Overview of EPA's MOtor Vehicle Emission Simulator (MOVES3)

United States
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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 MOVES3, 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 MOVES3 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.[b]
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,[c] diesel, compressed natural gas (CNG), electricity 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). 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] MOVES3.0.0 models nonroad only through 2050. This has been fixed in MOVES3.0.1.
[c] Including ethanol/gasoline blends of up to 15% ethanol.
[d] Including ethanol/gasoline blends of up to 10% ethanol.

	Onroad	**Nonroad**
Pollutants and Energy Outputs	MOVES models a long list of criteria pollutants and their precursor emissions,[e] 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)[f], 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 at various detail – including the CB05, CB6CMAQ, SAPRC07T and CB6AE7 "chemical mechanisms" used in air quality modeling.[5]	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.
Activity Outputs	MOVES can output vehicle miles travelled (VMT), 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.
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.[g]	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] The Clean Air Act identifies six criteria pollutants: ground-level ozone, particulate matter, carbon monoxide, lead, sulfur dioxide, and nitrogen dioxide.
[f] While not exactly equivalent, elemental carbon is often used as a surrogate for black carbon in GHG estimates.
[g] 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.

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 1-2 summarizes the public release history of MOVES and its predecessors, MOBILE and NONROAD.

Table 1-2: 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 VMT input
MOVES2014b	2018	• Improved emission estimates for nonroad mobile sources • Updated outputs used in air quality modeling
MOVES3[h]	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	2021	• Fixed several small issues with processing and aggregation, making it easier to use the model for variety of applications. • Includes scripts to assist with checking MOVES3 submissions for the 2020 National Emission Inventory.

[h] MOVES3 and subsequent minor releases and "patches", are documented at https://www.epa.gov/moves/moves3-update-log and https://github.com/USEPA/EPA_MOVES_Model.

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 evaluations, and analyses required under the National Environmental Policy Act (NEPA), among others.[6] EPA provides training and technical guidance on using MOVES for SIP and conformity modeling[7] and PM hot-spot analyses,[8] including information on how to choose appropriate model inputs. MOVES is also used for state and local greenhouse gas emission planning.[9]

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[6,7,9] and the limitations discussed in Section 8 below.

2. Updates for MOVES3

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

2.1 New Regulations

Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles—Phase 2

MOVES3 accounts for the Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles—Phase 2 Rule ("HD GHG2") published in 2016.[10] This rule set stricter fuel economy standards for HD vehicles which reduce CO_2 emissions,[14] but also impact other pollutants through changes in glider sales, hotelling activity, vehicle mass and road load coefficients.[13]

Safer Affordable Fuel Efficient (SAFE) Vehicles Rule

MOVES3 also accounts for the March 2020 SAFE standards for light-duty passenger cars and trucks.[11] These standards were less stringent than the preceding fuel economy standards, and thus increased fuel consumption and CO_2 emissions.[12]

2.2 New Features

Off-network Idle

MOVES3 now accounts for "off-network idle" (ONI) activity beyond the idling at traffic signals and in traffic that is part of the MOVES drive cycles. ONI includes activity such as idling during pick-up and drop-off of passengers and idling during deliveries. It does not include extended idling (>1 hour) that occurs during long-haul hotelling (see Section 3.3 below.)

ONI emission rates are the same as other idle mode running emissions. ONI activity is based on telematics data for LD and HD sources.[13] ONI activity is used only to calculate running exhaust emissions. It is not relevant for starts, brake wear or tire wear. MOVES3 evaporative emission calculations have not been updated to account for ONI activity and thus model this idle time as hours parked.

Glider Trucks

MOVES3 accounts for "glider" vehicles that incorporate older engines into new vehicle chassis. These gliders emit significantly more NO_X and PM than trucks meeting newer emission standards.[14] This change was implemented by assigning some combination trucks to a new glider "regulatory class." They are assumed to travel the miles typical of the vehicle age, but with emission rates equivalent to vehicles subject to model year 2000 standards. The fraction of glider vehicles in the fleet accounts for the number permitted under the HD GHG2 rule.[13]

Increased Detail for HD vehicles

With incorporation of the HD GHG2 rule, MOVES3 allows modeling of road load coefficients, including vehicle mass, by source type and regulatory class, and modeling of fuel economy by source type. This allows finer distinctions among heavy-duty vehicles.[13]

2.3 Updates to Emission Rates

MOVES3 includes improvements to HD diesel running emission rates based on manufacturer-run in-use testing data from hundreds of HD trucks. The model also includes updated emission rates for HD gasoline and CNG trucks.[14]

MOVES3 also includes updated LD emission rates for HC, CO and NO_X based on millions of test results from in-use testing data, and inspection and maintenance (I/M) data from the State of Colorado. Updates to LD PM rates for MY 2004+ incorporate data on gasoline direct injection (GDI) vehicles.[15]

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

2.4 Updates to Fuel Characteristics, Vehicle Populations and Activity

Gasoline fuel properties have been updated using data from EPA fuel compliance submissions and a new algorithm for estimating the relationship between E200 and T50 distillation parameters.[1] Updates to fuel effect calculations better characterize the base fuel used to develop LD base emission rates.[2]

Updates to default vehicle start and idling activity patterns were based on real-world data from millions of trips from Verizon for light-duty vehicles and over 120,000 hours of activity from the National Renewable Energy Lab (NREL) for HD vehicles. Default hotelling activity was substantially reduced from MOVES2014 based on the NREL instrumented truck data. 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. [13]

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

Table 2-1: Summary of Major Algorithm and Data Updates for MOVES3

Area	**Description of Change**
LD PM rates[15]	Included new data from GDI (Gasoline Direct Injection) vehicles, and updated PM temperature adjustments.
LD THC/CO/NO_X rates[15]	Updated LD running rates based on new data from inspection and maintenance (I/M) program, Portable Emission Measurement System (PEMS) and remote sensing. Updated running and start rates. Reduced high-power emission rates.
LD Fuel consumptions and CO_2[12]	Increased fuel consumption and thus CO_2 to account for the Safer Affordable Fuel Efficiency (SAFE) rule.
LD start emission rates vs. parked time[15]	Updated the relationship between starts and soak time based on data from EPA and the California Air Resources Board.
Fuel effects[2]	Updated fuel effect calculations to better characterize the base fuel used to develop LD gasoline base emission rates
HD Fuel consumption and CO_2[14]	Incorporated the effects of the HD GHG Phase 2 rule.
HD diesel running rates[14]	Updated the heavy-duty (HD) diesel running emission rates based on manufacturer-run in-use testing data from hundreds of HD trucks.
HD CNG and gasoline emission rates[14]	Updated MY 2007+ CNG and 2008+ gasoline emission rates. Updated data on onboard refueling vapor recovery systems used in HD gasoline vehicles
HD start emission rates[14]	Updated MY 2010+ diesel and MY2008+ gasoline starts based on compliance data. Updated relationship of starts and soak time.
HD extended idle rates[14]	Updated HD diesel emission rates for extended idling and auxiliary power units.
Hotelling activity[13]	Updated HD hotelling assumptions (extended idling for diesel long-haul combination trucks at truck stops) based on new information.
HD vehicle masses[13]	Increased resolution in vehicle masses using weigh-in-motion and other data.
Gliders[13,14]	Accounted for gliders (new vehicles using older engines) in vehicle fleet.
HD crankcase emissions[14]	Updated rates for MY 2010+ HD crankcase.
Improved speciation[5]	Updated organic gas speciation profiles, including methane emissions, and incorporated new chemical mechanism—CB6AE7.

Area	Description of Change
LD and HD off-network idle time[13]	Accounted for off-network and work-day idling (idling in parking lots, distribution centers, etc), based on detailed trip data for LD and HD vehicles.
LD and HD start activity[13]	Updated start activity based on detailed trip data for LD and HD vehicles. Accounted for fewer starts by vehicle age.
Road type categories[13]	Removed "ramps" as a separate road type. Ramp driving activity is now incorporated in rural and urban freeway driving.
LD and HD VMT, activity and vehicle characteristics[13]	Updated historic and projected VMT based on 2019 Highway Statistics and Annual Energy Outlook (AEO). Updated vehicle age distributions. Updated default speed distributions.
Fuel properties[1]	Updated information on gasoline and diesel fuel properties based on the latest fuel compliance data. These updates affect nonroad and onroad emissions.

2.5 Updates to User Interface and User Inputs

The structure of MOVES3 is fundamentally the same as MOVES2014, with some minor changes, including changes in the MOVES graphical user interface (GUI), run specifications, input and output databases.

Additional information is also included in the MOVES3 technical guidance[7] and the MOVES3 code documentation at https://github.com/USEPA/EPA_MOVES_Model. A converter tool is included in the MOVES3 model to assist in converting databases from MOVES2014 to MOVES3 format.

