	• Modeled Tier 3 and 2017+ LD GHG rules • Updated gasoline fuel effects • Improved evaporative emissions • Improved air toxics • Updated onroad activity, vehicle populations and fuels • Incorporated NONROAD model
MOVES2014a	2015	• Added nonroad VOC and toxics • Updated default nonroad fuels • Added new options for user vehicle miles travelled (VMT) input
MOVES2014b	2018	• Improved emission estimates for nonroad mobile sources • 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 • Updated onroad activity, vehicle populations and fuels • Added gliders and off-network idle • Revised inputs for hotelling and starts
MOVES3.0.1-MOVES3.0.4	2021-2022	• Incorporated many small updates 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[j]	2023	• Updates as explained in Section 2

[j] If updates are made to MOVES4, they will be documented in an update log available as a link from the MOVES4 page, https://www.epa.gov/moves/latest-version-motor-vehicle-emission-simulator-moves.

1.3 MOVES Uses

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

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.

2. Updates for MOVES4

Updates to MOVES4 are detailed in the MOVES4 technical reports for onroad. The most important changes between MOVES3.1 and MOVES4 are summarized here. The only change made for nonroad was a change to fuel properties.[1]

2.1 New Regulations

Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards

MOVES4 accounts for the Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards, ("HD2027") published in January 2023.[11] This rule sets tighter emission standards for NO_x and other pollutants from heavy-duty onroad vehicles starting in model year 2027.

Revised 2023 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions Standards

MOVES4 also accounts for the updated greenhouse gas standards for light-duty passenger cars and trucks ("LDGHG 2023") published in December 2021.[12] These standards set tighter carbon dioxide (CO_2) limits for light-duty (LD) vehicles and are expected to lead to more electric vehicles (EVs) in the future fleet.

Updated modeling of HDGHG2 rule

Due to a 2021 appeals court ruling vacating the portions of the heavy-duty greenhouse gas phase 2 standards (HDGHG2) that apply to trailers,[13] we revised MOVES inputs that describe weight, aerodynamics, rolling resistance and "other efficiency" improvements for combination trucks of model year 2018 and later to better represent the implemented program. We also now hold constant the "other efficiency" improvements for Class 2b and 3 vehicles in 2024 and beyond since we expect the Phase 2 requirements for these vehicles to be met via electrification starting in MY2025. These changes slightly increase the modeled emissions of CO_2 and other pollutants from these trucks.

2.2 New Features

Improved EV capabilities and EV fleet predictions

In MOVES4, we have updated the modeling of energy consumption by battery-powered light-duty vehicles by improving our estimates of the energy used to move the vehicle[14] and by explicitly accounting for charging losses, battery efficiency, and energy use for cabin heating and cooling.[15] Our national average default forecast of future year light-duty BEV population is informed by a detailed analysis of likely sales under the LDGHG 2023 standards and Inflation Reduction Act incentives.[16]

We also added the ability to model battery-powered heavy-duty vehicles,[17] similarly accounting for charging losses, battery efficiency, and energy use for cabin heating and cooling.[15] Our national average default forecast of future year heavy-duty BEV vehicle populations is informed by analysis of state adoption of the California Advanced Clean Trucks rule.[16]

New ability to model HD fuel cell vehicles

In MOVES4, we have added the ability to model energy consumption and activity from hydrogen fuel cell powered electric vehicles (FCEVs) for heavy-duty trucks. However, MOVES output combines FCEV values with the values for BEVs, so generating FCEV-specific output requires either multiple runs or results post-processing. MOVES does not model light-duty FCEVs. Our national average default forecast of future year heavy-duty FCEV population is informed by analysis of state adoption of the California Advanced Clean Trucks rule.[16]

THC, NO_x, and energy consumption adjusted to account for fleet averaging with EVs

Under the Tier 3 and LDGHG rules, manufacturers meet emission standards as an average across the fleet and can use credits from electric vehicles to offset higher emissions from vehicles with internal combustion engines (ICE). Thus, as future EV sales increase nationally, we expect average ICE emissions and energy consumption will also increase.[15] This is seen in higher per-vehicle emission rates for MOVES4 gasoline and diesel light-duty vehicles.[k] The fleet averaging algorithm always uses the national default EV sales fractions, regardless of what scale is selected in the RunSpec, because average, banking, and trading (ABT) happens at the national level and not at the local level.

Added hotelling for EV and CNG long-haul combination trucks

As detailed in Section 3.3, hotelling activity in MOVES is defined only for long-haul combination trucks. Previous MOVES versions modeled all long-haul combination trucks as diesel powered. MOVES4 can also model battery electric, fuel-cell electric, and compressed natural gas (CNG) long-haul combination trucks and can estimate the emissions and energy use associated with their hotelling. This now includes energy use associated with shore (grid) powered hotelling operation.

2.3 Updates to Emission Rates

Updated ammonia rates

MOVES3 ammonia (NH_3) emission rates were based on studies conducted in 2001 and earlier on a limited number of vehicles. These lacked current emission aftertreatment technologies such as selective catalytic reduction (SCR). The new MOVES4 rates are based on real-world measurements from more than 300,000 light-duty vehicles and hundreds of heavy-duty trucks from model year 1965 -2018. Compared to MOVES3, they show much higher ammonia emissions from both gasoline and diesel vehicles.

Updated rates for nitrous oxide, nitrogen oxide, and nitrogen dioxide

The same studies used to update diesel ammonia rates were used to update MOVES estimates of the greenhouse gas nitrous oxide (N_2O). This data was also used to update how total NOx Is allocated between nitrogen oxide (NO) and nitrogen dioxide (NO_2). As a result, MOVES4 estimates of N_2O emissions are much higher than in previous MOVES versions and, for a given quantity of NO_x emissions, MOVES4 estimates more NO and less NO_2.

For a more complete list of emission rate updates, see Table 2-1.

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[k] Note, the rule also allows fleet averaging with electric vehicles for Regulatory Class 41 vehicles, but this is not modeled in MOVES4.

2.4 Updates to Fuel Characteristics, Vehicle Populations and Activity

Gasoline fuel properties have been updated using data from EPA fuel compliance submissions. We also forecast gasoline parameter changes for Dallas area counties that will soon be required to use reformulated gasoline (RFG).

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 fuel, regulatory class, and age distributions were based on newer vehicle registration data, as well as the EV sales forecasts mentioned in Section 2.2.[16]

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

Table 2-1: Algorithm and Data Updates for MOVES4 and Emission Implications

Area	Description of Change and Emission Implications
Heavy-duty diesel emissions for MY 2027 and later	Reduced emissions from heavy-duty diesel vehicles due to HD2027 rule. In particular, there are notable reductions in running, start and extended idle NOx. There are also reductions in running $PM_{2.5}$, THC, and CO and reductions in crankcase emissions of all pollutants.
Heavy-duty gasoline emissions for MY 2027 and later.	Slight reductions in NOx, THC, CO and $PM_{2.5}$ emission rates for running processes due to the HD2027 rule.
Heavy-duty energy consumption for MY 2018 and later	Slight increases in energy consumption due to updated modeling of HDGHG2 rule.
Light-duty gasoline PM emissions for MY 2017 and later	Slight decreases in PM due to updated data and projections of prevalence of gasoline direct injection engines.
Light-duty vehicle energy consumption and NOx and THC emissions for internal combustion engine vehicles of MY 2017 and later	Adjusted to account for manufacturer "averaging, banking and trading" with electric vehicles. Compared to MOVES3, this increases per-vehicle emissions from gasoline, diesel and E-85 light-duty vehicles.
Light heavy-duty diesel emissions	Reduced emission deterioration rates for THC, CO & NOx emissions from light heavy-duty vehicles based on corrected warranty period.
Heavy-duty diesel extended idle elemental carbon (EC) and non-EC emissions for MY 2007 and earlier.	Corrected database for speciation of diesel extended idle $PM_{2.5}$ emissions, increasing EC fraction of PM emissions and decreasing non-EC fraction.
Light- and heavy-duty ammonia emissions for gasoline vehicles of MY 1981 and later, and diesel vehicles of MY 1960 and later.	Increased NH_3 emissions based on new data.
Heavy-duty diesel vehicle N_2O for MY 2004+	Increased N_2O emissions based on new data.
Diesel vehicle NO_2 and NO for all model years	Updated NO_2:NO_x and NO:NO_x ratios such that NO fraction increases and NO_2 fraction decreases.

Area	Description of Change and Emission Implications
Crankcase emissions for HD diesel vehicles	Updated algorithm that calculates crankcase emissions by regulatory class. Net emission impacts are small and vary by pollutant.
Speciation for air quality modeling	Removed chemical mechanisms and updated rocspeciation and nrrocspeciation tables. No impact on total emissions of hydrocarbons, NonHAPTOG, or any PM species.
Refueling vapor emissions from gasoline and E-85 vehicles	New data and improved algorithm generally increase refueling vapor emissions. HD gasoline vehicle refueling emissions decrease in later years because of HD2027 rule requirements. We also updated default information on the location of Stage II vapor recovery programs.
I/M Coverage	Updated the default list of counties with I/M programs to account for corrections, program changes, and program terminations.
Updated NOx humidity adjustments	NO_x emissions are slightly more sensitive to ambient humidity due to improved algorithms for all fuel types.
Default national VMT, default national vehicle populations, and default vehicle age distributions	Updated historical data and forecasts.
Default vehicle fuel type and regulatory class mix	Updated historical mix and forecasts. Moved engine-certified Class 3 trucks from regulatory class 41 to 42 to better match emissions. Reduced population of heavy-duty “glider” trucks. Unlike MOVES3, MOVES4 includes non-zero EV fractions.
Relative Mileage Accumulation	Updated LD mileage accumulation based on DOT analysis of odometer data from a random national sample of one million light-duty vehicles. The new analysis shows that cars and light trucks/SUVs are driven more similarly. It also shifts the distribution of VMT from newer to older vehicles
U.S. Counties	Accounted for split in Alaska county equivalent by removing one county and adding two more.
Gasoline properties	Updated gasoline properties for calendar years 2018 and later.
Fuel energy and carbon content	Updated fuel density, energy density, and carbon content for diesel and gasoline fuels. Declines in energy density and increased carbon content led to very small increases in CO_2 and SO_2 emissions. We also updated the fuel densities used in nonroad calculations.

2.5 Updates to User Interface and User Inputs

The structure of MOVES4 is fundamentally the same as MOVES3, with some minor changes, including changes in the MOVES graphical user interface (GUI), run specifications, input and output databases.

Since we have updated the source type and fuel type combinations available in MOVES4, RunSpecs created with MOVES3 will be missing these combinations. If a fuel type is missing from a particular source type, vehicle activity apportioned to that fuel type will not be accounted for in the emissions estimates. Therefore, to prevent accidental "missing VMT", MOVES4 will automatically add all missing fuel types associated with each selected source type in the RunSpec and provide a warning message. Additionally, because we changed how MOVES models speciated emissions in MOVES3.0.4, RunSpecs created with versions prior to MOVES3.0.4 that included chemical mechanisms will not work with MOVES4. If you intend to use MOVES to generate speciated emissions for air quality modeling, you will need to recreate your RunSpecs with MOVES4.

Changes to input databases mean that user input databases created for MOVES3 cannot be used with MOVES4. MOVES4 includes a converter tool to assist this process. However, all existing CDBs and PDBs will need to be manually updated to import the new default fuels data.

Additional information is also included in the MOVES4 technical guidance[7] and the MOVES4 code documentation at https://github.com/USEPA/EPA_MOVES_Model.

For nonroad runs, the only inputs that have changed since MOVES3.0.3 are related to speciation of chemical mechanisms. Nonroad RunSpecs developed for MOVES3 should generally work with MOVES4 unless chemical mechanisms were selected for output.

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

Table 2-2: Changes in MOVES interface from MOVES3 to MOVES4

Description		Notes
RunSpec Selections		
	Added vehicle/fuel combinations	MOVES4 adds electricity as a fuel type for all heavy-duty source types, as well as CNG for long-haul combination trucks
	Changed pollutant/process combinations	MOVES4 does not model chemical mechanism species, but adds NonHAPTOGMechanism as a selectable pollutant, intended to be used with the Speciation Profile Scripts tool
	Added option to skip domain database validation	If selected, MOVES will skip the domain database validation step, allowing the model to be run without getting a green check on the Create Input Database Panel in the GUI. This may be useful in advanced situations where domain databases are split into separate databases. However, its use is not recommended for most analyses as it can easily lead to invalid results
User Input Tables		
	HotellingActivityDistribution	Added fuelTypeID column and changed the definition of some of the hotelling operating modes
	ZoneMonthHour	Added molWaterFraction column, removed temperatureCV and relativeHumidityCV columns, and changed columns temperature, relHumidity, heatIndex, and specificHumidity to type DOUBLE
	AVFT	MOVES4 Alternative Vehicle Fuels and Technologies (AVFT) table includes more fuel types (see “Added vehicle/fuel combinations” above.)
Changed Definitions		
	Regulatory Class 41 and 42	Engine-certified Class 3 trucks moved from regulatory class 41 to 42
	Long-haul Combination Trucks	No longer required to be diesel only
	Hotelling operating modes	opModeID 203 corresponds to hotelling shore power (plug in) and opModeID 204 corresponds to hotelling battery or all engines/accessories off
New Output		
	New rows and SCCs	There are new SCCs for heavy-duty electric vehicles and for CNG long-haul combination trucks.
	Translation tables	To aid in decoding MOVES output, MOVES4 output databases include sixteen new tables that “translate” MOVES numeric codes. These table names all start with “translate.” As such, the former “activitytype” is now named “translate_activitytype”.