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

Table 2-2: Changes in MOVES user interface from MOVES2014b to MOVES3

Description		Notes
New RunSpec Requirements		
	All roadtypes are required for onroad County Scale and Default Inputs (formerly “National Scale”) runs where the running process is selected	Needed to accurately estimate the emissions from off-network idle
New Input Tables		
	Start activity input tables have different names and structures	More details are available in the County database (CDB) converter help file and the technical guidance
	Hotelling activity input tables have different names and structures	More details are available in the CDB converter help file and the technical guidance
Changed Definitions		
	SourceTypeID 41, “Intercity Bus” is now called “Other Bus”	The previous definition only included diesel Class 8 buses on long distance routes. The new definition includes any kind of bus that is not owned or operated by a transit agency and is not a school bus.
	Changes to regulatory classes	RegClassID 40 & 41 were combined into RegClassID 41 that includes all 'Class 2b and 3 Trucks (8,500 lbs < GVWR <= 14,000 lbs)'; RegClassID 40 no longer exists; RegClassID 49 was added for "Glider Vehicles"
New Capabilities and Output		
	Off-network idle emissions	Running emissions on the “off-network” roadtype
	Ability to model calendar years up to 2060	MOVES2014 modeled only through 2050.
	Ability to model CNG vehicles for all heavy-duty source types	MOVES2014 modeled only CNG transit buses. Users can now set CNG fractions for all HD source types using the Alternative Vehicle Fuels & Technologies (AVFT) importer.
Changes in GUI		
	Renamed “National Scale” as “Default Inputs”	Reflects that the distinction between Default and County Scales is based on the source of the inputs rather than the geographic area that can be modeled.
	Reorganized panels	To improve logical flow of activity and to better separate “typical” and “advanced” features
	Better keyboard-only navigation	To improve accessibility

	Description	Notes
Software Changes		
	MariaDB	MariaDB replaces MySQL as the database server for MOVES since the latest versions of MySQL have removed features that MOVES relies on, but MariaDB continues to support these features. MariaDB is a drop-in replacement for MySQL. It is also easier to install.
	JAVA	JAVA is embedded in MOVES3 so users will not need to install a separate version of JAVA on their computers.
No Longer Available		
	Custom Domain (an option within the County Scale) is no longer available	Users who have used custom domain to model partial counties or multiple counties will need to run at County Scale instead.
	Ramps are no longer a separate road type; their emissions are included in the restricted access road types	Ramps can still be modeled separately in the Project Scale.
	MOVES no longer accepts input of fuel with MTBE, TAME or ETBE content >0.	Use of these oxygenates in U.S. gasoline is now negligible.
	The “Rate of Progress” strategy, also referred to as the “No Clean Air Act Amendments” strategy, is no longer available.	The ozone NAAQS implementation rules no longer require states to exclude emission reductions from pre-1990 motor vehicle control programs; therefore, it is no longer necessary to include this capability in MOVES.

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.[5]

3.1 Running Exhaust

Running emissions are the archetypal mobile source emissions—exhaust emissions from a running vehicle. 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.[15]

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.[13]

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.[14,15]

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 vehicle characteristics, MOVES may adjust the running emissions to account for local fuel parameters,[2] air conditioning effects, humidity, LD inspection and maintenance programs[16] and fuel economy adjustments.[12]

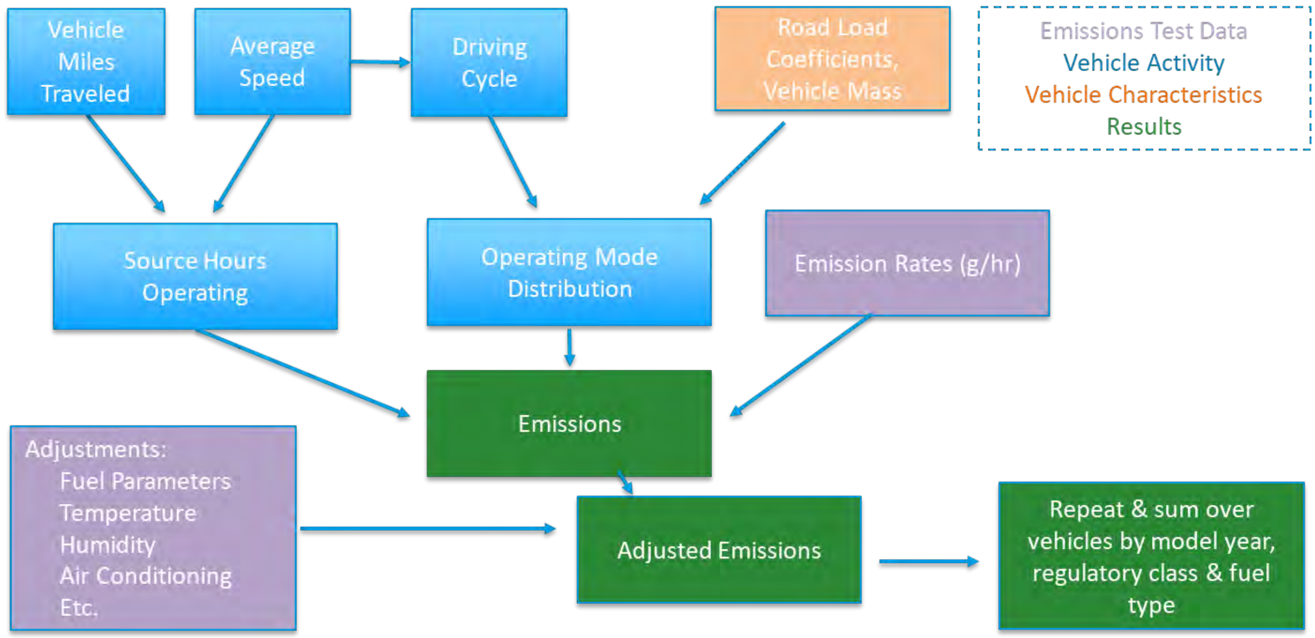

Figure 3-1: Calculating Running Emissions for Onroad Vehicles

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. .[14,15]

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).

MOVES computes hotelling emissions only for diesel long-haul combination trucks. The default MOVES hotelling hours are computed as a fixed ratio to the miles these trucks travel on restricted access roads.

Hotelling activity is allocated among four operating modes: engine idle ("extended idle"), diesel auxiliary power unit (APU) use, battery or plug-in, and "All Engines and Accessories Off." This allocation varies by model year.[13] MOVES computes emissions for the first two modes based on the hours and source-bin specific emission rates. Hotelling NO_X emissions are adjusted for ambient humidity. In MOVES output, the extended idle and APU emissions are assigned separate emission processes.[14]

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.[17]

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, source type, fuel type, model year and exhaust process.[14]

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 MOVES3 vary by vehicle regulatory class to account for average vehicle weight. 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.[18]

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.[18]

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.[19]

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). MOVES3 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.[19]

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).[19]

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.[19]

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.[20]

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 adjusted emission factor for THC, CO, NO_X, PM and 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.[21] Temperature effects are applied to THC, CO and NO_X exhaust emissions from 4-stroke SI engines.[22]

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 SI engines that have open crankcases[23] and for all CI engines prior to implementation of the Tier 4 NR diesel standard.[24]

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.[25]

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.[26]

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 SI 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.[26]

5. MOVES Software Structure

MOVES is written in Java (compiled with AdoptOpenJDK), 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 master–worker program architecture that enables multiple computers to work together on a single model run. A single computer can be used to execute MOVES runs by running both the master 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 Master and Worker programs.

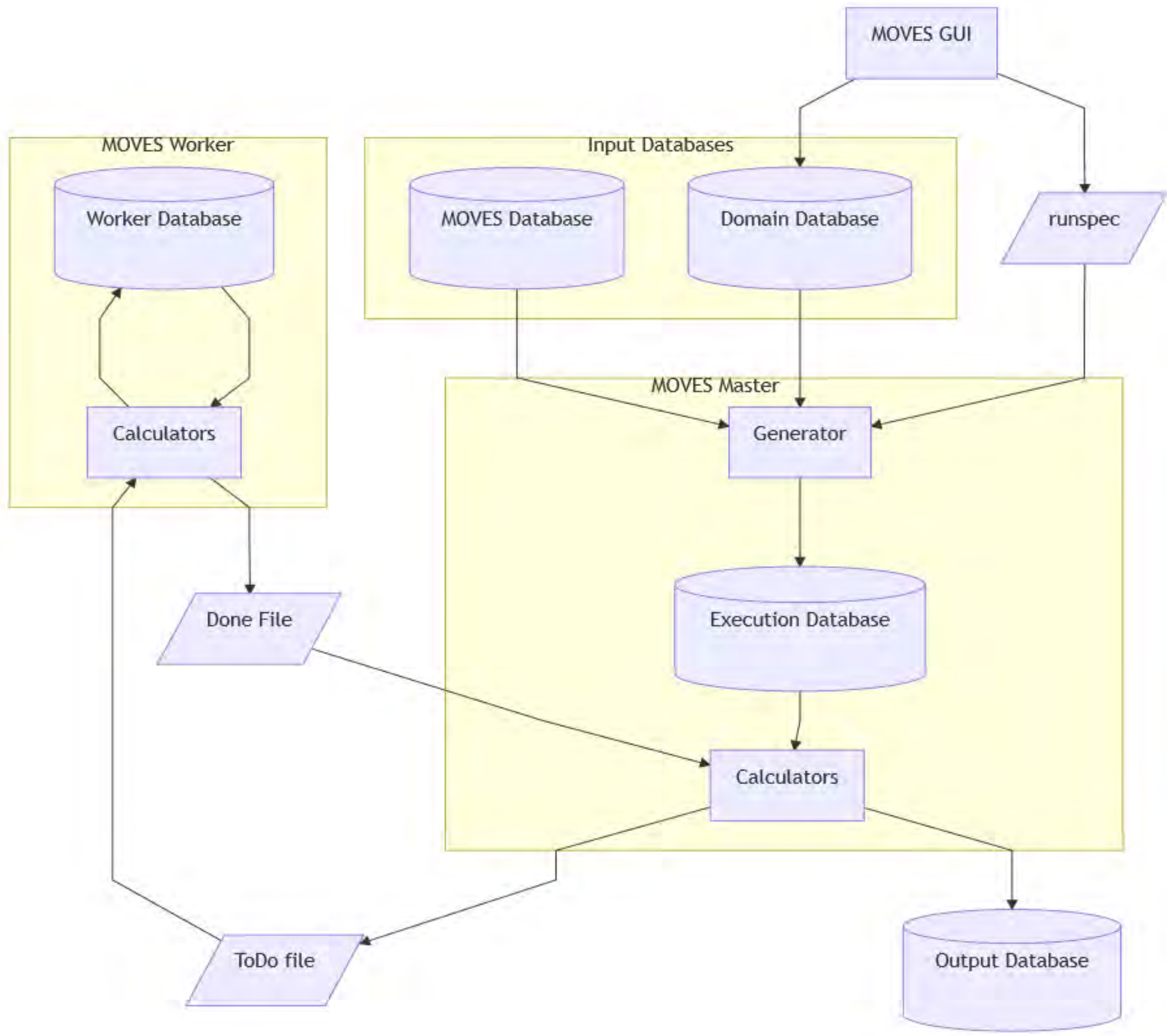

Figure 5-1-- Diagram of MOVES information flow

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 MOVES3 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 help assure that the RunSpec and inputs are consistent with MOVES algorithms and capabilities.

MOVES Master Program

When the run is started, MOVES Master 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 Master program then bundles data and calculation instructions into ToDo files to be processed by MOVES Workers. The MOVES Master 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 Master and Worker programs.

Note that only one executing MOVES Master program can be used during a MOVES run.

MOVES Worker Program

The MOVES Worker program processes the ToDo files created by the MOVES Master 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 Master 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 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 MOVES3 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 Master 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, 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. MOVES3.0 Results

Vehicle and equipment emissions vary by location and time. This section shows MOVES3 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.   These graphs were prepared with MOVES3.0.0, but results with MOVES3.0.1 are interchangeable at this scale.

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 2017 were generated with previous versions of MOVES and thus lack MOVES3 updates.

6.1 Onroad

The following plots summarize key results for onroad vehicles from running MOVES3 at the national, annual level using default inputs as compared to runs using the previous model, MOVES2014b. 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. The percentages shown in these figures represent the change in total emissions between MOVES2014b and MOVES3 for each analysis year.

Figure 6-1 shows a gradual increase in VMT over time. Shifts between MOVES2014b and MOVES3 reflect changes to the MOVES default inputs of historical VMT and future year activity projections.

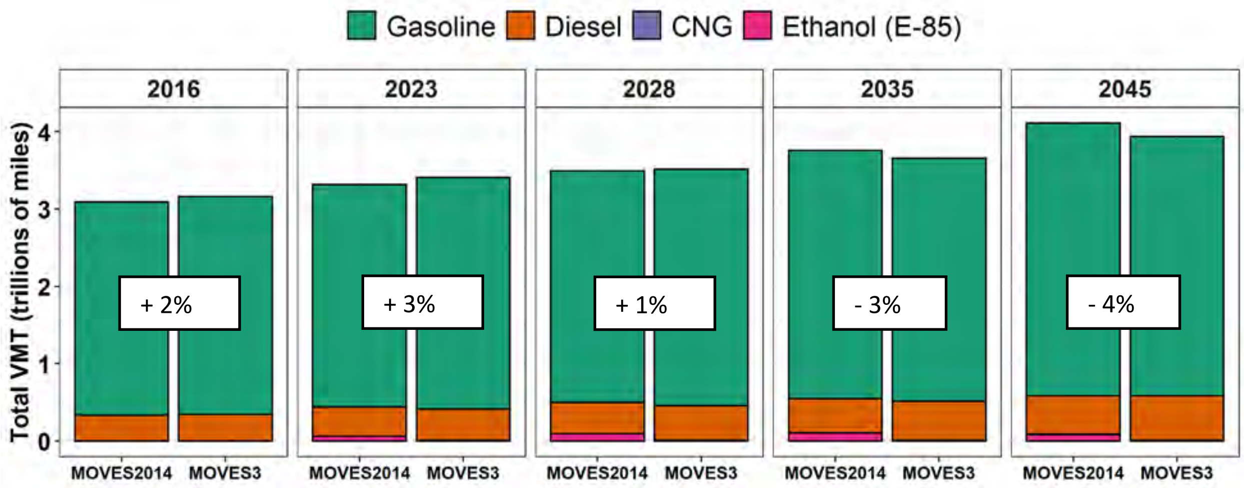

Figure 6-1—National onroad vehicle miles travelled (VMT) in MOVES3 as compared to MOVES2014b

While VMT increases over time, for CO2 (Figure 6-2), the MOVES model projects short-term increases, followed by decreases that reflect both the changes in activity and the phase-in of the HD GHG2 rule and the SAFE rule.

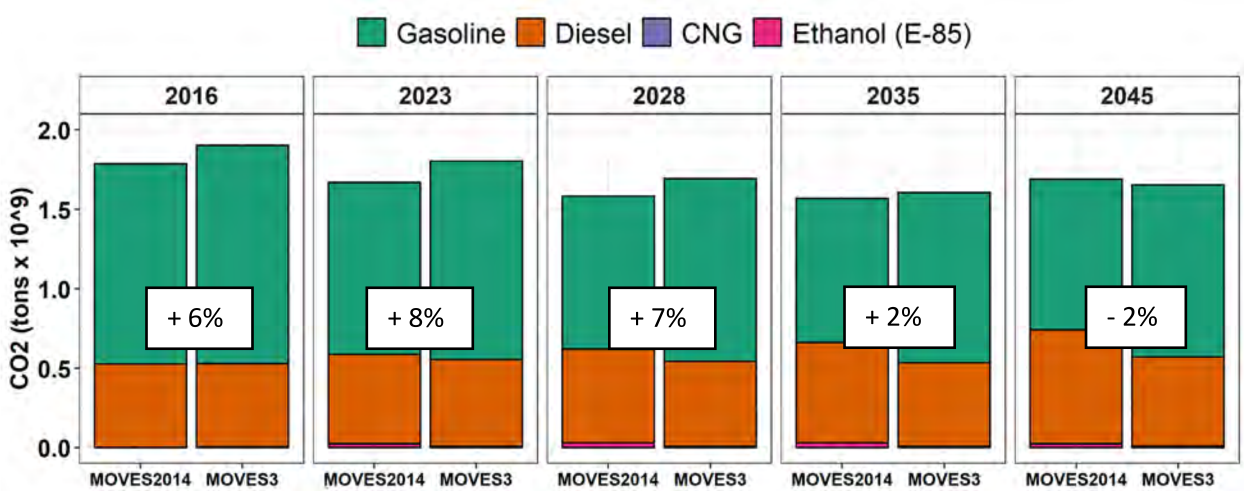

Figure 6-2—National onroad carbon dioxide in MOVES3 as compared to MOVES2014b

As shown in Figure 6-3, MOVES3 predicts a decline and subsequent increase in methane emissions from onroad vehicles. The change between model versions reflects updates in the way MOVES speciates hydrocarbons into methane and non-methane fractions as well as a predicted increase in the use of CNG HD vehicles, which have relatively high CH_4 emissions. Note the different units used for Figure 6-2 and Figure 6-3; the CH_4 increases are small compared to CO_2 when considered as CO_2 equivalents.

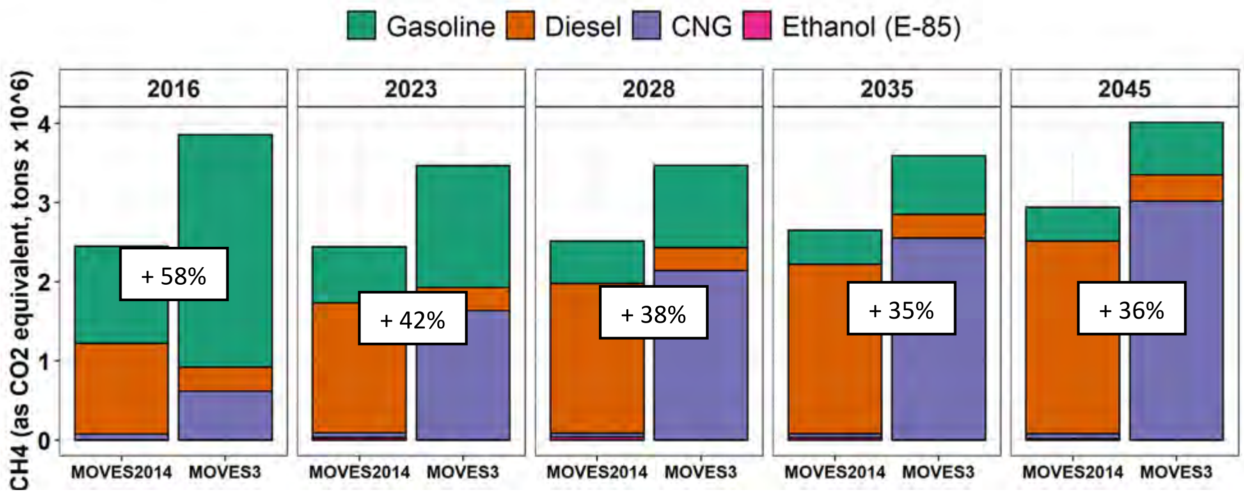

Figure 6-3—National onroad methane in MOVES3 as compared to MOVES2014b

Figure 6-4 shows national NO_X emissions from gasoline vehicles decline with the phase-in of the Tier 3 regulations for LD vehicles.[27] It also shows that diesel NO_X emissions decrease due to fleet turnover, i.e., additional vehicles compliant with the 2010 heavy-duty NO_X standards[28] entering the fleet over time. Two updates to MOVES3 are the main drivers of the difference in diesel NOx between MOVES2014b and MOVES3. First, MOVES3 has updated running rates based on data that show less effective NOx control at idle, low speed, and low power operations. This update has the effect of increasing NOx HD diesel emissions. Second, MOVES3 has updated extended idle rates, which reduce the amount of time HD trucks are hotelling. This update has the effect of reducing NOx HD diesel emissions. At the national scale, NO_X from diesel vehicles is lower in MOVES3 than in MOVES2014b because the reduced hotelling outweighs the increased running rates.[13] However, as shown in Figure 6-5, urban counties with congested roads and little hotelling activity in MOVES2014b may see higher total NO_X with MOVES3 than with MOVES2014b. Other counties with less congested roads may see different trends.