Description	**Notes**
Changes in GUI	
Added information to Help menu	
Changed process column name	With the addition of shore power as a hotelling operating mode, the "Auxiliary Power Exhaust" process column on the Pollutants and Processes Panel has been renamed "Other Hotelling Exhaust". Note that this change does not have a corresponding change in the RunSpec; MOVES will automatically calculate shore power energy demand if Auxiliary Power Exhaust is selected in the RunSpec
Added options to the Tools menu	MOVES4 contains tools to convert MOVES3 databases to MOVES4, the AVFT Tool, and Speciation Profile Scripts
Software Changes	
Version updates	MOVES4 is distributed with updated versions of MariaDB, Go, and Java
Command Line Changes	
"MOVESMaster.bat" changed to "MOVESMain.bat"	Important if you have automated your process for running MOVES
Improved input database validation	MOVES4 will execute all the input database validation steps when running on the command line as it would when running through the GUI, preventing a run that does not have "all green checks" from starting.
Default Database Schema	
Added new tables	• ActivityType • EVEfficiency • EvPopICEAdjustLD • NOxHumidityAdjust • NRROCSpeciation • RefuelingControlTechnology • ROCSpeciation
Removed tables	• ExtendedIdleHours • LumpedSpeciesName • TemperatureFactorExpression • TOGSpeciation • TOGSpeciationProfile

Description		Notes
	Changed schema for existing tables	• atratio: fuelFormulationID is now type INT(11) • basefuel: fuelFormulationID is now type INT(11) • crankcaseemissionratio: added column regClassID • criteriaratio: fuelFormulationID is now type INT(11) • emissionratebyagelev: polProcessID is now type int(11) • emissionratebyagenlev: polProcessID is now type int(11) • fueladjustment: fuelFormulationID is now type INT(11) • fuelformulation: fuelFormulationID is now type INT(11) • fuelsupply: fuelFormulationID is now type INT(11) • fueltype: removed the humidityCorrectionCoeff and humidityCorrectionCoeffCV columns • generalfuelratio: fuelFormulationID is now type INT(11) • hotellingactivitydistribution: added column fuelTypeID • hotellinghours: added column fuelTypeID • nrfuelsupply: fuelFormulationID is now type INT(11) • nrfueltype: removed the humidityCorrectionCoeff and humidityCorrectionCoeffCV columns • zonemonthhour: added molWaterFraction column, removed temperatureCV and relativeHumidityCV columns, and changed columns temperature, relHumidity, heatIndex, and specificHumidity to type DOUBLE
No Longer Available		
	Chemical mechanisms	• Like MOVES3.0.4 and MOVES3.1, MOVES4 does not quantify chemical mechanism species for air quality modeling. Instead, MOVES4 can estimate emissions of aggregate residual organic gases and particulate matter and provides a speciation table that modelers can use to generate the corresponding SPECATE profile during post-processing.

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.[18]

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. 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.[19]

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.[16]

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.[20,17,19]

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[15] and fuel economy adjustments.[14]

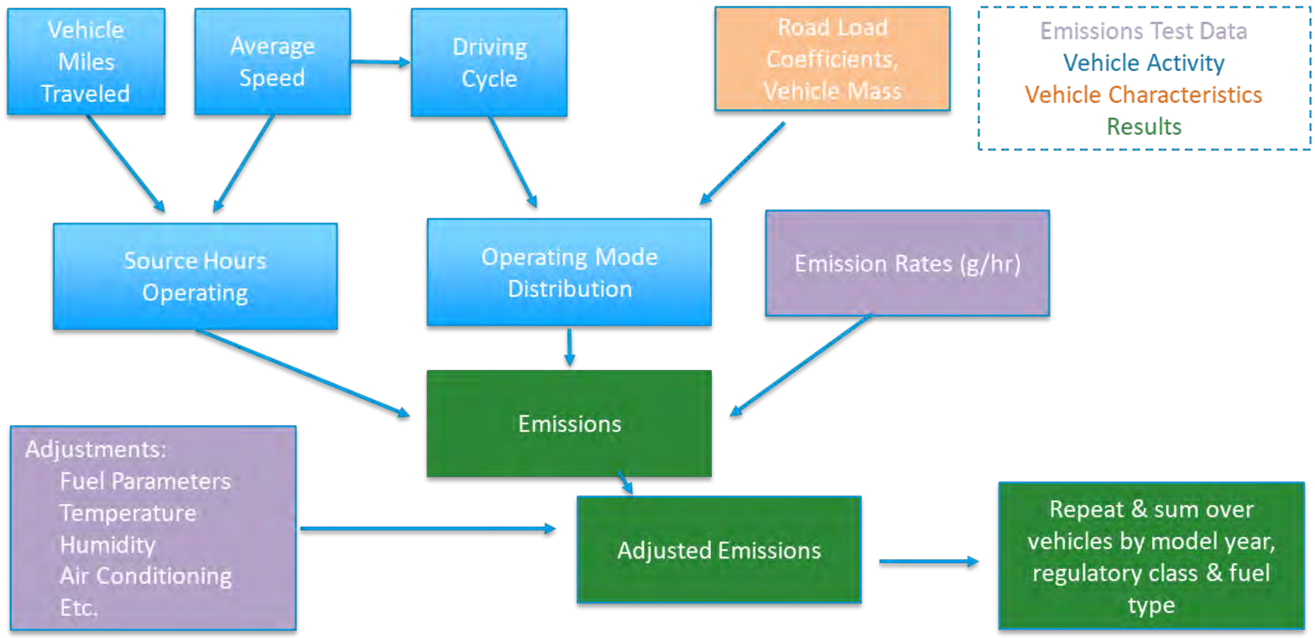


Figure 3-1: Calculating Running Emissions for Onroad Vehicles

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, and ambient temperatures.[17,19]

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 engines are often idling under load while hotelling (e.g., to maintain cabin climate or run accessories).

The default MOVES hotelling hours are computed as a fixed ratio to the miles these trucks travel on restricted access roads.[16]

In MOVES4, the hotelling algorithm was updated to cover CNG and electric vehicles and to revise the available operating modes. In MOVES4, 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.[16] 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.[17]

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.[17]

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 that consider brake pad composition, number and type of brakes and braking intensity. The emission rates in MOVES vary by vehicle regulatory class to account for average vehicle weight. They are the same for electric and conventional vehicles. Braking activity is modeled as a portion of running activity. In MOVES, the running operating modes for braking, idling and coasting are all modeled as including some amount of braking. The operating mode "brakewear; stopped" can be used at the project scale to model emissions of an idling vehicle with no braking.[22]

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 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.[22]

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. [23]

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). MOVES4 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.[23]

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).[23]

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.[23]

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 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.[24]

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) 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.[25] Temperature effects are applied to THC, CO and NO_X exhaust emissions from 4-stroke SI engines.[26]

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 emissions for four-stroke spark-ignition engines that have open crankcases[27] and for all compression-ignition engines prior to implementation of the Tier 4 NR diesel standard.[28]

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.[29]

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, HotSoak 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.[30]

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.[30]

5. MOVES Software Structure

MOVES is written in Java (compiled with Microsoft's build of OpenJDK), MariaDB, and the Go programming language. The Nonroad model component 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 that 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.

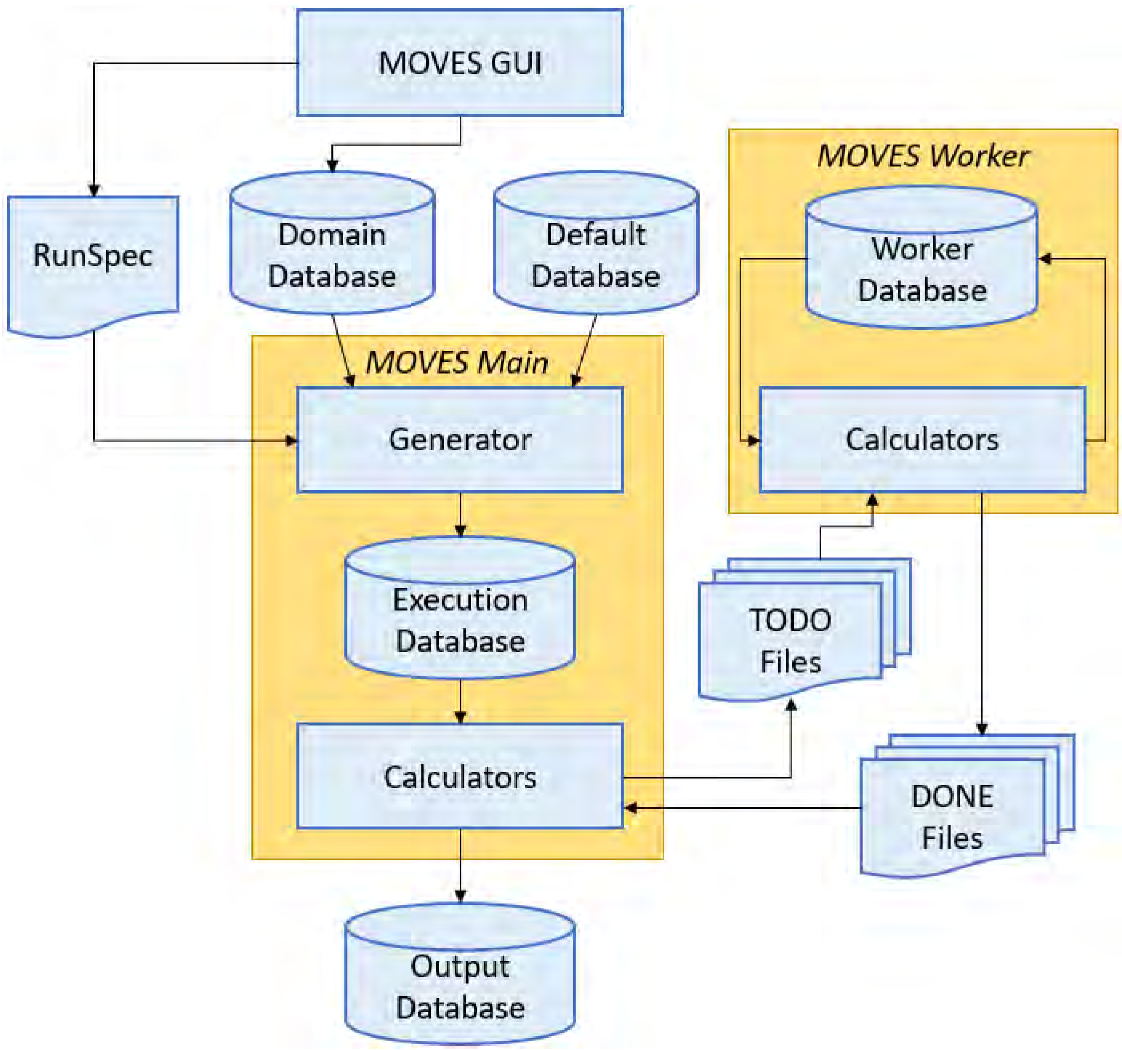


Figure 5-1-- Diagram of MOVES information flow

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.

MOVES Graphical User Interface (GUI)

The MOVES GUI is a Java program that may be used to create, save, load, and modify a run specification or "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.

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.

MOVES Nonroad Code

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.

Later minor releases of MOVES2014 improved 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 of the necessary data for a MOVES run.

The MOVESExecution Database

This database is created by the MOVES Main program. It is used for temporary working storage during the MOVES run. Users typically do not interact with this database; however, it may be saved for troubleshooting purposes.

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. MOVES4.0 Results

Vehicle and equipment emissions vary by location and time. This section shows MOVES4 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 has provided 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 through 2020 were generated with previous versions of MOVES and thus lack MOVES4 updates.

6.1 Onroad

The following plots summarize key results for onroad vehicles from running MOVES4 at the national, annual level using default inputs as compared to runs using the previous model, MOVES3.1[l]. 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.

Note that, compared to MOVES3, MOVES4 generally predicts higher national emissions in 2017. This reflects a shift in the default vehicle mix for historic years, including an older vehicle population. The impact of this shift varies by pollutant.

Figure 6-1 shows a shift to electric vehicles in MOVES4 and a very slight decrease in projections of total vehicle miles travelled.

[l] MOVES3.1 emissions are very similar to those in previous versions of MOVES3. See Table 1-2.

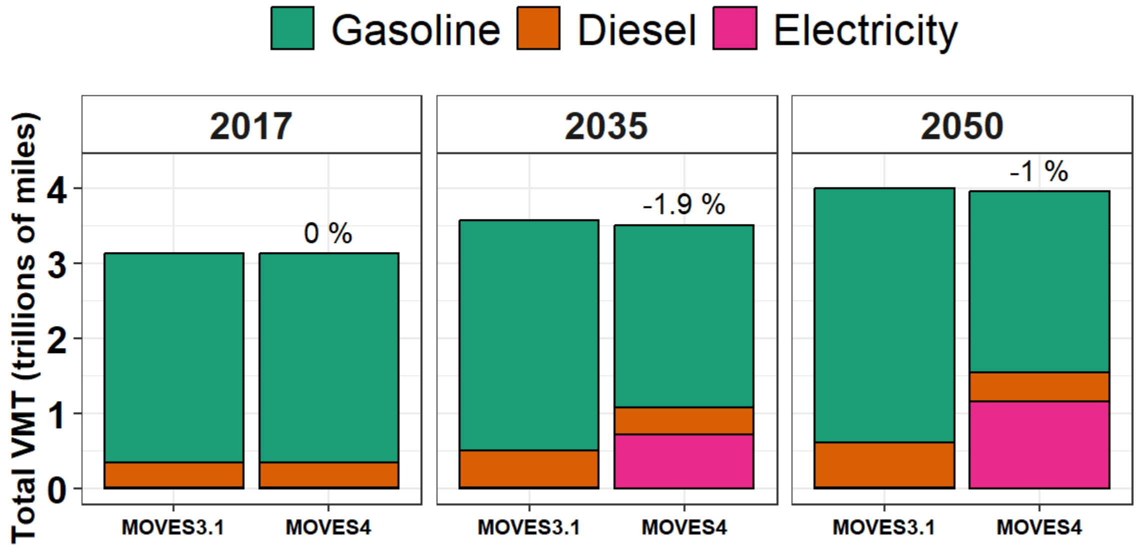
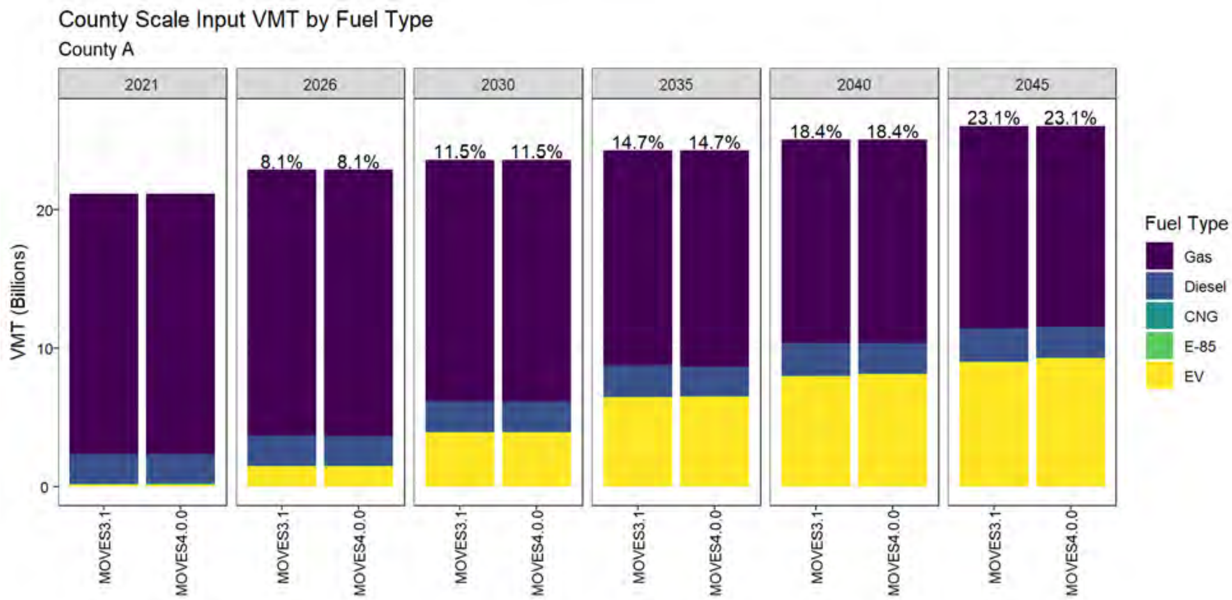