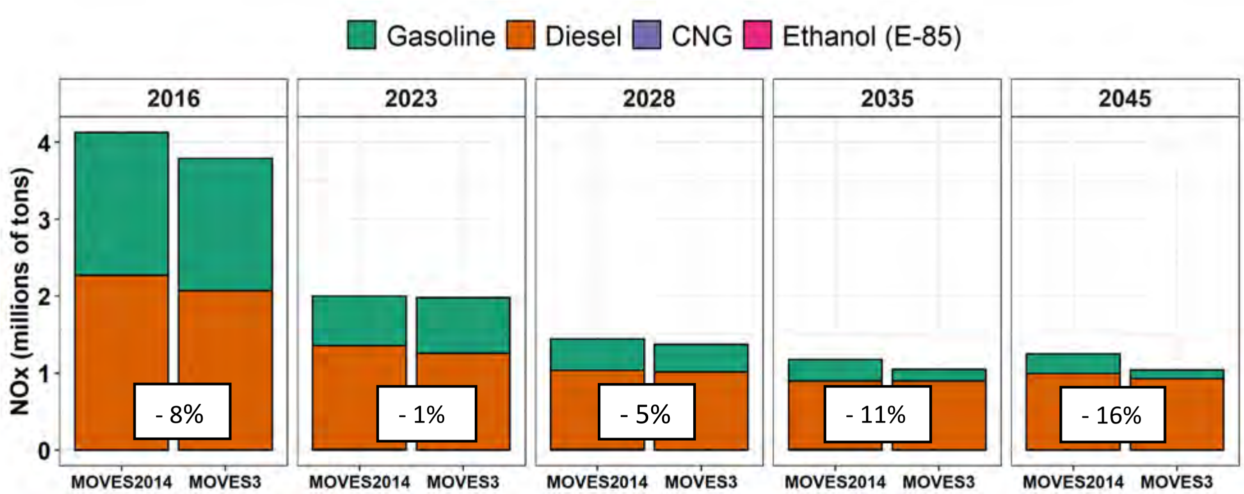

Figure 6-4—National onroad NO_X in MOVES3 as compared to MOVES2014b

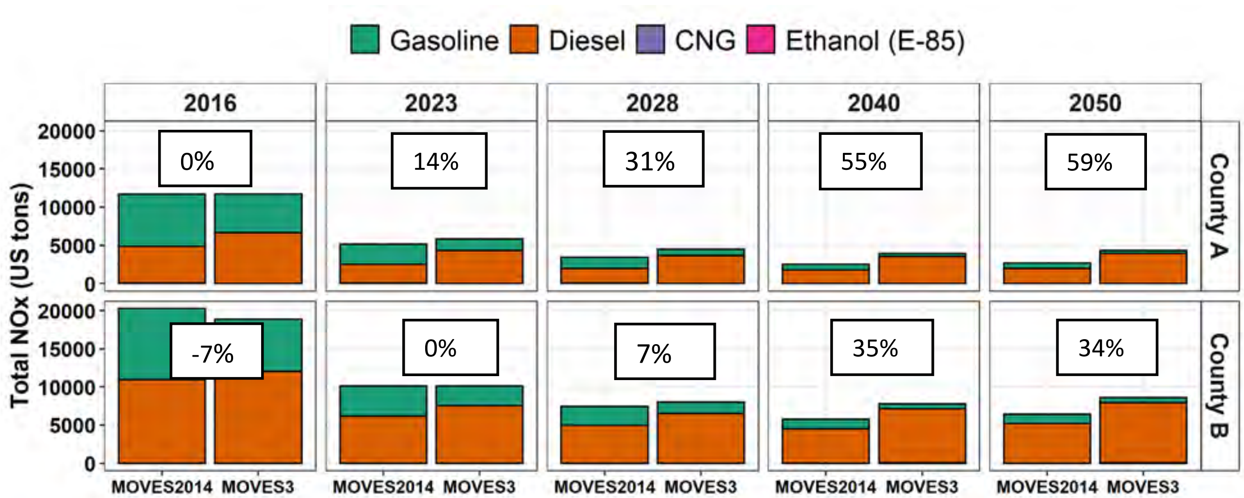

Figure 6-5—Onroad NO_X from two sample urban counties in MOVES3 as compared to MOVES2014b

Figure 6-6 shows national $PM_{2.5}$ inventory declining with the phase-in of light-duty and heavy-duty PM regulations. Compared to MOVES2014b, MOVES3 results in less PM exhaust primarily due to changes in heavy-duty diesel truck emission rates and hotelling activity. PM exhaust from gasoline vehicles also changed, with an increase in emissions from starts and a decrease in running emissions. The graph also shows that brake and tire wear emissions are similar in MOVES3 and MOVES2014b; in both versions of MOVES they form an increasing fraction of total onroad direct $PM_{2.5}$ emissions. The PM trend observed in select urban counties in Figure 6-7 is similar to the national PM trend, but other areas may see different results depending on their local inputs.

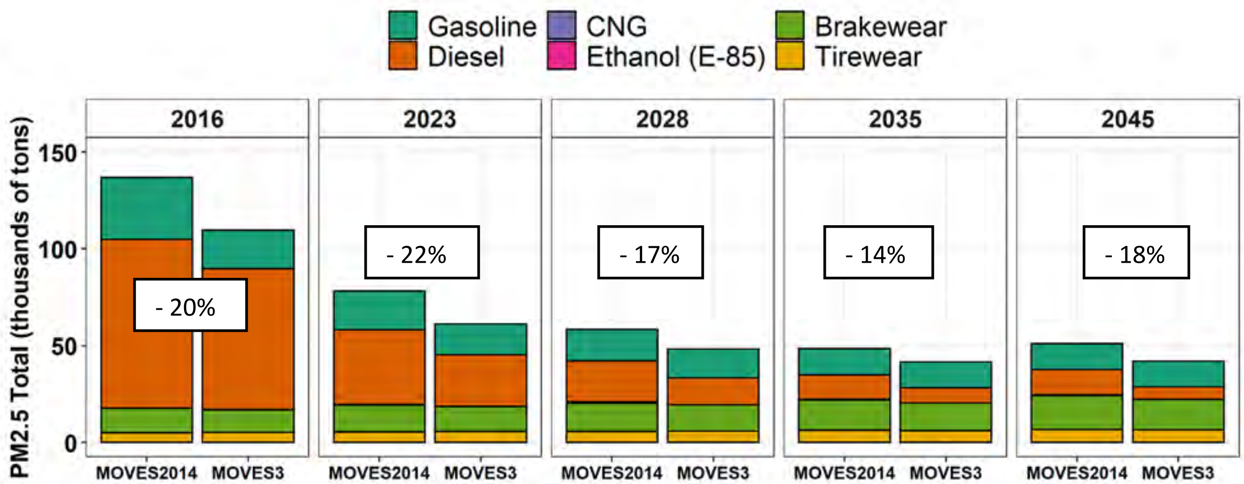

Figure 6-6—National $PM_{2.5}$ in MOVES3 as compared to MOVES2014b

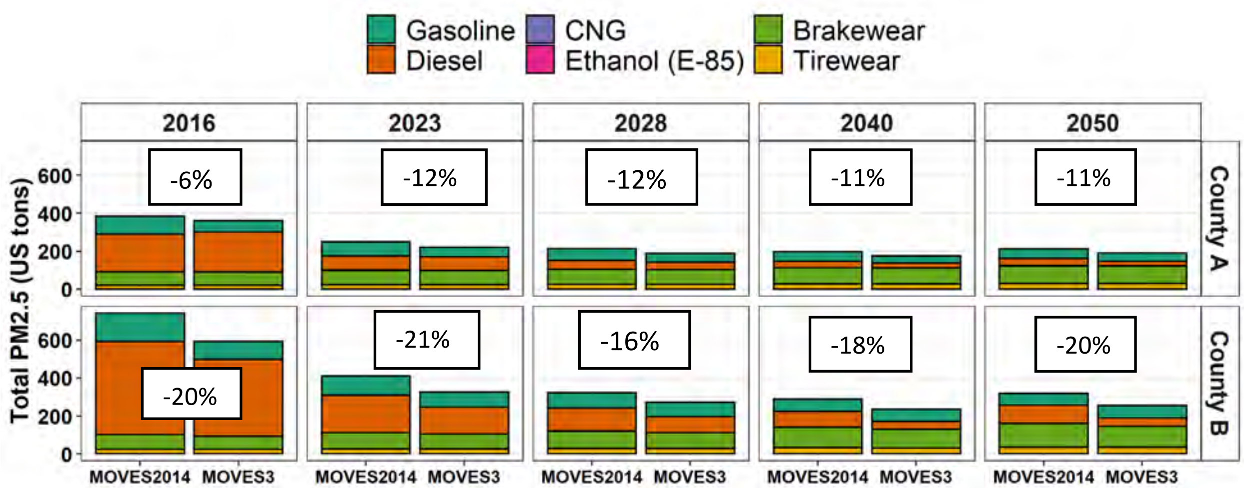

Figure 6-7—Onroad PM from two sample urban counties in MOVES3 as compared to MOVES2014b

Onroad VOC emissions are dominated by emissions from gasoline vehicles, which decline with the phase-in of Tier 3 regulations. Diesel VOC is lower in MOVES3 than in MOVES2014b because of decreased emission rates and hotelling activity. As illustrated in Figure 6-9, gasoline start emissions are lower in MOVES3 and gasoline running emissions are higher compared to MOVES2014b based mostly on new deterioration trends from vehicle test results. Also, 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 6-10 is similar to the national VOC trend, but other areas may see different results depending on their local inputs.