Figure 6-1—National onroad vehicle miles travelled (VMT) in MOVES4 as compared to MOVES3.1. Percentage values indicate change between MOVES3.1 and MOVES4.

For county level runs, modelers must enter county-specific VMT and fuel mix. Figure 6-2 illustrates VMT for two example counties. 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. In these county runs, the MOVES3 and MOVES4 inputs are the same for light-duty vehicles, but the MOVES4 inputs also include HD EVs. The values shown here are used as inputs in the sample county illustrations below.



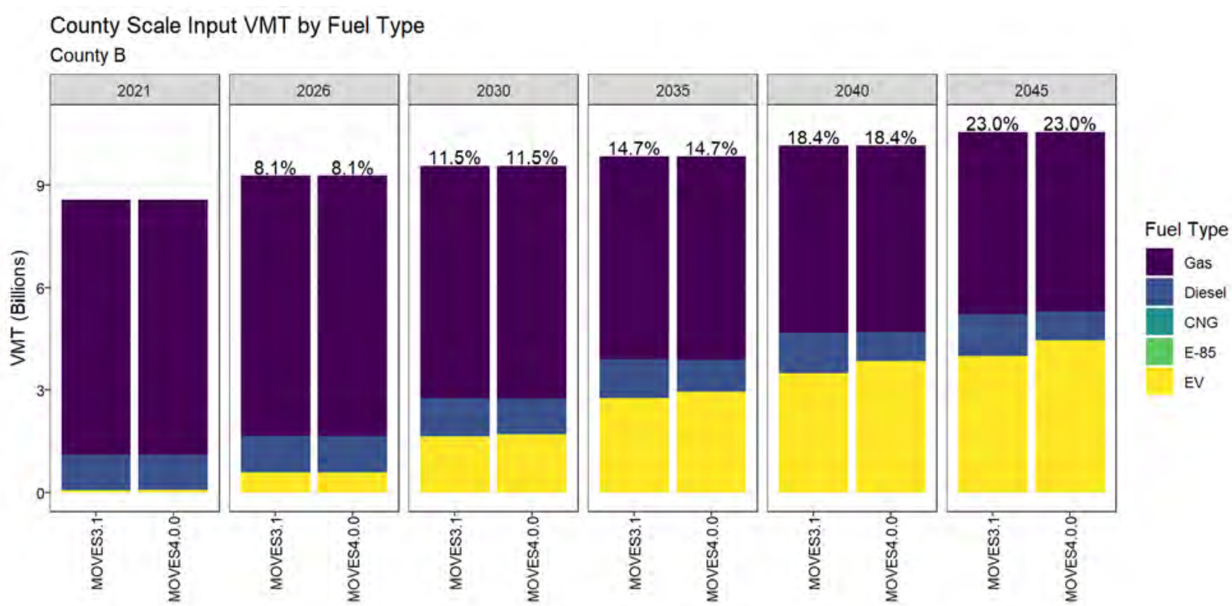


Figure 6-2—Sample county-specific onroad vehicle miles travelled (VMT) in MOVES3 and MOVES4. Percentage values indicate change compared to calendar year 2021. The values shown here are used in the sample county illustrations below.

Greenhouse Gases

While VMT is quite similar in both models, for exhaust CO_2 (Figure 6-3), MOVES4 projects greater decreases over time than MOVES3. This reflects both changes in fleet mix and activity, and the phase-in of the Revised Light Duty GHG Standards for 2023 and Later.

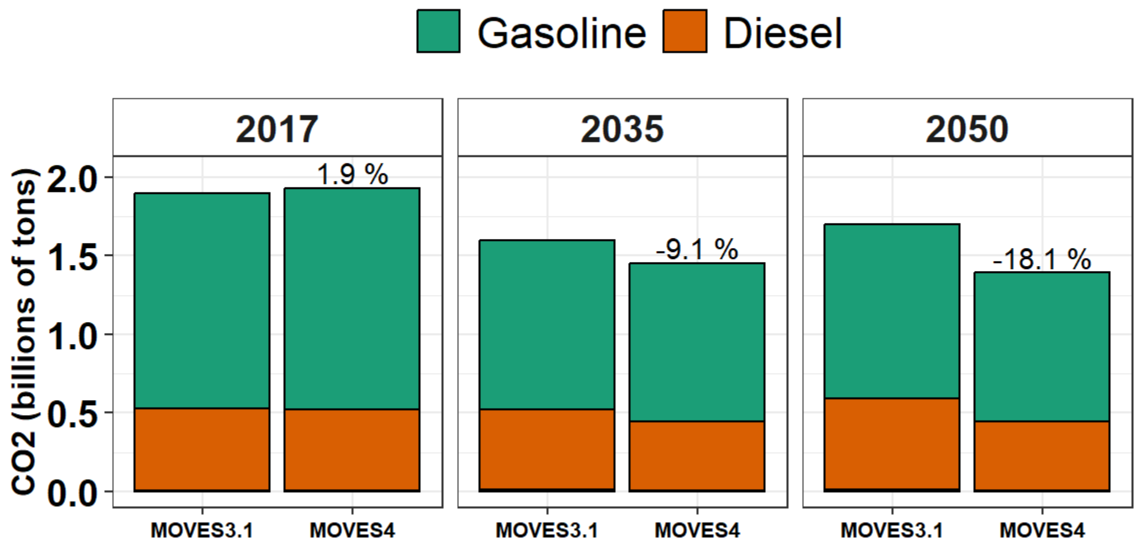


Figure 6-3—National onroad carbon dioxide in MOVES4 as compared to MOVES3.1. Percentage values indicate change between MOVES3.1 and MOVES4.

As shown in Figure 6-4, MOVES4 predicts declining methane emissions from onroad vehicles. The change between model versions reflects a shift in the default vehicle population from CNG vehicles, which have high methane emissions, to electric vehicles, which have none.

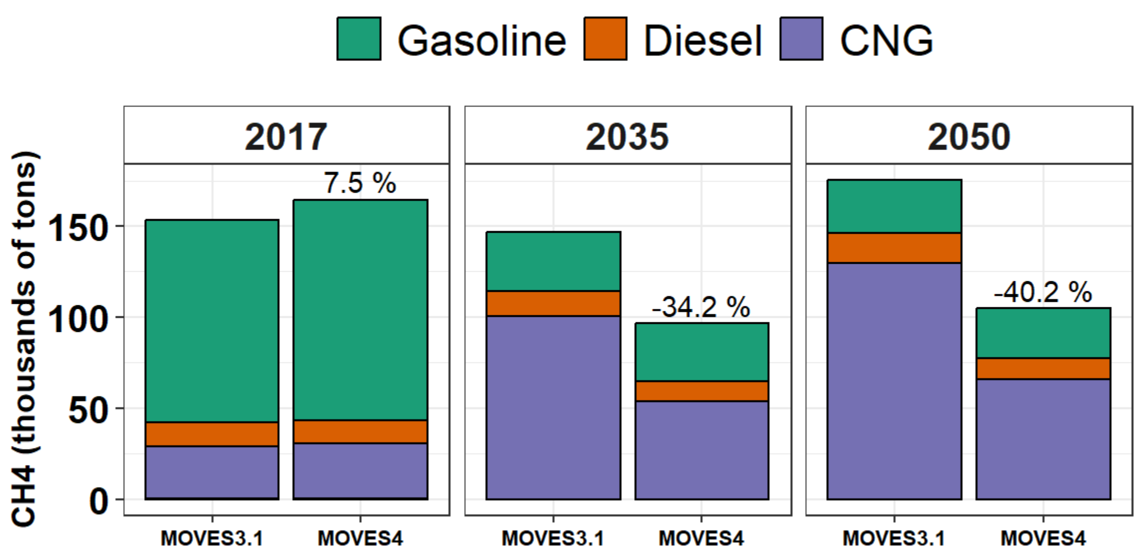


Figure 6-4—National onroad methane in MOVES4 as compared to MOVES3.1. Percentage values indicate change between MOVES3.1 and MOVES4.

As shown in Figure 6-5, MOVES4 nitrous oxide emissions are significantly higher than MOVES3. This reflects the incorporation of new real-world data for diesel vehicles.

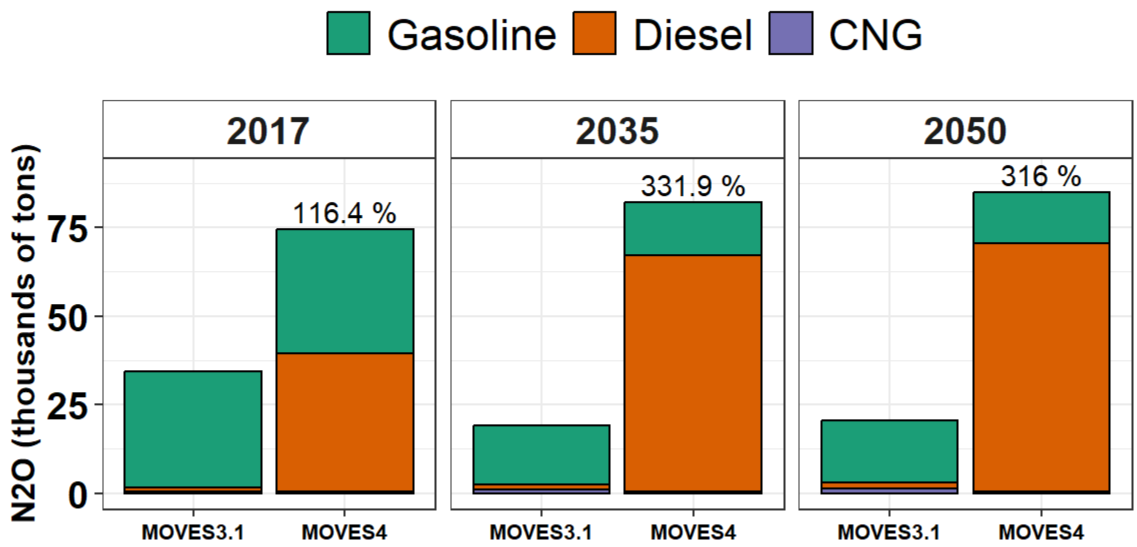


Figure 6-5—National onroad N_2O in MOVES4 as compared to MOVES3. Percentage values indicate change between MOVES3.1 and MOVES4.

The net CO_2 equivalent emissions based on the emissions of CO_2, CH_4 and N_2O as weighted by their global warming potentials are shown in Figure 6-6. The MOVES4 increase in N_2O is outweighed by decreases in CO_2 and CH_4.

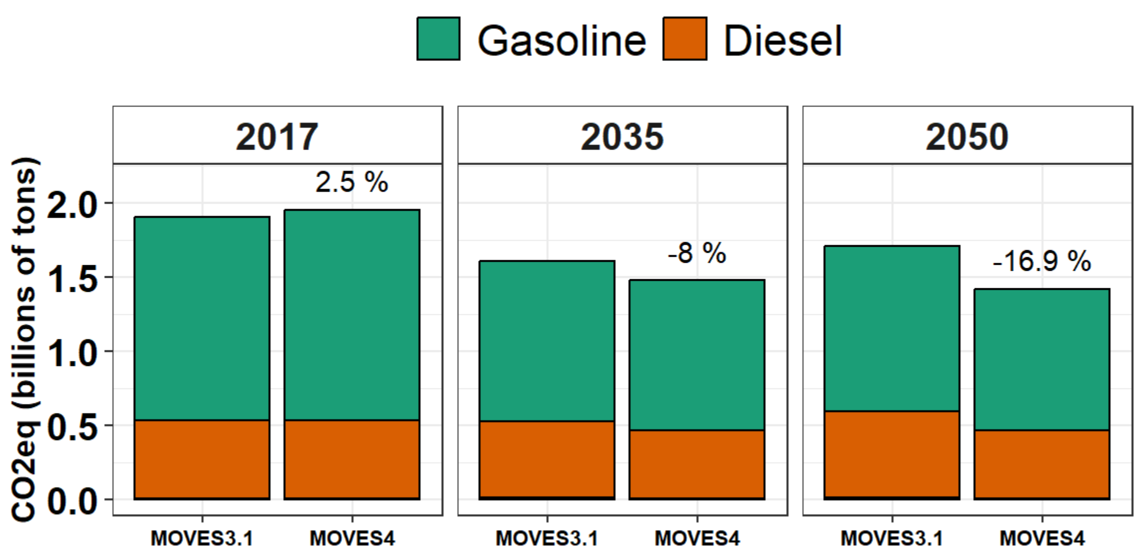


Figure 6-6—National onroad CO_2 equivalent in MOVES4 as compared to MOVES3. Percentage values indicate change between MOVES3.1 and MOVES4.