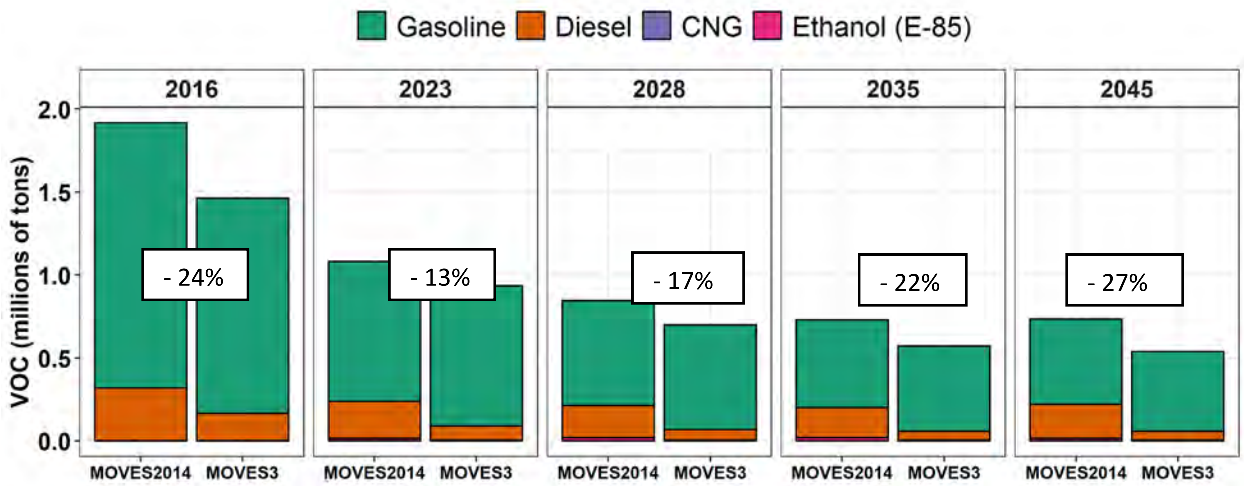

Figure 6-8—National onroad VOC in MOVES3 as compared to MOVES2014b

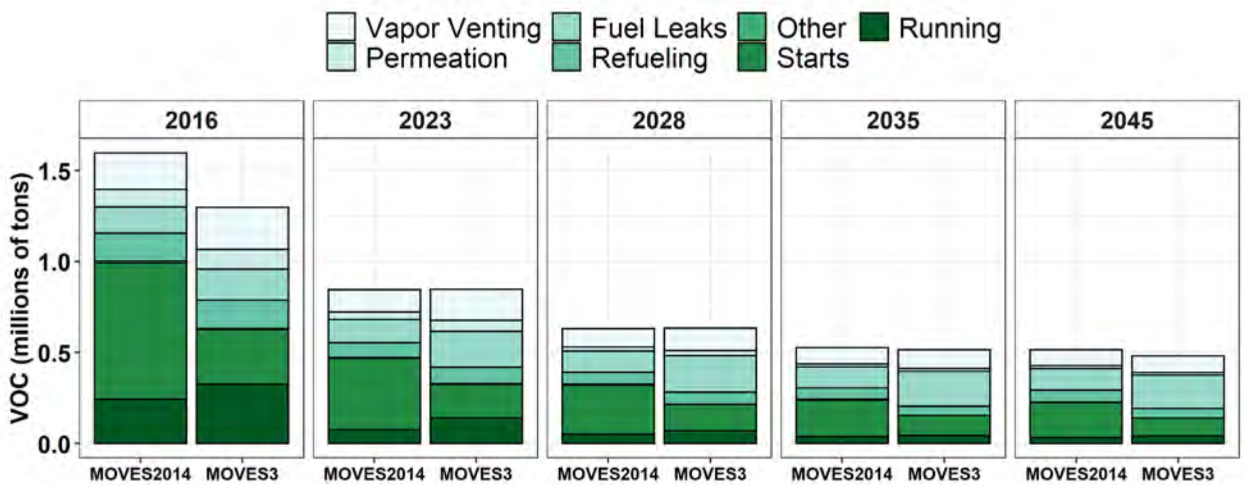

Figure 6-9—National onroad VOC from gasoline vehicles by emission process in MOVES3 as compared to MOVES2014b

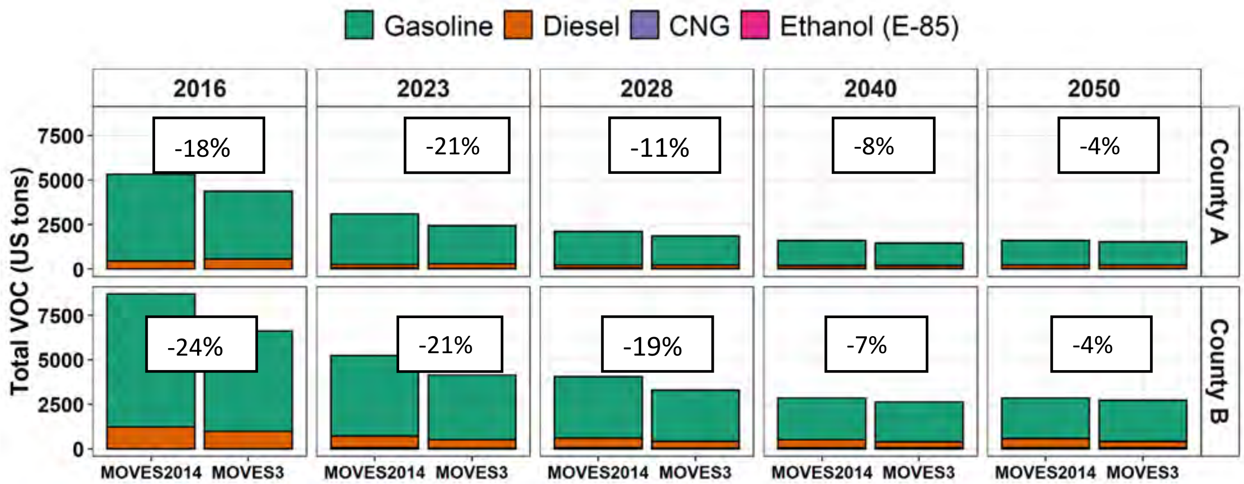

Figure 6-10—Onroad VOC from two sample urban counties in MOVES3 as compared to MOVES2014b

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 regulations and improved technology. However, the rates in MOVES3 are higher than in MOVES2014b based on changes to running emissions from in-use light-duty and heavy-duty vehicles, as shown in Figure 6-11.[14,15] The CO trend observed in select urban counties in Figure 6-12 is similar to the national CO trend for most years, but County B shows a decline in 2016 due to a decrease in CO start emissions from gasoline vehicles. Other areas may see different trends depending on their local inputs.

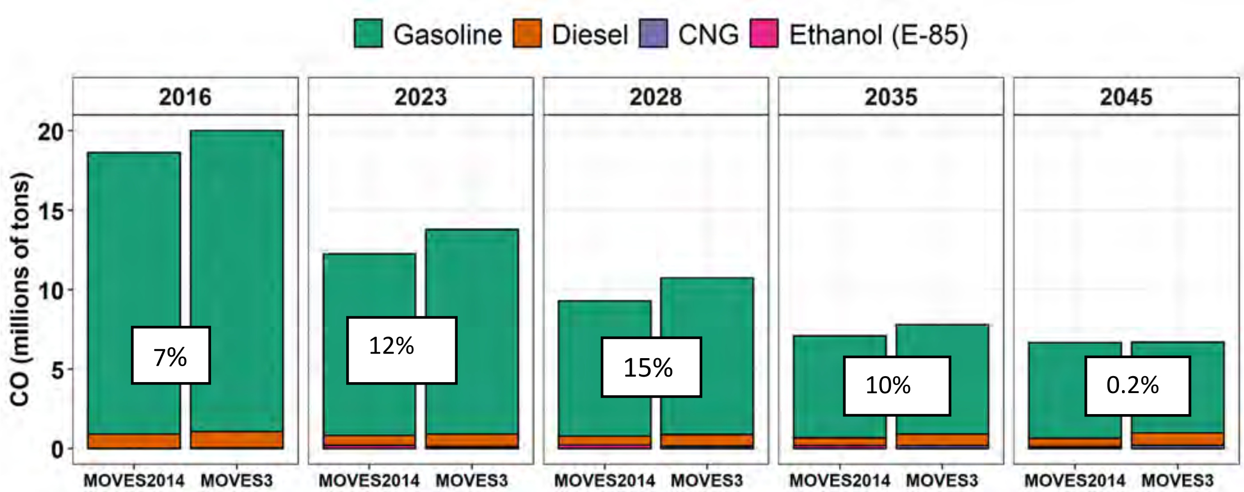

Figure 6-11—National onroad CO in MOVES3 as compared to MOVES2014b

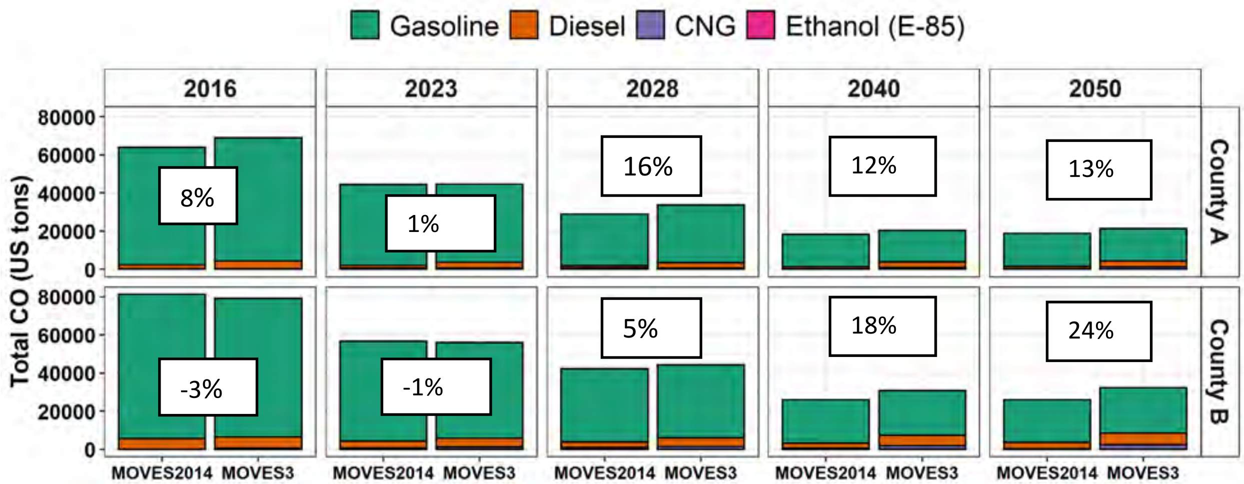

Figure 6-12—Onroad CO from two sample urban counties in MOVES3 as compared to MOVES2014b

6.2 Nonroad

The only nonroad input that was changed for MOVE3 was the sulfur level of nonroad diesel fuel. This leads to very small decreases in exhaust $PM_{2.5}$ as shown below in Figure 6-13 and in SO_2 (not shown).