Criteria Pollutants and Precursors

Figure 6-7 shows national NO_X emissions decline over time with the phase-in of light-duty and heavy-duty rules in MOVES3 and MOVES4. MOVES4 shows additional declines primarily due to significantly reduced heavy-duty diesel emissions with the phase-in of the Heavy-Duty NOx Rule for 2027 and Later, as well as the growing share of electric vehicles. As noted above, the higher emissions for 2017 are due to a change in the default fleet mix.

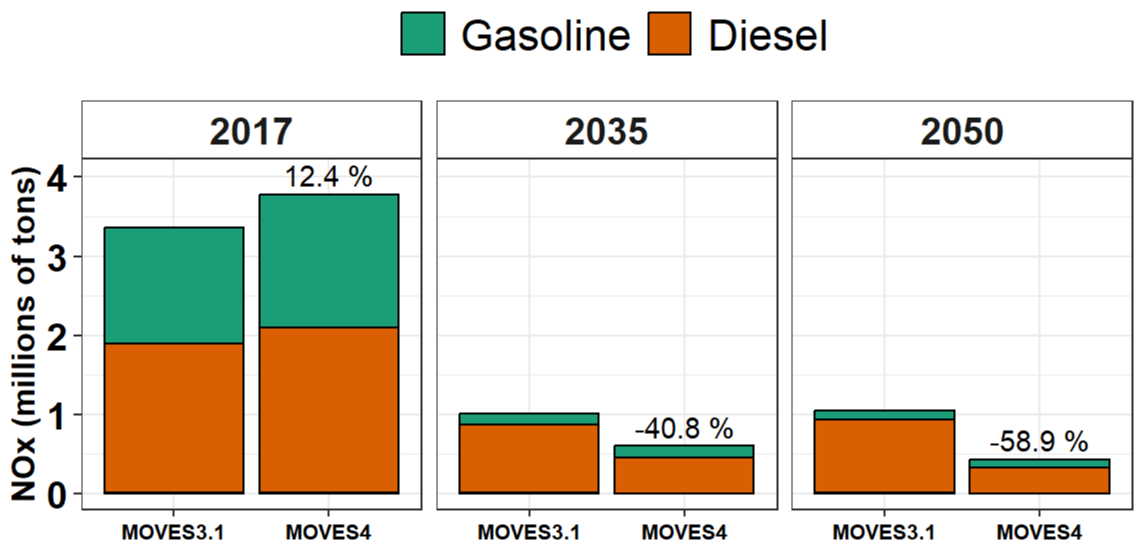


Figure 6-7—National onroad NO_X in MOVES4 as compared to MOVES3. Percentage values indicate change between MOVES3.1 and MOVES4.

Figure 6-8 illustrates NO_x for two example counties with the VMT shown in Figure 6-2 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 Truck (2020) rules requiring electric vehicle sales for light- and heavy-duty vehicles. In these county runs, the MOVES3 and MOVES4 inputs are the same for light-duty vehicles, but the MOVES4 inputs also include HD EVs. The declining gasoline emissions in MOVES3 reflect the Tier 3 standards for gasoline vehicles and a shift from gasoline to electric vehicles. The additional diesel reductions in MOVES4 demonstrate the effect of the Heavy-Duty NOx Rule for 2027 and Later, a reduction in the number of gliders, and a shift of the heavy-duty vehicle population from diesel to battery and fuel cell electric vehicles.

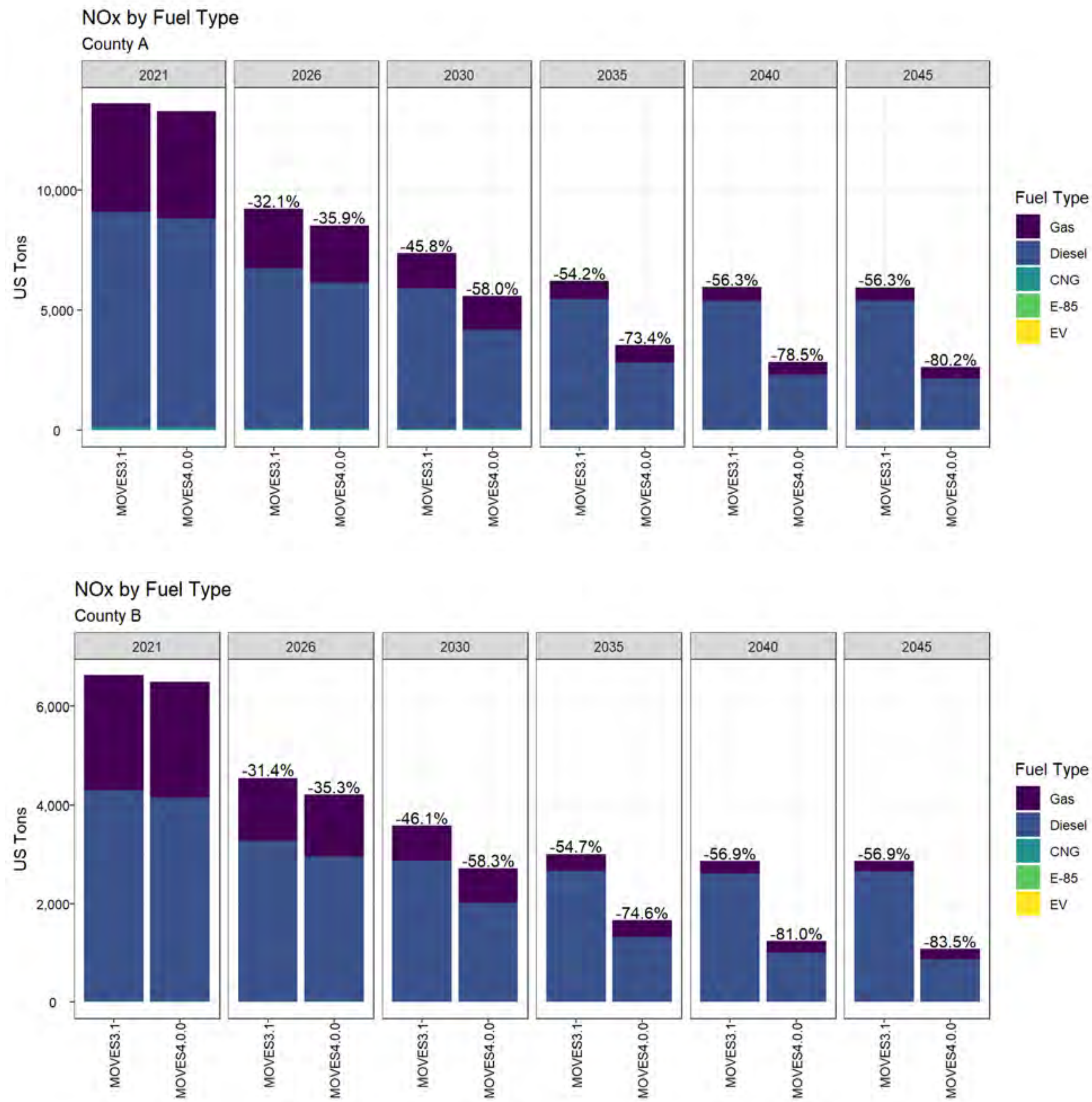


Figure 6-8—Onroad NO_X from two sample urban counties in MOVES4 as compared to MOVES3.1. Percentage values indicate change compared to 2021.

Figure 6-9 shows national $PM_{2.5}$ inventory declining with the phase-in of light-duty and heavy-duty PM regulations. Compared to MOVES3, MOVES4 results in less PM exhaust primarily due to a reduction in the number of glider vehicles and shifts to electric vehicles.

The graph also shows that brake and tire wear emissions are similar in MOVES3 and MOVES4. MOVES uses the same brake and tire wear rates for all fuel types, and in both versions of MOVES brake and tire wear form an increasing fraction of total onroad direct $PM_{2.5}$ emissions.

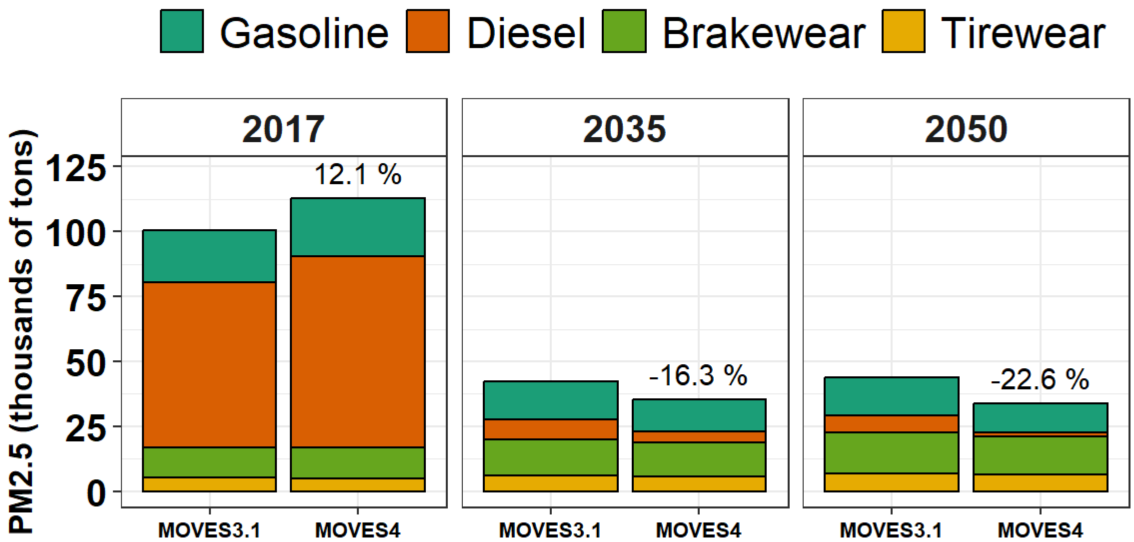


Figure 6-9—National $PM_{2.5}$ in MOVES4 as compared to MOVES3.1. Percentage values indicate change between MOVES3.1 and MOVES4.

The PM trend observed in select urban counties in Figure 6-10 depicts total $PM_{2.5}$ emissions by fuel type. The gasoline and diesel emissions include exhaust, brake and tire wear. The electric emissions are from brake and tire wear only. The results are similar to the national PM trend and illustrate both the reduced emissions from diesel vehicles and the growing importance of brake and tire emissions.

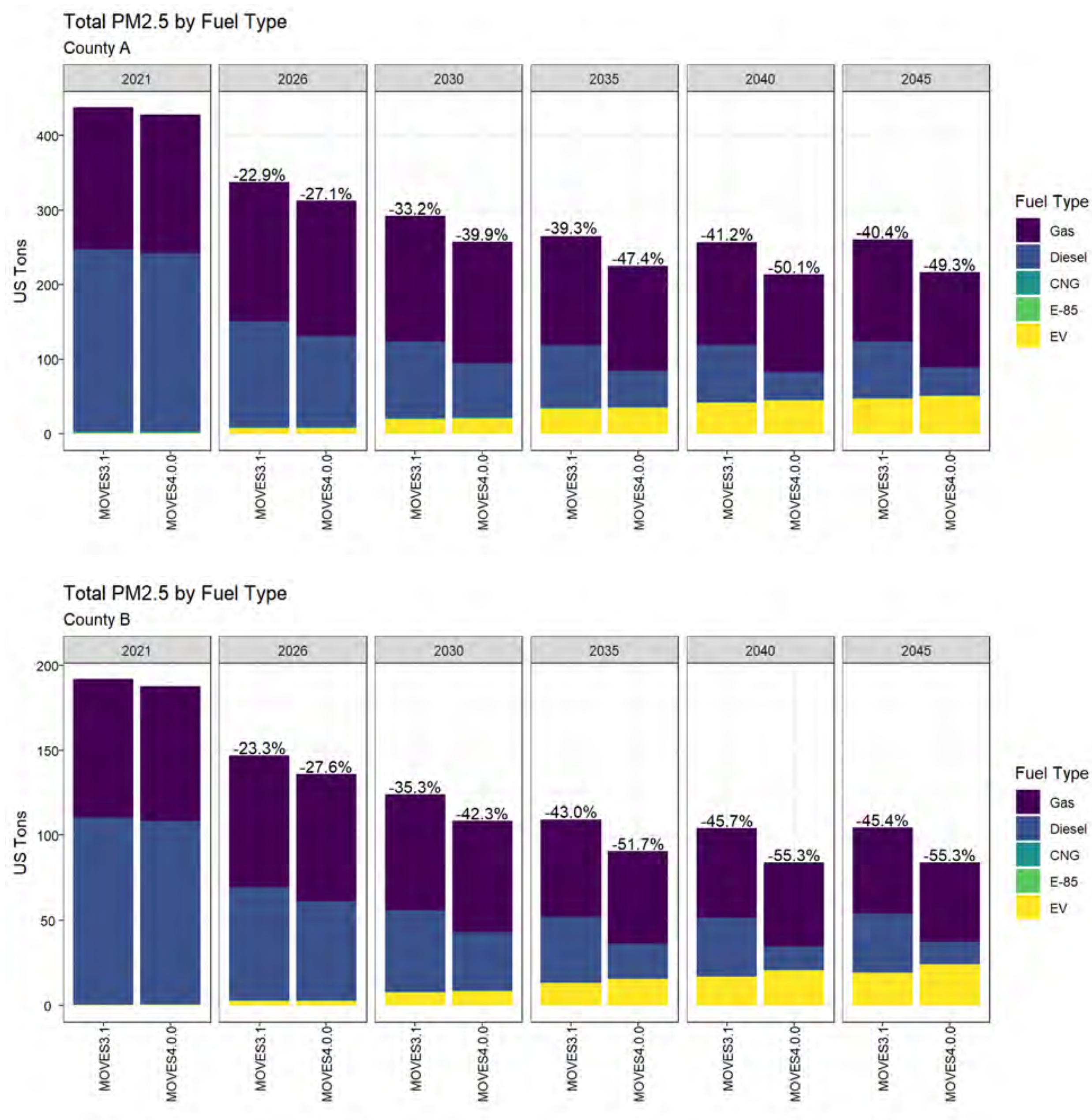


Figure 6-10—Onroad PM from two sample urban counties in MOVES4 as compared to MOVES3.1. The graph includes exhaust PM as well as brake and tire wear. Percentage values indicate change compared to calendar year 2021.

Onroad VOC emissions are dominated by emissions from gasoline vehicles, which decline with the phase-in of Tier 3 standards in both MOVES3 and MOVES4, and the increased fraction of electric vehicles in the MOVES4 national results (Figure 6-11). As illustrated in Figure 6-12, evaporative emissions are a growing fraction of future onroad VOC, especially emissions from vapor venting and liquid fuel leaks.

The VOC trend observed in select urban counties as shown in Figure 6-13 highlight near-term increases in VOC. Figure 6-14 illustrates that these county-scale increases are primarily due to MOVES4 changes in refueling emissions.

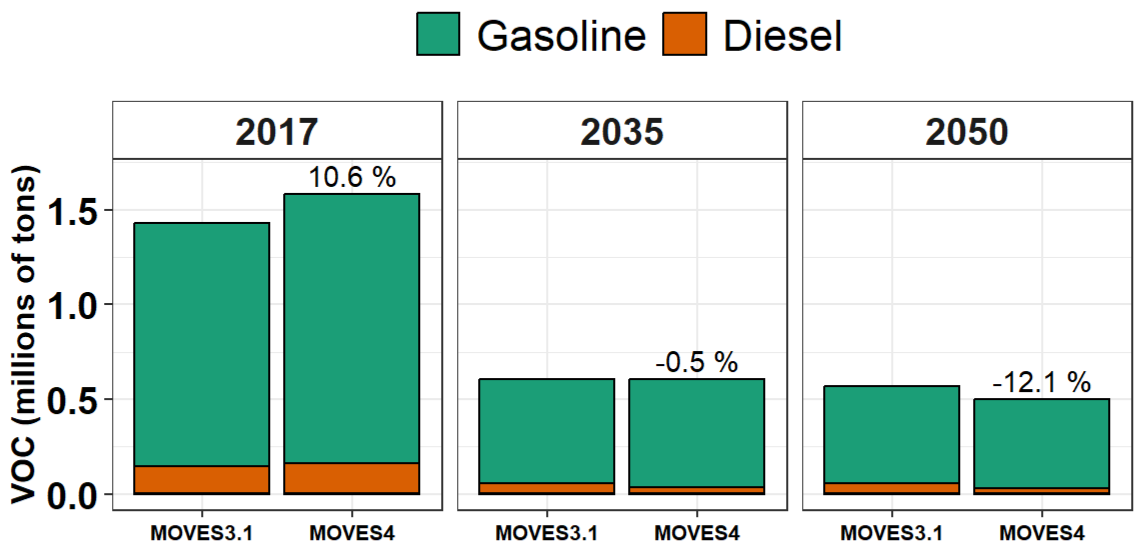


Figure 6-11—National onroad VOC in MOVES4 as compared to MOVES3.1. Percentage values indicate change between MOVES3.1 and MOVES4.

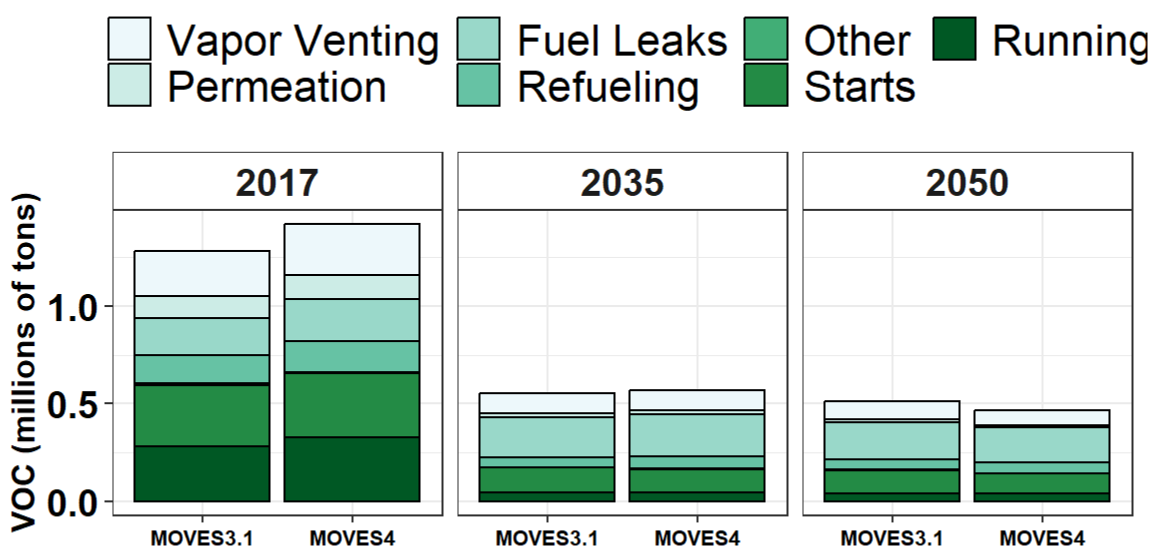


Figure 6-12—National onroad VOC from gasoline vehicles by emission process in MOVES4 as compared to MOVES3.1.

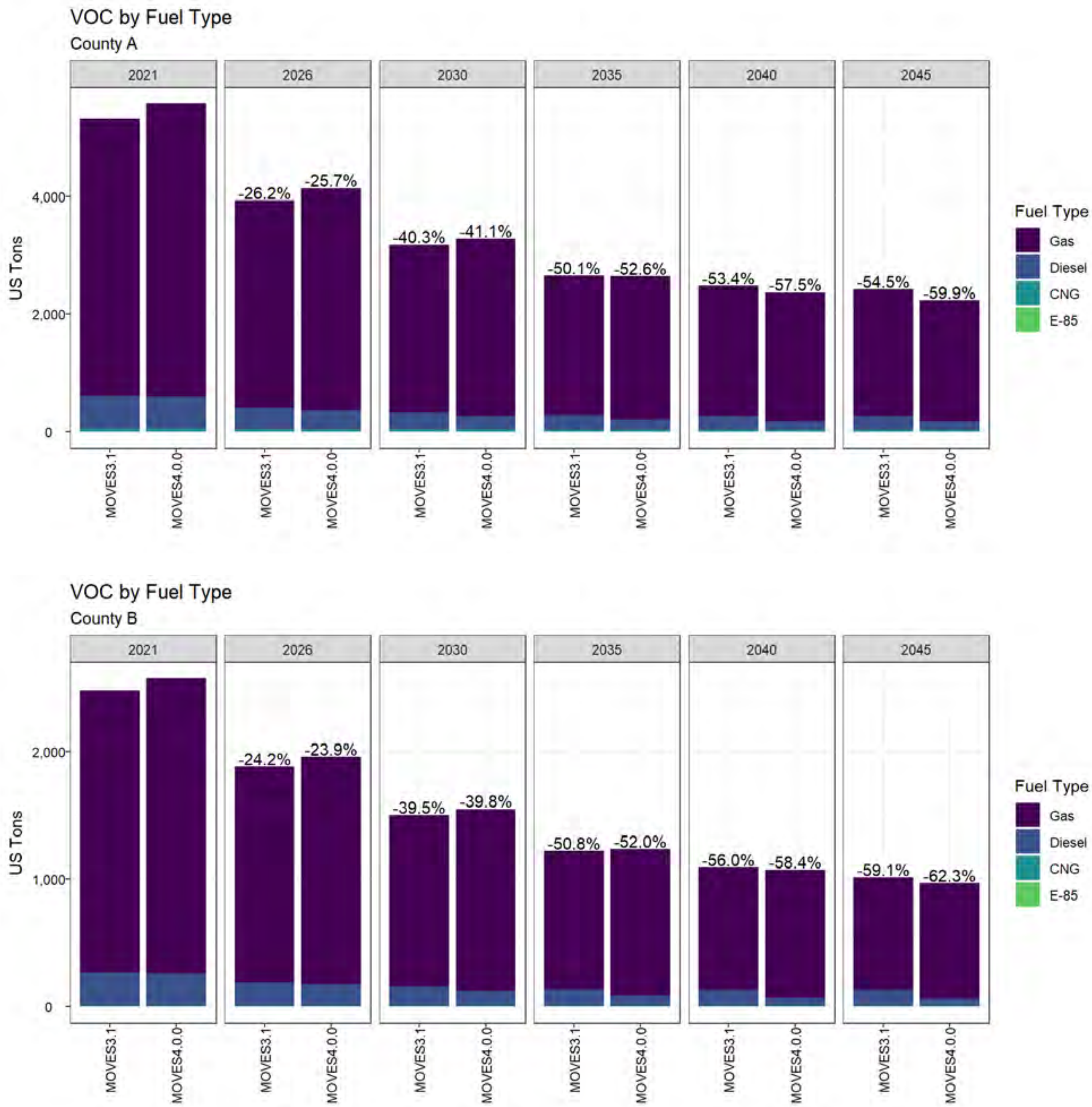


Figure 6-13—Onroad VOC by fuel type from two sample urban counties in MOVES4 as compared to MOVES3.1. Percentage values indicate change compared to calendar year 2021.

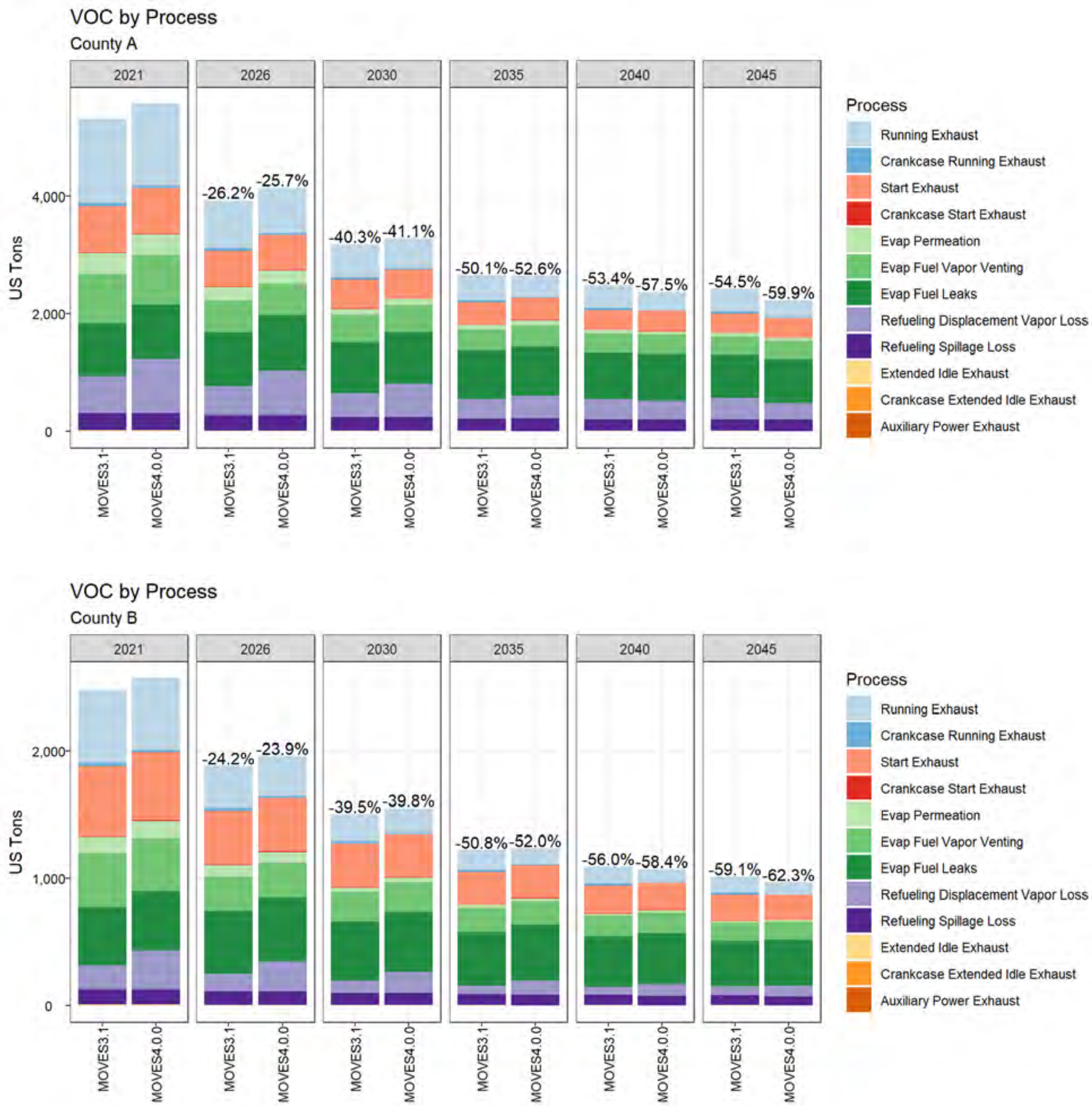


Figure 6-14—Onroad VOC by process from two sample urban counties in MOVES4 as compared to MOVES3.1. Percentage values indicate change compared to calendar year 2021.

Like VOC, onroad CO emissions are heavily dominated by emissions from gasoline vehicles. The CO emissions decline over time with the phase-in of Tier 3 standards and improved technology. MOVES4 changes compared to MOVES3 in Figure 6-15 are primarily due to changes in the vehicle fleet mix, as well as declines in diesel CO with the HD2027 regulations. Figure 6-16 shows similar trends in sample urban counties.