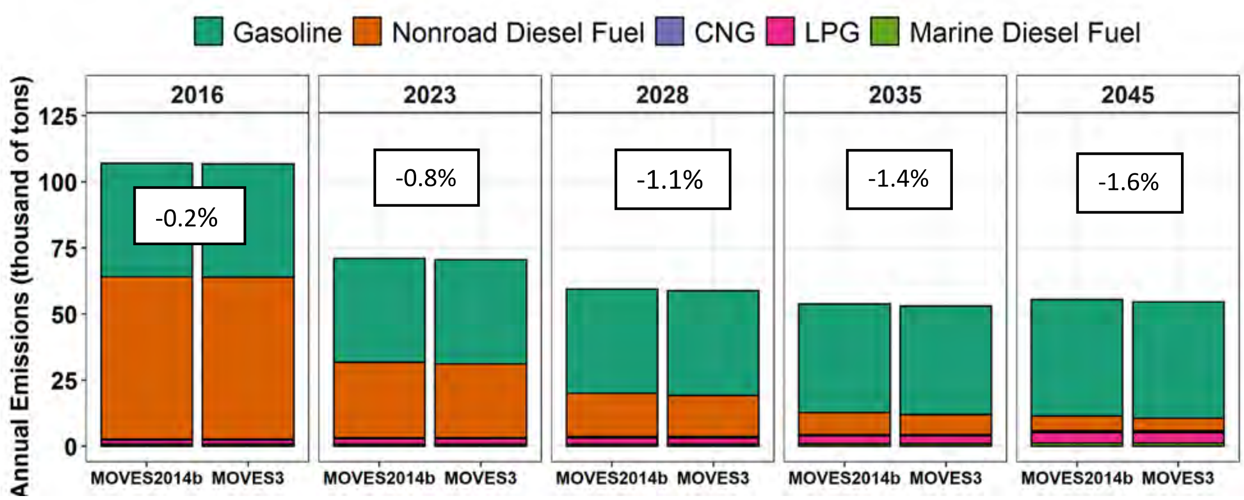

Figure 6-13 Nonroad exhaust $PM_{2.5}$ total in MOVES3 as compared to MOVES2014b

Emissions of other nonroad pollutants are the same in MOVES3 as in MOVES2014b. Figure 6-14 summarizes annual nonroad emissions for key pollutants from running MOVES3 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.

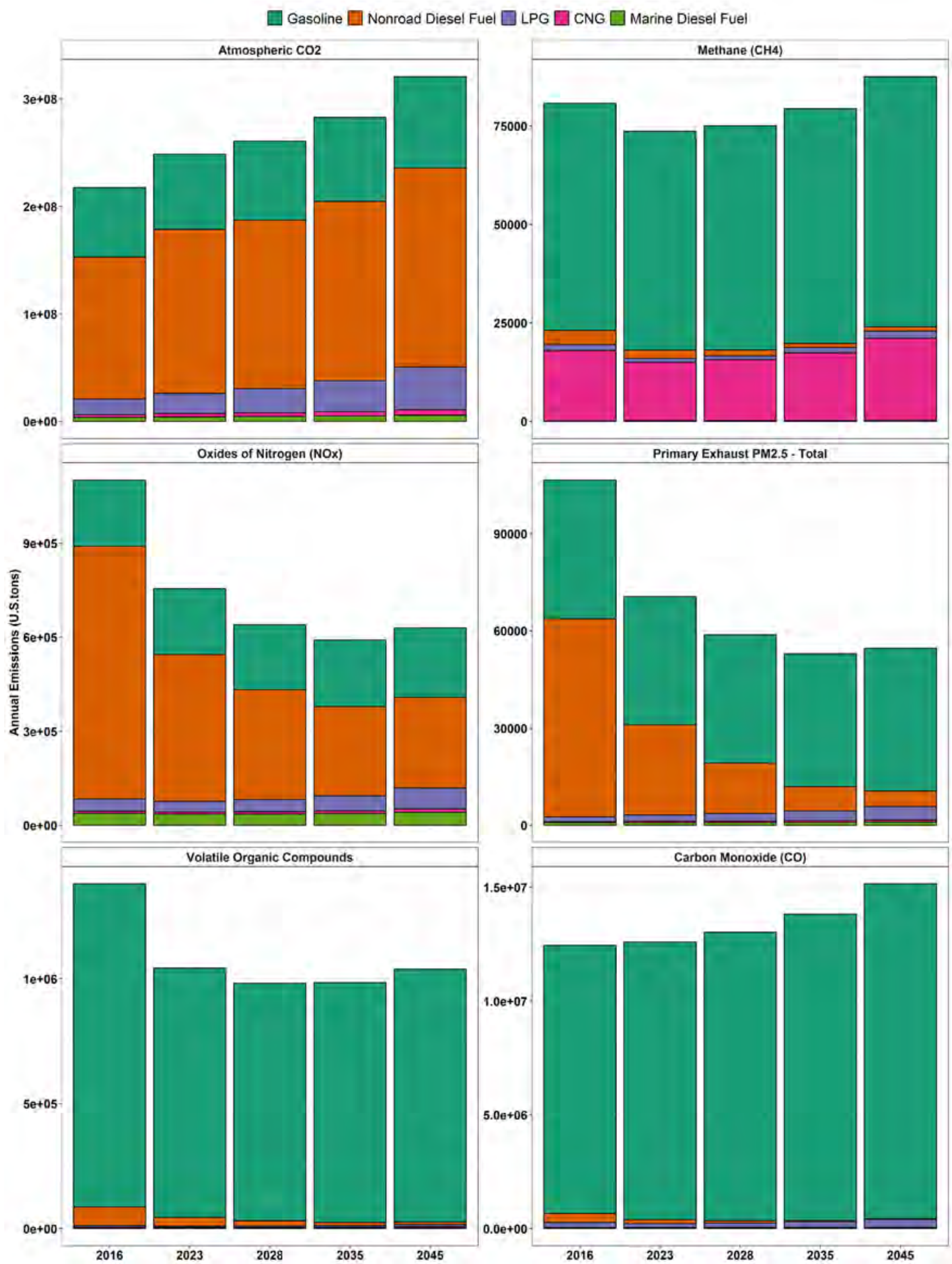

Figure 6-14 MOVES3 Nonroad emissions by calendar year

7. MOVES3 Evaluation

To assure that the MOVES model does the best possible job estimating emissions from mobile sources, the model is subject to review and evaluation in several different ways.

7.1 Peer Review

Since MOVES2014b, we have conducted three rounds of peer review for the updates to MOVES3 data and algorithms, following EPA's peer review policies and procedures.[29]

- In 2017, the updates to the following topics were peer reviewed: 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.
- 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.
- 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.

Reviewer comments and EPA's responses are documented online at https://cfpub.epa.gov/si/index.cfm (search for "Motor Vehicle Emission Simulator"). Peer review documents for previous versions of MOVES are also available at this location.

7.2 MOVES Review Work Group

The MOVES Review Work Group provides MOVES-related recommendations to EPA via the Mobile Source Technical Review Subcommittee (MSTRS) of the Clean Air Act Advisory Committee. 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. Throughout the development of MOVES3, the EPA presented ongoing analyses, model evaluation, and MOVES updates to the MOVES Review Work Group, starting in September 2016 and ending in 2020. In addition, several MOVES Review Work Members presented issues that informed the MOVES Review Work Group recommendations to MSTRS.[30,31,32] Notes and presentations from past workgroup meetings are available at https://www.epa.gov/moves/moves-model-review-work-group.

7.3 Beta Testing

A draft version of MOVES3 was tested by a small group of experienced MOVES users who alerted EPA to potential errors in the code and provided comments on the new features, including the updated interface and new installer.

7.4 Evaluation by Industry-Funded Research Group

The MOVES2014 model that preceded MOVES3 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.[33] The report provided detailed recommendations in 10 areas. EPA used these recommendations to help prioritize efforts for MOVES3 and published a detailed response.[34]

An additional review (CRC project E-116) investigated MOVES2014 evaporative inputs.[35] 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.

7.5 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 identify areas in need of improvement, guiding future work and research. However, it is not appropriate to evaluate MOVES with comparisons 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 past 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 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.[36]

Other studies compare "localized composite" emissions, using composite emission measurements from many vehicles by tunnel[37] or roadside emission monitors[38] 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 only assess the operating conditions represented at the specific location. The heavy-duty exhaust technical report includes comparisons of MOVES heavy-duty emission rates to tunnel and roadside measurements.[14]

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.[39,40]

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.