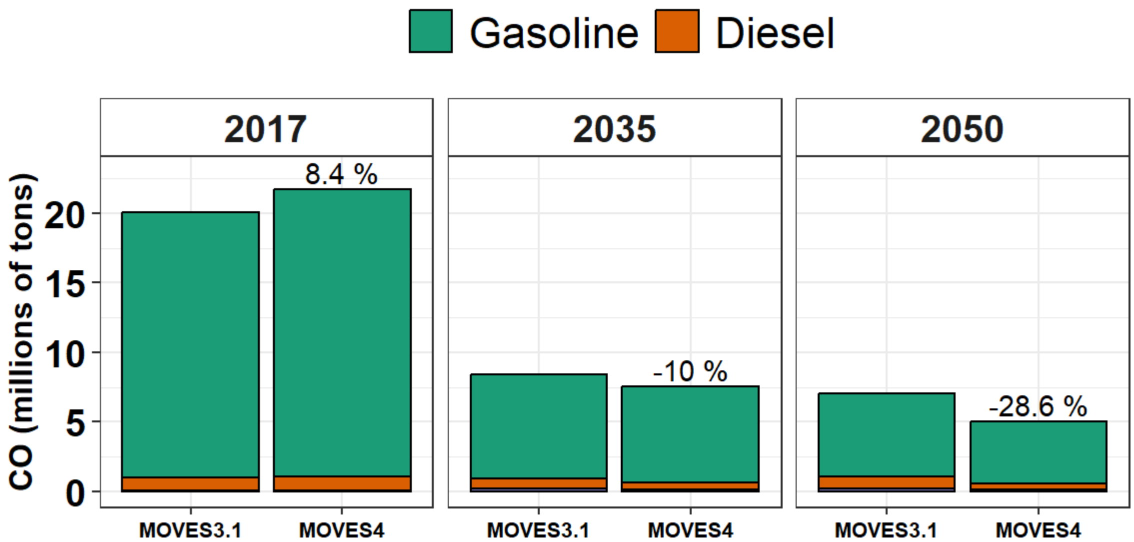
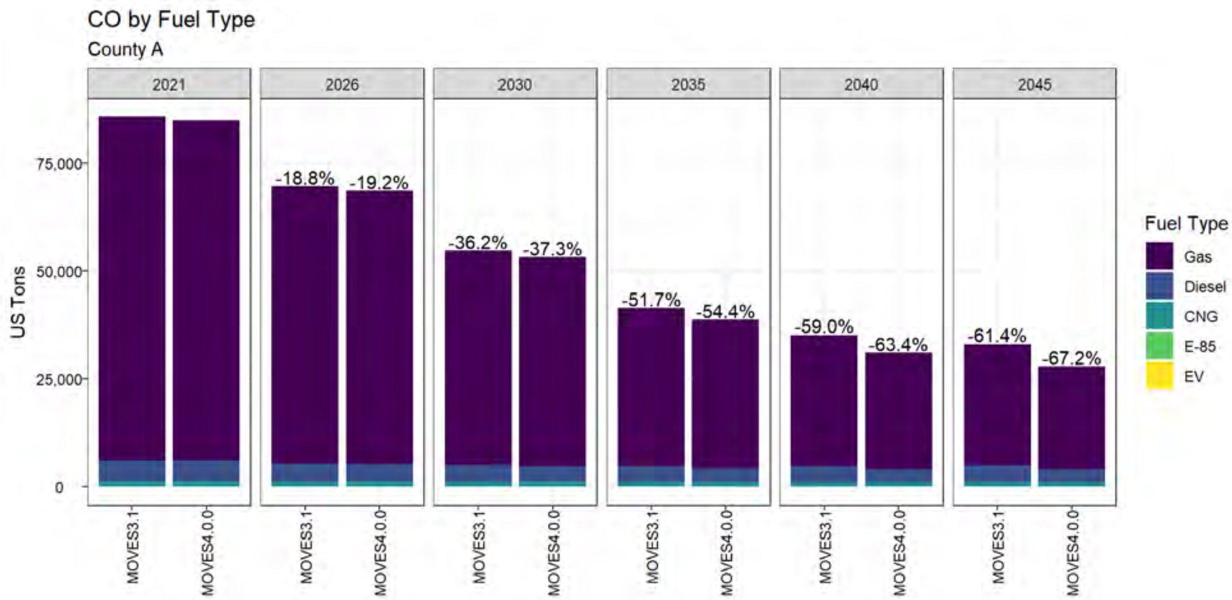


Figure 6-15—National onroad CO in MOVES4 as compared to MOVES3.1. Percentage values indicate change between MOVES3.1 and MOVES4.



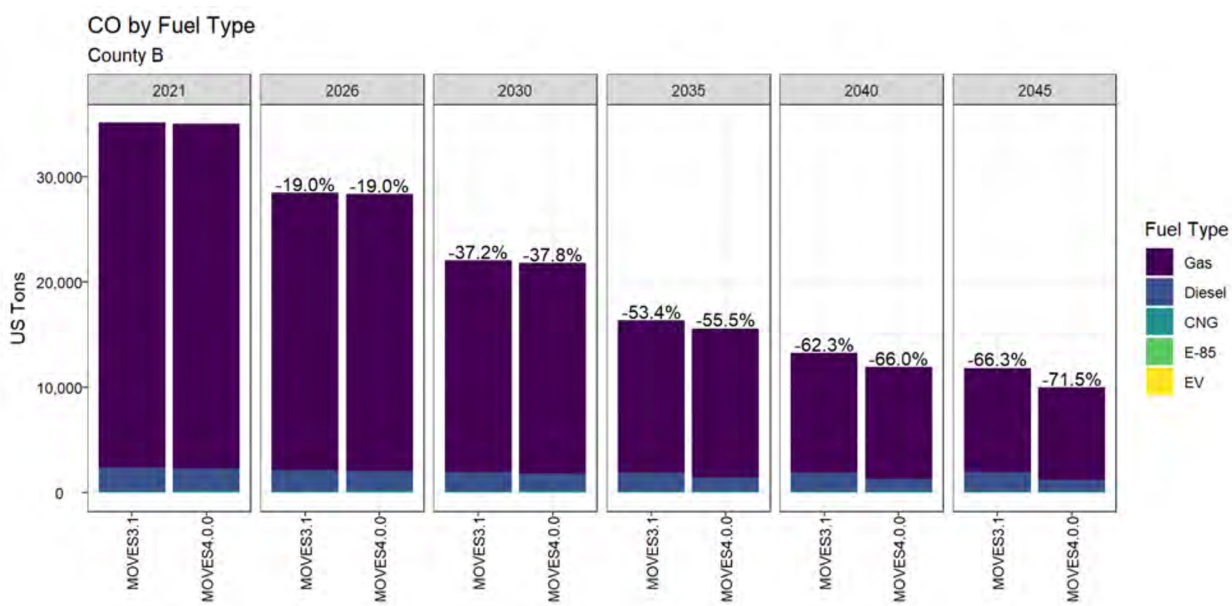


Figure 6-16—Onroad CO from two sample urban counties in MOVES4 as compared to MOVES3.1. Percentage values indicate change compared to calendar year 2021.

Figure 6-17 and Figure 6-18 show notable increases to the onroad ammonia inventory at the national and county level. The change reflects the updated ammonia emission rates for gasoline and diesel vehicles in MOVES4 to incorporate new data.

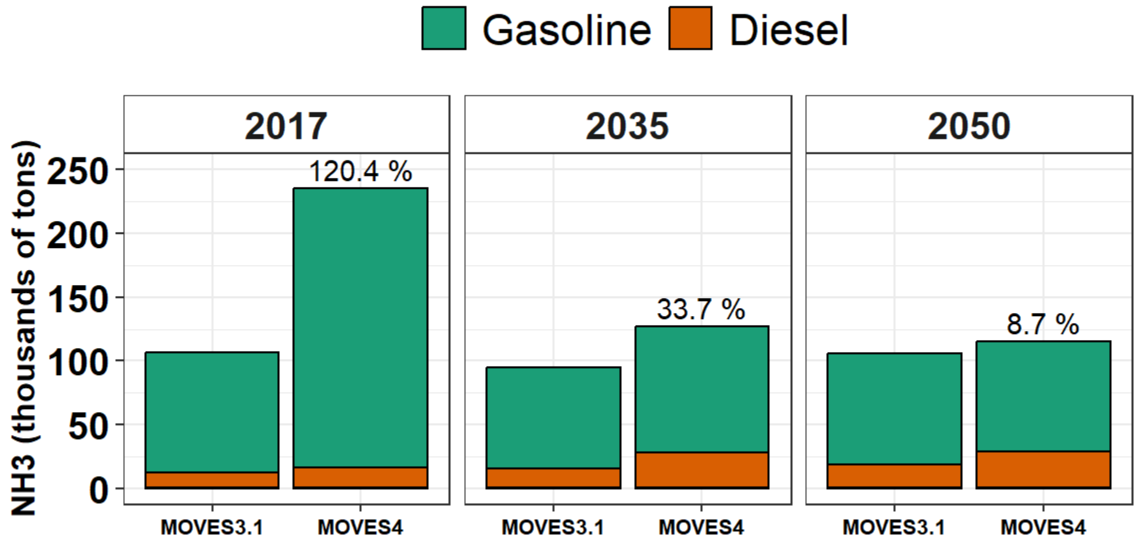
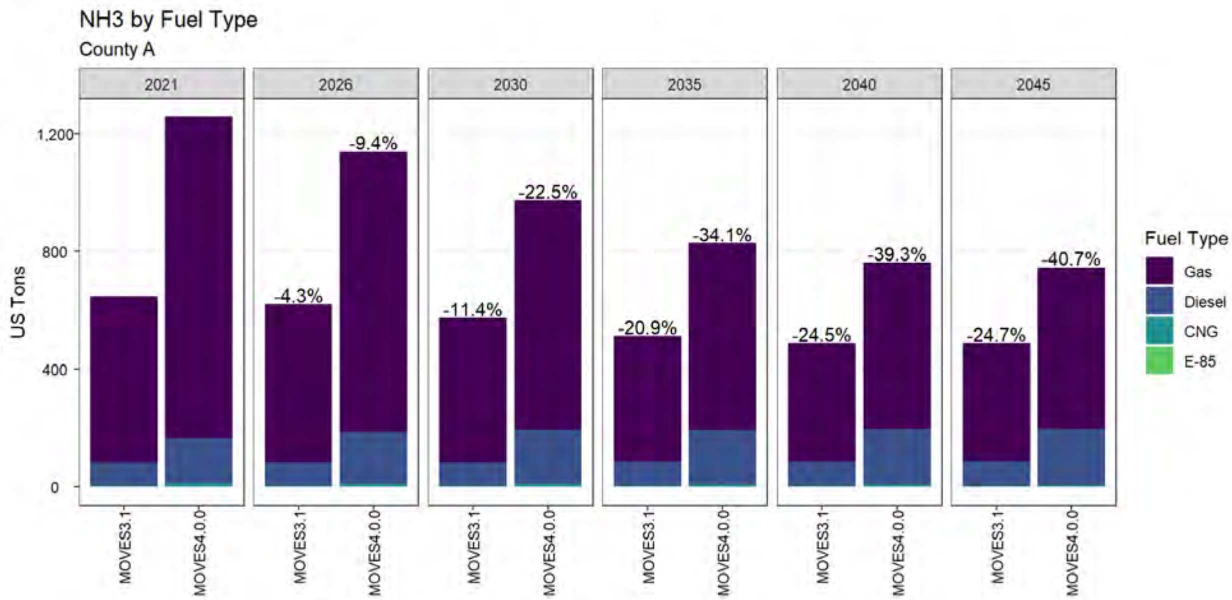


Figure 6-17—National onroad NH_3 in MOVES4 as compared to MOVES3.1. Percentage values indicate change between MOVES3.1 and MOVES4.



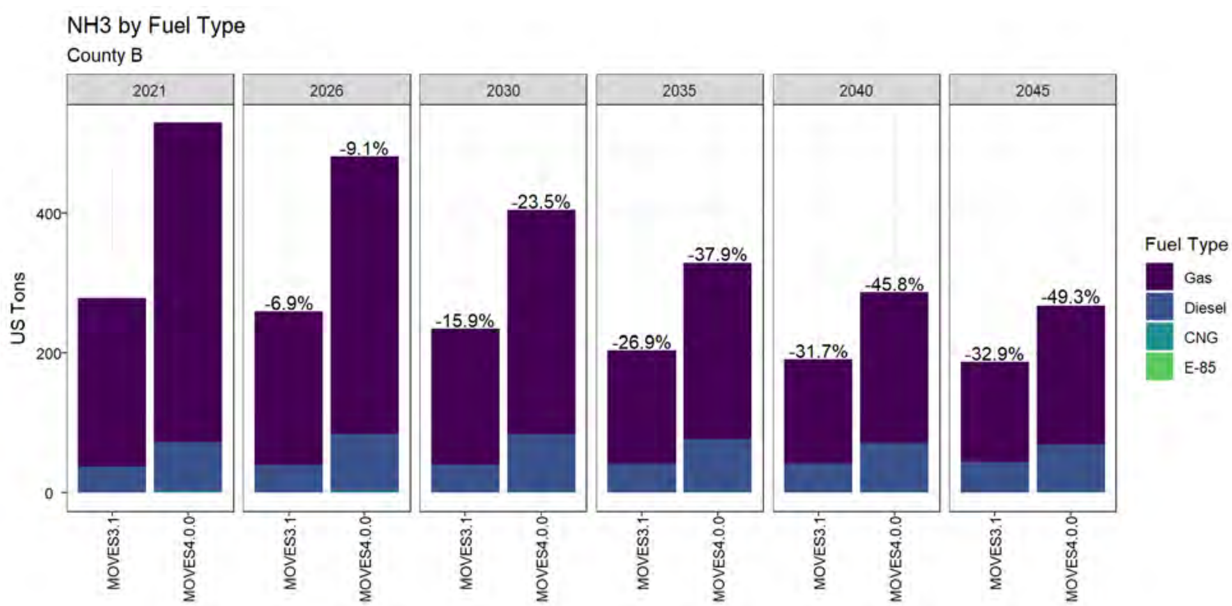


Figure 6-18—Onroad NH_3 from two sample urban counties in MOVES4 as compared to MOVES3.1. Percentage values indicate change compared to calendar year 2021.

As illustrated in Figure 6-19 and Figure 6-20, for future years, MOVES4 estimates lower SO_2 emissions as compared to MOVES3. This reflects MOVES4 updates to gasoline sulfur content as well as lower estimated gasoline consumption.

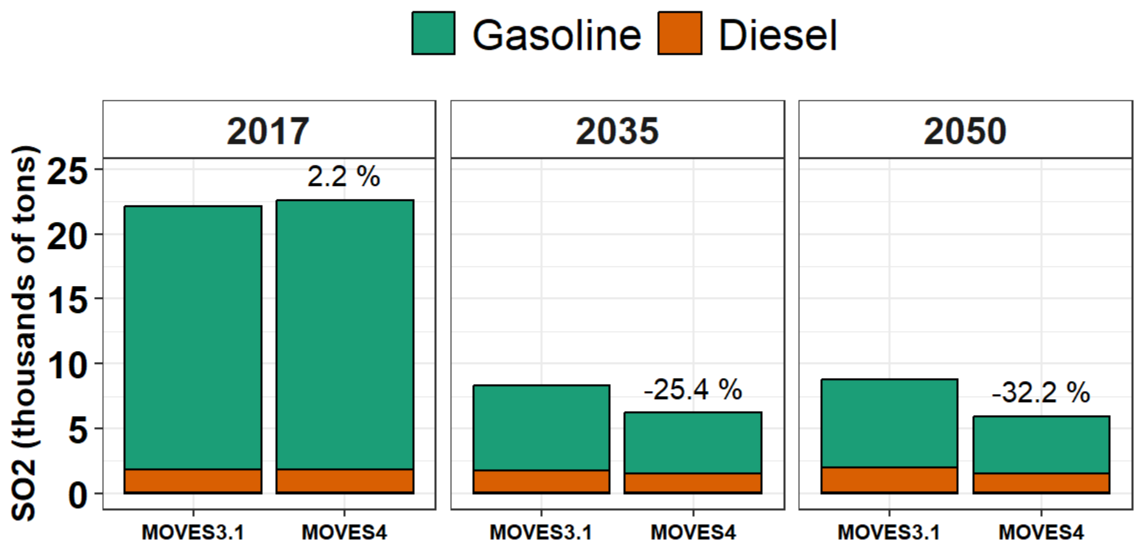


Figure 6-19—National onroad SO_2 in MOVES4 as compared to MOVES3.1. Percentage values indicate change between MOVES3.1 and MOVES4.

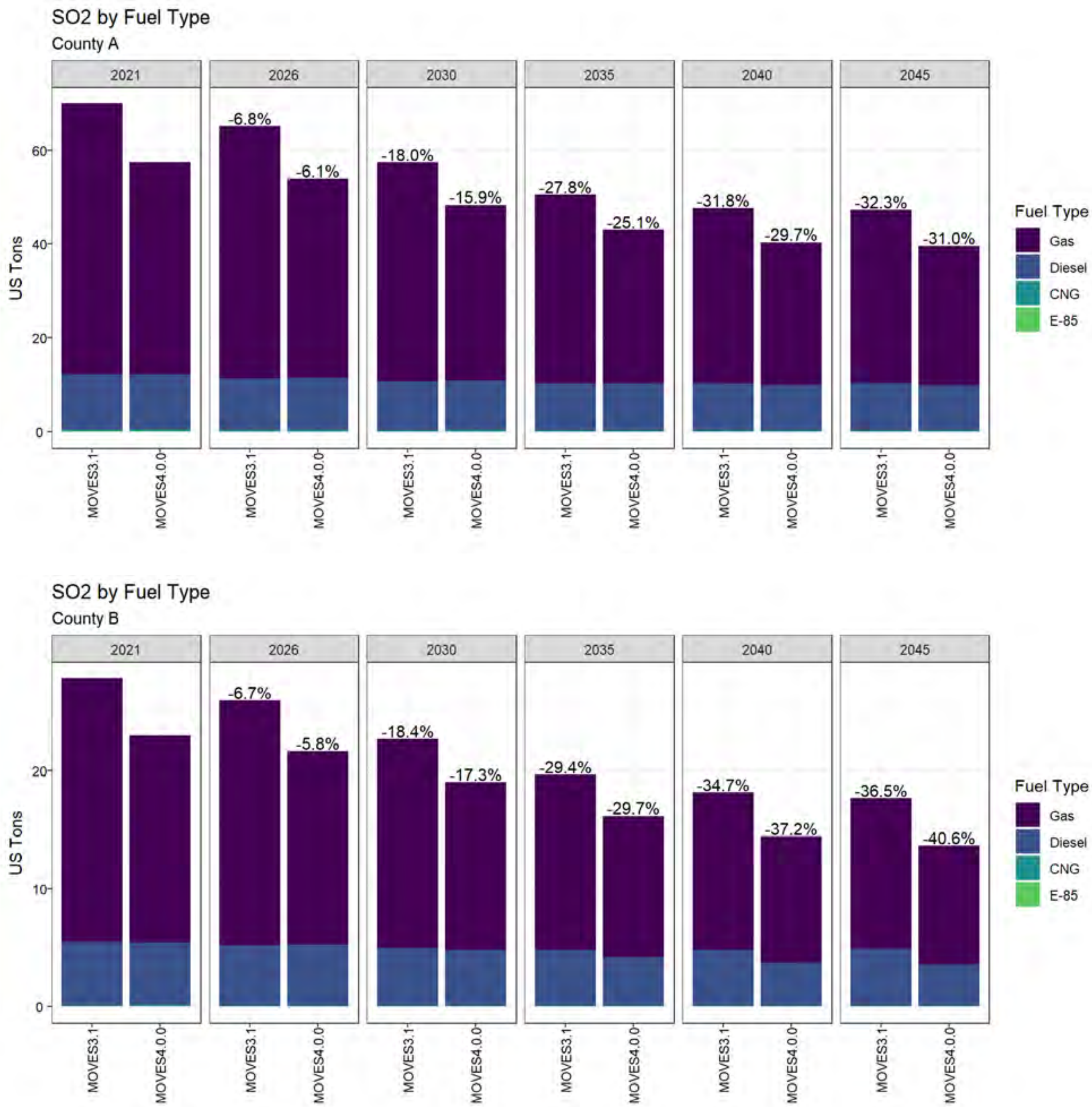


Figure 6-20—Onroad SO_2 from two sample urban counties in MOVES4 as compared to MOVES3.1. Percentage values indicate change compared to calendar year 2021.

6.2 Nonroad

The only nonroad input that was changed for MOVE4 was the sulfur level of nonroad gasoline fuel, resulting in decreases in SO_2 as show in Figure 6-21.

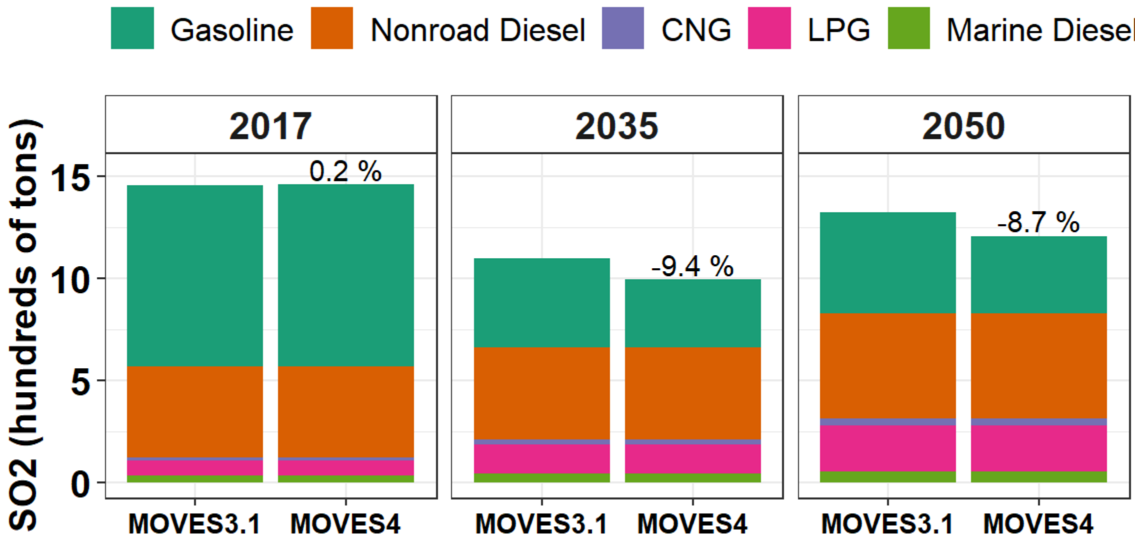


Figure 6-21 Nonroad SO_2 in MOVES4 as compared to MOVES3.1. Percentage values indicate change between MOVES3.1 and MOVES4.

Emissions of other nonroad pollutants are the same in MOVES4 as in MOVES3. Figure 6-22 summarizes annual nonroad emissions for key pollutants from running MOVES4 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.

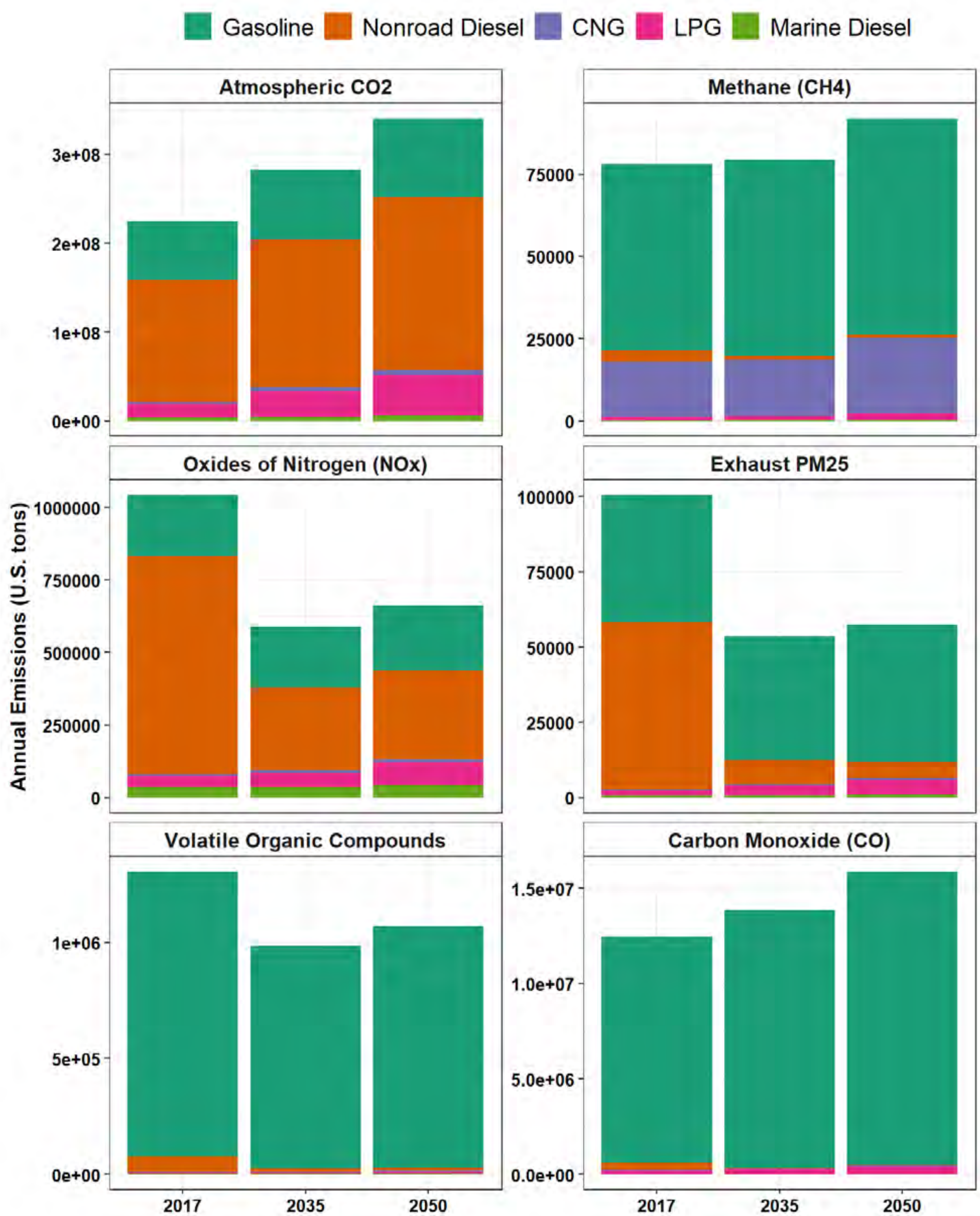


Figure 6-22 MOVES4 Nonroad emissions by calendar year

7. MOVES Testing and Evaluation

To ensure that the MOVES model contains the state-of-the-science when estimating emissions from mobile sources, and 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, review and evaluation of earlier versions of MOVES is often relevant even for later versions.

7.1 Peer Review

Since MOVES2014b, we have conducted four rounds of peer review for the updates to MOVES3 and MOVES4 data and algorithms, following EPA's peer review policies and procedures.[31] Reviewer comments and EPA's responses are documented 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)

Peer review documents for previous versions of MOVES are also available at this location.

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 represent 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 same output if used with consistent inputs.

7.4 Beta Testing and Shared "Release Candidate"

Beginning in November 2022, a draft version of MOVES4 was tested by a small group of experienced MOVES users who identified potential errors in the code and provided comments on the new features and documentation, including the updated interface and database converter.

Furthermore, prior to the final release of MOVES4, we also posted a draft version of MOVES4 (referred to as a "release candidate") to the MOVES GitHub site (https://github.com/USEPA/EPA_MOVES_Model/releases/tag/MOVES4-RC2). This posting allowed additional user testing and helped modelers to become familiar with functional changes between MOVES3 and MOVES4 before MOVES4.0 was released.