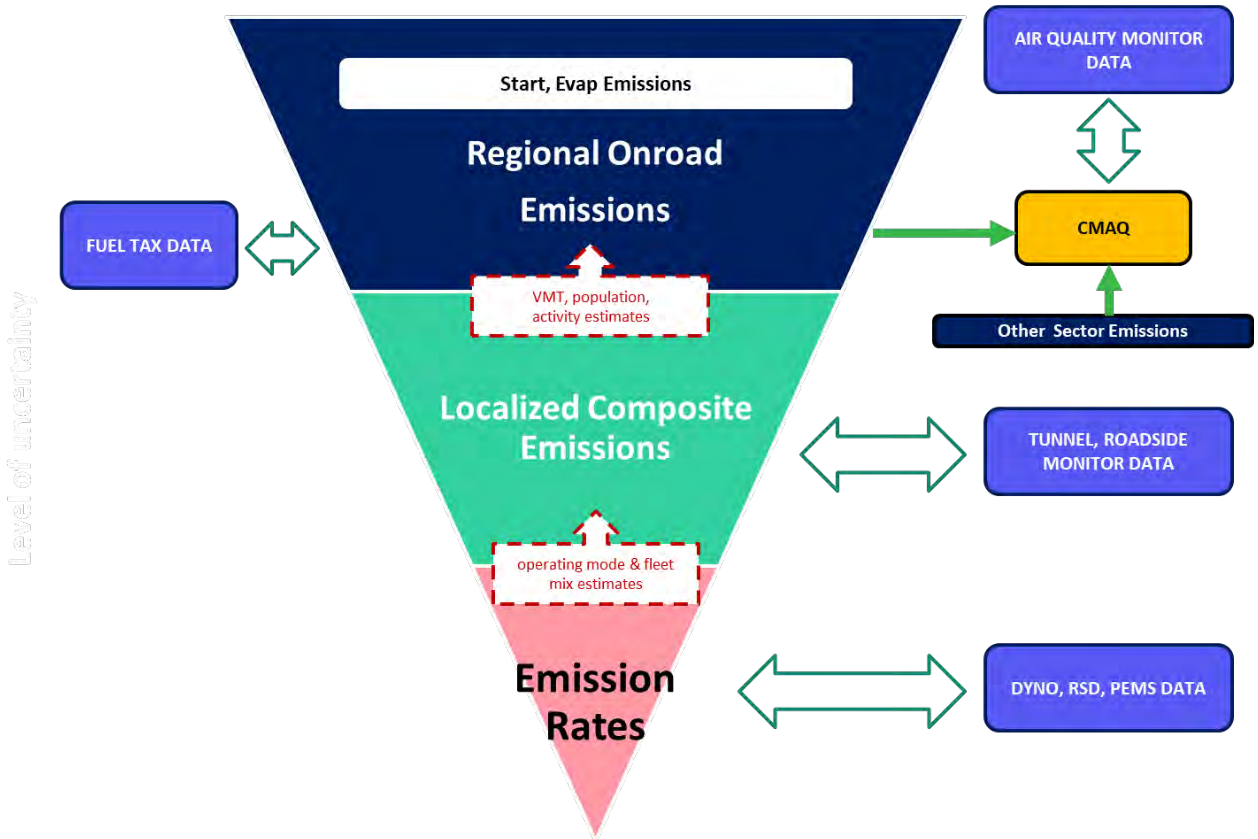

Figure 7-1--MOVES evaluation opportunities at rising levels of generalization and uncertainty

NO_X Evaluation Work

Several studies using emissions generated with previous versions of MOVES 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[41,42] particularly from LD gasoline vehicles.[43] Other studies have questioned some of these conclusions[39,44] and more recent work has demonstrated significant impact on modeled summer NOx caused by improvements in meteorology assumptions related to vertical mixing in CMAQv5.1.[40]

Nonetheless, as part of MOVES3 development efforts, we evaluated the MOVES2014 light-duty emission rates against in-use measurements and, based on the comparisons,[36, 15] we updated the emission rates in MOVES3, generally decreasing light-duty NO_X emissions in MOVES3 (see Figure 6-4). However, detailed analysis shows gasoline NO_X emissions can be higher in MOVES3 than MOVES2014 for some calendar years and scenarios (e.g., calendar year 2023 in Figure 6-4). EPA is currently investigating the net impact of MOVES3 on modeled air quality.

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., deterioration of 2010+ heavy-duty diesel emissions beyond 10 years of age).

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.[45,46]
- 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.[47]
- 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.
- 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 models electric vehicles by allowing users to enter electric vehicle fractions in their fleet. However, MOVES assumes that the energy consumption rates for electric vehicles are the same as

gasoline and diesel vehicles. In addition, MOVES does not account for the manufacturer fleet averaging allowed under fuel economy and Tier 3 regulations, in which manufacturers may offset electric vehicles by producing more high emission gasoline and diesel vehicles, thus potentially increasing the average emissions allowed from gasoline and diesel vehicles.

- 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.
- MOVES3 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.[14] MOVES3 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. While the MOVES3 updates are based on millions of emission test results, coverage varies depending on data availability. MOVES3 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 2018 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.[15] MOVES motorcycle emissions rates were last analyzed in 2010.[48] Light-duty gasoline running emission rates were updated for MOVES3 based on millions of test results from in-use testing data, and inspection and maintenance (I/M) data from the State of Colorado, 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.[15] Evaporative emissions also were not updated for MOVES3, and while we updated the vehicle activity patterns used to estimate exhaust emissions, MOVES evaporative emission calculations rely on older, more limited, trip pattern data.[13]

We have updated MOVES3 with 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. In addition, while we also updated rates for heavy-duty gasoline and heavy-duty CNG vehicles, data are sparse for these vehicles.[14]

MOVES3 brake and tire wear emission rates are based primarily on a literature review from 2006 and 2007.[18] Some MOVES adjustment factors are based on testing of older vehicle technologies.[2,16]

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, we are currently working on acquiring nonroad emissions and activity data to improve the emissions characterization of the nonroad sector.

9. MOVES3 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 MOVES3 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 MOVES3.0.0 in general:

> USEPA (2020) *Motor Vehicle Emission Simulator: MOVES3.0.0.* Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2020. https://www.epa.gov/moves

To cite MOVES3.0.1:

> USEPA (2021) *Motor Vehicle Emission Simulator: MOVES3.0.1.* Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. March 2021. 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 MOVES3 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#guidance
	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
	MOVES3 Introduction and Overview	December 8, 2020 webinar that introduces MOVES3 and summarizes guidance on its use.	https://www.epa.gov/moves/moves-training-sessions#moves3

Using MOVES for Regulatory and Other Purposes:			
	Federal Register Notice of Availability	Announced the official release of MOVES3 for use in SIP development and transportation conformity purposes in states other than California.	https://www.govinfo.gov/content/pkg/FR-2021-01-07/pdf/2021-00023.pdf
	MOVES3 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 MOVES3 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
	Policy Guidance on the Use of MOVES3 and Subsequent Minor Revisions for State Implementation Plan Development, Transportation Conformity, and Other Purposes	How and when to use the MOVES3 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., diesel retrofits/replacements), and using MOVES to estimate GHGs	Until updated, existing guidance is generally applicable to MOVES3 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/MOVES3CheatsheetOnroad.pdf
	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/MOVES3CheatsheetNonroad.pdf
	MOVES3 Webinar for Experienced Modelers	Instruction for experienced MOVES2014 users on what has changed in MOVES3	Will be posted at https://www.epa.gov/moves/moves-training-sessions
	MOVES2014b Hands-On Training for new Users	A detailed hands-on course for state and local agency staff who will use MOVES3 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 Most of the MOVES2014b material is still relevant for MOVES3.	https://www.epa.gov/moves/moves-training-sessions#hands-on-training

	Project-Level Training for Quantitative PM Hot-Spot Analyses	EPA and DOT have developed a multi-day training course in accordance with EPA's "Transportation Conformity Guidance for Quantitative Hot-spot Analyses in $PM_{2.5}$ and PM_{10} Nonattainment and Maintenance Areas". This technical, hands-on course is geared toward state and local agency staff and focuses on using emission models (including EPA's MOVES model) and air quality models (AERMOD) for quantitative PM hot-spot analyses. Most of the MOVES2014b material is still relevant for MOVES3.	https://www.epa.gov/moves/moves-training-sessions#hotspot

Installation and Computer-Related Aspects of Using MOVES			
	Installation Suite	Executable program to install MOVES3 and all required databases and tools. Instructions are embedded in the installer	https://www.epa.gov/moves/latest-version-motor-vehicle-emission-simulator-moves#download
	MOVES3 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
	MOVES3 Database Conversion Tool Help	Explains use of tool to convert MOVES2014 databases for use with MOVES3	https://github.com/USEPA/EPA_MOVES_Model/blob/master/database/ConversionScripts/InputDatabaseConverstionHelp.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
	Input Database Changes in MOVES3	Description of the schema changes to MOVES County Scale and Project Scale input databases	https://github.com/USEPA/EPA_MOVES_Model/blob/master/docs/inputDBchanges.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
	MOVES3 Update Log	Chronological listing of updates to MOVES3	https://www.epa.gov/moves/moves3-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 MOVES3 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 MOVES3 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
AEO	Department of Energy Annual Energy Outlook
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
DOE	Department of Energy
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
HD	Heavy duty
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
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

11. References

[1] USEPA (2020). *Fuel Supply Defaults: Regional Fuels and the Fuel Wizard in MOVES3*. EPA-420-R-20-017. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2020. https://www.epa.gov/moves/moves-technical-reports

[2] USEPA (2020). *Fuel Effects on Exhaust Emissions from Onroad Vehicles in MOVES3*. EPA-420-R-20-016. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2020. https://www.epa.gov/moves/moves-technical-reports

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

[4] USEPA (2020). *Air Toxic Emissions from Onroad Vehicles in MOVES3*. EPA-420-R-20-022. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2020. https://www.epa.gov/moves/moves-technical-reports

[5] USEPA (2020). *Speciation of Total Organic Gas and Particulate Matter Emissions from Onroad Vehicles in MOVES3*. EPA-420-R-20-021. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2020. https://www.epa.gov/moves/moves-technical-reports

[6] USEPA (2020). *Policy Guidance on the Use of MOVES3 for State Implementation Plan Development, Transportation Conformity, General Conformity, and Other Purposes.* EPA-420-B-20-044. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2020. https://www.epa.gov/state-and-local-transportation/policy-and-technical-guidance-state-and-local-transportation

[7] USEPA (2020). *MOVES3 Technical Guidance: Using MOVES to Prepare Emission Inventories for State Implementation Plans and Transportation Conformity.* EPA-420-B-20-052. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2020. https://www.epa.gov/state-and-local-transportation/policy-and-technical-guidance-state-and-local-transportation