7.5 Accessibility Testing

The MOVES3 graphical user interface was reviewed for accessibility under the Voluntary Product Accessibility Template (VPAT).[33] The interface partially supports the accessibility requirements. Interface changes for MOVES4 were minimal and the MOVES3 VPAT 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 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 are 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., 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, and it is useful when the comparison data 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]

A more recent 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 and 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 suspect 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]

Other studies compare "localized composite" emissions, using composite emission measurements from many vehicles by tunnel[44] or roadside emission monitors[45] 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.[46] 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.[17] A near-road study that suggests increases in heavy-duty diesel emissions with decreasing ambient temperature[47] is discussed in more detail in the MOVES adjustment report.[15]

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,[48] 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.[49]

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.[50,51]

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.

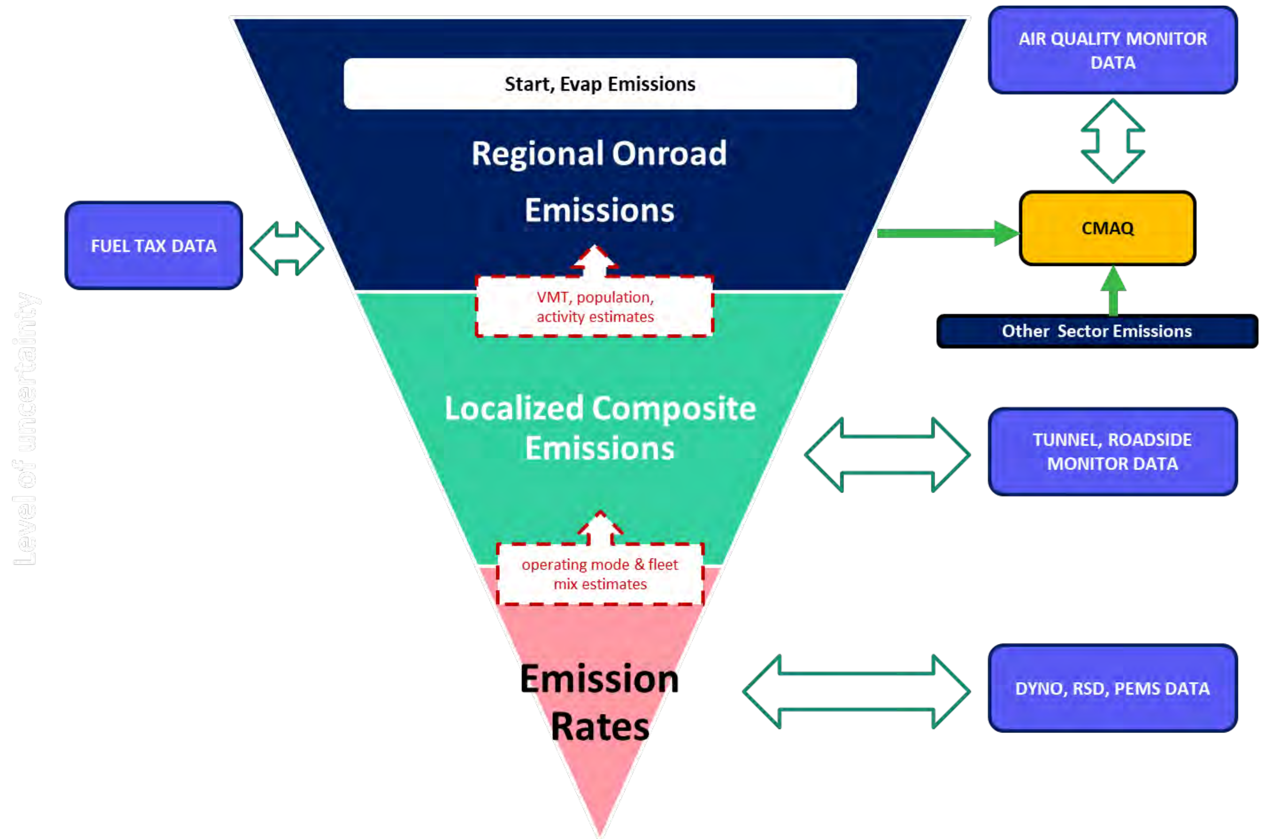


Figure 7-1--MOVES evaluation opportunities at rising levels of generalization and uncertainty.

Fuel Consumption Comparisons

For MOVES3, we conducted a detailed comparison of the gasoline and diesel fuel consumption estimated by MOVES and estimated by FHWA based on fuel tax data. The study noted 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. For the calendar years in the comparison, MOVES gasoline consumption was overestimated, but within 10 percent of FHWA estimates, with better comparisons for more recent years. MOVES diesel consumption was also overestimated but within 20 percent for all years except 2009 and within 10 percent for calendar years 2016 and later.[52]

For MOVES4, we repeated this comparison using the same methodology. The MOVES4 gasoline consumption estimates were higher, reflecting an update to MOVES default fuel energy content for E10 gasoline (see the MOVES4 GHG and Energy report for details[14]) and a change in the age distribution with more older cars and fewer vehicles covered by more stringent standards; thus, as illustrated in the figures below, MOVES4 gasoline consumption compared less well to FHWA estimates, especially in past years. Note that for performance purposes, certain inputs to MOVES do not capture changes over time, such as relative mileage accumulation rates and fuel energy consumption. In these cases, given the importance of MOVES in forecasting future emissions, we have chosen updates such that MOVES better represents current and future conditions rather than past.

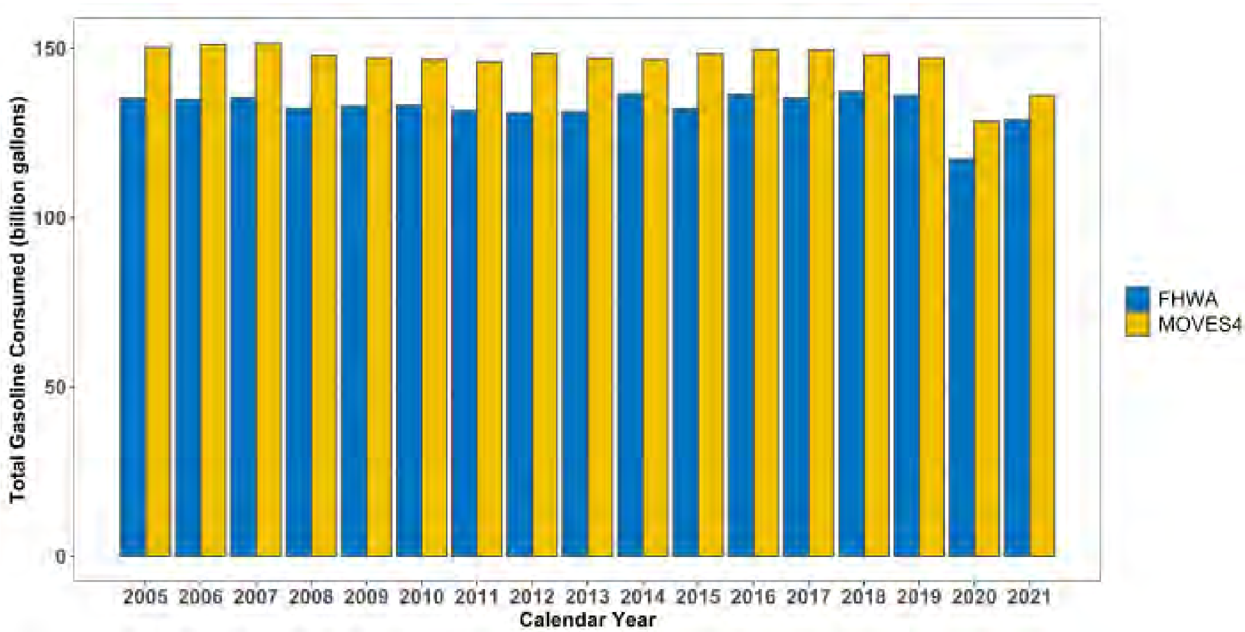


Figure 7-2—National gasoline consumption (in billion gallons) by calendar year estimated by MOVES4 and FHWA.

The MOVES4 diesel comparisons were similar to MOVES3, with a close match in the most recent years.

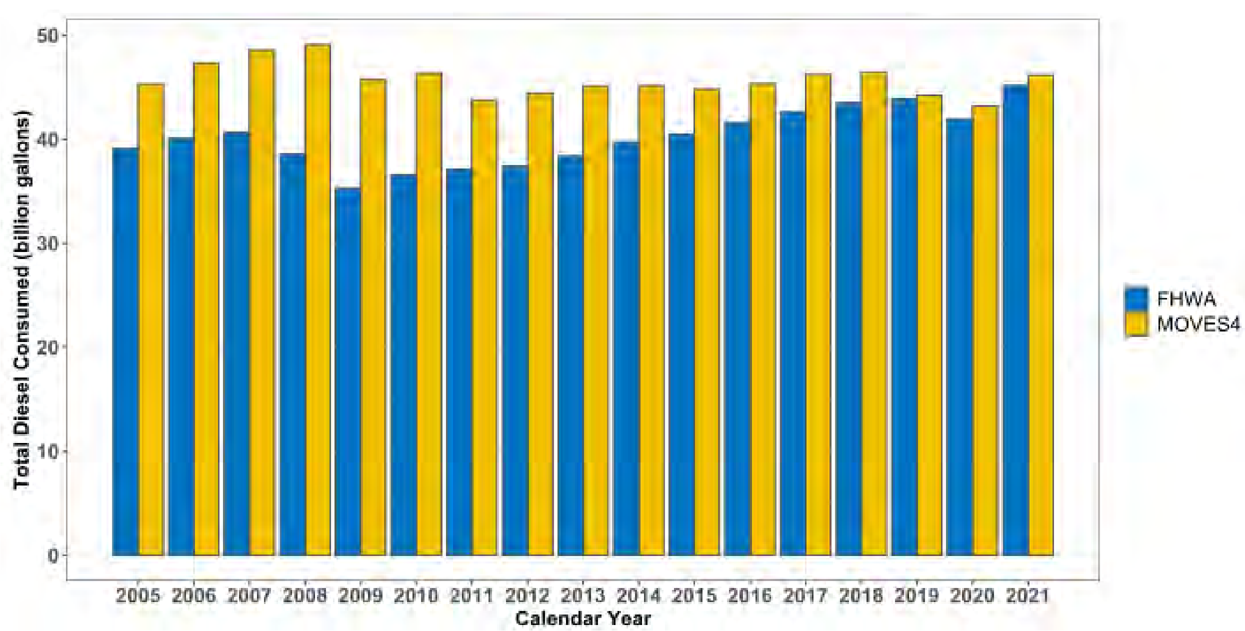


Figure 7-3—National diesel consumption (in billion gallons) by calendar year estimated by MOVES4 and FHWA.

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[53,54,55] particularly from LD gasoline vehicles.[56]

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 in MOVES3.

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.*[57]

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 2010+ light-duty gasoline emissions).

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

- 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.[58,59]
- 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.[60]
- 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.
- 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 emission processes is updated.
- 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.[17] 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. The MOVES4 updates were limited in scope as described in Section 2.3, above, 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.[19] MOVES motorcycle emissions rates were last analyzed in 2010.[61] Light-duty gasoline running emission rates were updated for MOVES3 based on millions of test results, but differences between “with I/M” and “non I/M” rates for THC, CO and NOx emission rates are based on previous analysis, and LD gasoline start deterioration with age is derived from information on running emissions.[19] Evaporative emissions other than refueling also were not updated for MOVES3 or MOVES4, 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.[16]

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, 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.[17]

MOVES4 brake and tire wear emission rates are based primarily on a literature review from 2006 and 2007.[22] Some MOVES adjustment factors are based on testing of older vehicle technologies.[2,15]

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 the nonroad emission factors 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. MOVES4 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 MOVES4 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 MOVES4.0.0 in general:

USEPA (2023) *Motor Vehicle Emission Simulator: MOVES4.0.0.* Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. August 2023. https://www.epa.gov/moves

Table 9-1 lists the various documentation currently available for MOVES3 and provides information on accessing each document.

Table 9-1 MOVES Documentation

General:			
	EPA Releases MOVES4 Mobile Source Emissions Model: Questions and Answers	Highlights the difference between MOVES3 and earlier versions of MOVES and explains EPA policy on using MOVES3 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 Introduction and Overview 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 MOVES4 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
	MOVES4 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 MOVES4 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
	MOVES4 Policy Guidance: Use of MOVES for State Implementation Plan Development, Transportation Conformity, General Conformity, and Other Purposes	How and when to use the MOVES4 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 MOVES4 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/MOVES4CheatsheetOnroad.pdf 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/MOVES4CheatsheetNonroad.pdf 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.	Will be posted at 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. The course is based on MOVES2014b and still largely applicable to MOVES4.	https://www.epa.gov/moves/moves-training-sessions#hotspot

Installation and Computer-Related Aspects of Using MOVES			
	Installation Suite	Executable program to install MOVES4 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
	MOVES4 Database Conversion Tool Help	Explains use of tool to convert MOVES3 databases for use with MOVES4	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/database/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.md
	MOVES4 Update Log	Chronological listing of updates to MOVES3	https://www.epa.gov/moves/moves4-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 MOVES4 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 MOVES4 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
AVFT	Alternative vehicle fuels and technologies
BSFC	Brake-specific fuel consumption
CH_4	Methane
CI	Compression ignition
CMAQ	Community Multiscale Air Quality Modeling System
CO	Carbon monoxide
CO_2	Carbon dioxide
EPA	Environmental Protection Agency
EV	Electric vehicle
FHWA	Federal Highway Administration
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
I/M	Inspection and maintenance
LD	Light duty
LHD	Light Heavy-Duty
MOVES	Motor Vehicle Emission Simulator
NMHC	Non-methane hydrocarbons
NMOG	Non-methane organic gases
NonHAPTOG	Residual total organic gases
NO_X	Oxides of nitrogen
NREL	National Renewable Energy Laboratory
PEMS	Portable emission measurement systems
PM_{10}	Particulate matter <= 10 µm
$PM_{2.5}$	Particulate matter <= 2.5 µm
SAFE	Safer Affordable Fuel Efficient Vehicles standard
SI	Spark ignition
THC	Total hydrocarbons
TOG	Total organic gases
VMT	Vehicle miles travelled
VOC	Volatile organic compounds

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