[8] USEPA (2015). *Transportation Conformity Guidance for Quantitative Hot-spot Analyses in PM2.5 and PM10 Nonattainment and Maintenance Areas*. EPA-420-B-15-084 Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2015. https://www.epa.gov/state-and-local-transportation/project-level-conformity-and-hot-spot-analyses

[9] USEPA (2016) *Using MOVES for Estimating State and Local Inventories of Onroad Greenhouse Gas Emissions and Energy Consumption.* EPA-420-B-16-059. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. June 2016. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100OW0B.pdf

[10] USEPA (2016). *Final Rulemaking to Establish Greenhouse Gas Emission Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles – Phase 2: Regulatory Impact Analysis*. EPA-420-R-16-900, August 2016. https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-phase-2-greenhouse-gas-emissions-standards-and

[11] USEPA (2020). The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Model Years 2021-2026 Passenger Cars and Light Trucks (85 FR No.84, April 30, 2020). https://www.epa.gov/regulations-emissions-vehicles-and-engines/safer-affordable-fuel-efficient-safe-vehicles-final-rule

[12] USEPA (2020). *Greenhouse Gas and Energy Consumption Rates for Onroad Vehicles in MOVES3*. EPA-420-R-20-015. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2020. https://www.epa.gov/moves/moves-technical-reports

[13] USEPA (2020). *Population and Activity of Onroad Vehicles in MOVES3*. EPA-420-R-20-023. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2020. https://www.epa.gov/moves/moves-technical-reports

[14] USEPA (2020). *Exhaust Emission Rates of Heavy-Duty Onroad Vehicles in MOVES3*. EPA-420-R-20-018. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2020. https://www.epa.gov/moves/moves-technical-reports

[15] USEPA (2020). *Exhaust Emission Rates for Light-Duty Onroad Vehicles in MOVES3*. EPA-420-R-20-019. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2020. https://www.epa.gov/moves/moves-technical-reports

[16] USEPA (2020). *Emission Adjustments for Temperature, Humidity, Air Conditioning, an Inspection and Maintenance for Onroad Vehicles in MOVES.* EPA-420-R-20-014. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2020. https://www.epa.gov/moves/moves-technical-reports

[17] Jääskeläinen, H. *Crankcase Ventilation. DieselNet Technology Guide.* www.DieselNet.com. Copyright © Ecopoint Inc. Revision 2012.12.

[18] USEPA (2020). *Brake and Tire Wear Emissions from Onroad Vehicles in MOVES3*. EPA-420-R-20-014. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2020. https://www.epa.gov/moves/moves-technical-reports

[19] USEPA (2020). *Evaporative Emissions from Onroad Vehicles in MOVES3*. EPA-420-R-20-012. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2020. https://www.epa.gov/moves/moves-technical-reports

[20] USEPA (2018). *Speciation Profiles and Toxic Emission Factors for Nonroad Engines in MOVES2014b*. EPA-420-R-18-011. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. July 2018. https://www.epa.gov/moves/nonroad-technical-reports

[21] USEPA (2005). *Exhaust Emission Effects of Fuel Sulfur and Oxygen on Gasoline Nonroad Engines.* NR-003c EPA420-R-05-016, Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI December 2005. https://www.epa.gov/moves/nonroad-technical-reports

[22] USEPA (2005). *Temperature Corrections for Nonroad Exhaust Emissions*. NR-001c EPA-420-R-05-014. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. December, 2005. https://www.epa.gov/moves/nonroad-technical-reports

[23] USEPA (2010). *Exhaust Emission Factors for Nonroad Engine Modeling -- Spark-Ignition*. NR-010f. EPA-420-R-10-019. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. July 2010. https://www.epa.gov/moves/nonroad-technical-reports

[24] USEPA (2018). *Exhaust and Crankcase Emission Factors for Nonroad Compression-Ignition Engines in MOVES2014b*. EPA-420-R-18-009. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. July 2018. https://www.epa.gov/moves/moves-technical-reports

[25] USEPA (2004). *Refueling Emissions for Nonroad Engine Modeling*. NR-013b EPA-420-P-04-013. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. April, 2004. https://www.epa.gov/moves/nonroad-technical-reports

[26] USEPA (2010). *Nonroad Evaporative Emission Rates*. NR-012d EPA-420-R-10-021. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. July, 2010. https://www.epa.gov/moves/nonroad-technical-reports

[27] USEPA (2014). *Control of Air Pollution from Motor Vehicles: Tier 3 Motor Vehicle Emission and Fuel Standards Final Rule Regulatory Impact Analysis.* EPA-420-R-14-005. March 2014. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100ISWM.PDF?Dockey=P100ISWM.PDF

[28] USEPA (2000). *Regulatory Impact Analysis: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements*. EPA420-R-00-026. December 2000. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100K576.PDF?Dockey=P100K576.PDF

[29] USEPA (2015). *Peer Review Handbook. 4th Edition.* EPA/100/B-15/001. Science and Technology Council, US Environmental Protection Agency. Washington, DC. October 2015. https://www.epa.gov/sites/production/files/2020-08/documents/epa_peer_review_handbook_4th_edition.pdf

[30]Kliesch, J. (2016). *MOVES FACA Review Work Group Update.* Mobile Source Technical Review Subcommittee, October 2016. https://www.epa.gov/sites/production/files/2016-10/documents/kliesch_1016.pdf

[31] Barth, M. (2017) *MOVES FACA Review Work Group Update.* Mobile Source Technical Review Subcommittee, May 2017. https://www.epa.gov/sites/production/files/2017-06/documents/053120217-barth.pdf

[32] Barth, M. (2018) *MOVES FACA Review Work Group Update.* Mobile Source Technical Review Subcommittee, May 2018. https://www.epa.gov/sites/production/files/2018-05/documents/052218-moves-wg-barth.pdf

[33] Sierra Research (2016). *Review of EPA's MOVES2014 Model.* CRC Project No. E-101. August 2016. http://crcsite.wpengine.com/wp-content/uploads/2019/05/FINAL-E101-Report-SR-20160810-w-CRC-Cover-and-Appendices.pdf

[34] USEPA (2016). *U.S. EPA Response to CRC Project No. E-101, Review of EPA's MOVES2014 Model*. 420-R-16-012. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. October 2016. https://www.epa.gov/moves/moves-technical-reports

[35] Sierra Research (2017). *Assessment of MOVES Model Evaporative Emission Inputs.* CRC Project No. E-116. June 2017. http://crcsite.wpengine.com/wp-content/uploads/2019/05/CRC_E-116_MOVES_Final-Report_2017-06-14.pdf

[36] Toro, C., J. Warila, D. Sonntag, D. Choi and M. Beardsley (2019). *Updates to "high-power" emission rates and start deterioration for light-duty vehicles* MOVES Review Workgroup, Ann Arbor, MI. April 10, 2019 https://www.epa.gov/sites/production/files/2019-06/documents/03-updates-ld-emission-rates-start-deterioration-2019-04-10.pdf

[37] Wang, X., et al. (2019). *Real-World Vehicle Emissions Characterization for the Shing Mun Tunnel in Hong Kong and Fort McHenry Tunnel in the United States*. Research Report 199. Health Effects Institute. Boston, MA. March 2019. https://www.healtheffects.org/publication/real-world-vehicle-emissions-characterization-shing-mun-tunnel-hong-kong-and-fort

[38] Bishop, G. A. and D. H. Stedman (2015). Reactive Nitrogen Species Emission Trends in Three Light-/Medium-Duty United States Fleets. *Environ Sci Technol,* 49 (18), 11234-11240. DOI: 10.1021/acs.est.5b02392.

[39] Simon, H., et al. (2018). Characterizing CO and NOy Sources and Relative Ambient Ratios in the Baltimore Area Using Ambient Measurements and Source Attribution Modeling. *Journal of Geophysical Research: Atmospheres,* 123 (6), 3304-3320. DOI: doi:10.1002/2017JD027688.

[40] Toro et al. (2021)"Evaluation of 15 years of modeled NOX across the contiguous United States", Elementa: Science of the Anthropocene. In Press

[41] Anderson, D. C., et al. (2014). Measured and modeled CO and NOy in DISCOVER-AQ: An evaluation of emissions and chemistry over the eastern US. *Atmospheric Environment,* 96 (0), 78-87. DOI: http://dx.doi.org/10.1016/j.atmosenv.2014.07.004

[42] Travis, K. R., et al. (2016). NOx emissions, isoprene oxidation pathways, vertical mixing, and implications for surface ozone in the Southeast United States. *Atmos. Chem. Phys. Discuss.,* 2016, 1-32. DOI: 10.5194/acp-2016-110.

[43] McDonald, B. C., et al. (2018). Modeling Ozone in the Eastern U.S. using a Fuel-Based Mobile Source Emissions Inventory. *Environ Sci Technol,* 52 (13), 7360-7370. DOI: 10.1021/acs.est.8b00778.

[44] Kemball-Cook, S., G. Yarwood, J. Johnson, B. Dornblaser and M. Estes (2015). Evaluating NOx emission inventories for regulatory air quality modeling using satellite and air quality model data. *Atmospheric Environment,* 117, 1-8. DOI: http://dx.doi.org/10.1016/j.atmosenv.2015.07.002

[45] A Framework for the development of an International version of the MOVES model https://www.epa.gov/sites/production/files/2019-08/documents/moves-international-2012-02.pdf

[46] USAID/INECC (2016). *Adaptation of the Vehicle Emission Model MOVES to Mexico: Final Technical Report.* MEXICO LOW EMISSIONS DEVELOPMENT PROGRAM (MLED), CONTRACT: AID-523-C-11-00001. https://www.epa.gov/moves/presentation-using-moves-model-other-countries

[47] CARB (2021) Mobile Source Emissions Inventory – Modeling Tools https://ww2.arb.ca.gov/our-work/programs/mobile-source-emissions-inventory/msei-modeling-tools

[48] USEPA (2012). *Use of Data from "Development of Emission Rates for the MOVES Model," Sierra Research, March 3, 2010.* EPA-420-R-12-022. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. August 2012. https://www.epa.gov/moves/moves-technical-reports