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MOVES-Matrix 4.0 for High-Performance On-road Energy Use and Emission Rate Modeling Applications

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16. Abstract

This study introduces MOVES-Matrix 4.0, an innovative high-performance implementation of MOVES 4.0.1 that generates exactly same energy and emission rate results as the Environmental Protection Agency's latest version of MOVES 4.0.1, but allows users to deploy MOVES model in complex and dynamic analyses. The team utilized the same conceptual design used in MOVES-Matrix 2014 and MOVES-Matrix 3.0, and updated the configurations on PACE supercomputing clusters to account for the programming changes with respect to MOVES databases (e.g., migration to MariaDB) and MOVES' algorithm updates since MOVES2014b (e.g., extended VSP/STP parameters). The MOVES-Matrix 4.0 system develops sub-matrices of energy and emission rates by executing 181,818 MOVES runs to generate more than 5.8 trillion energy and emission rates in the populated matrix for a single modeling region (represented by a unique combination of fuel specification regime and inspection and maintenance program). Performance tests demonstrate that MOVES-Matrix 4.0 produces the exact same results as MOVES4 (insignificant internal rounding errors that are less than 0.0005%). In modeling applications, generating emission rates from MOVES-Matrix is 200 times faster than running a MOVES instance. MOVES-Matrix 4.0 is ready to be used for large-scale, dynamic transportation network analyses and emissions modeling, given its open-source nature, and its compatibility with various scripting languages.

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Disclaimer

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MOVES-Matrix 4.0 for High-Performance On-road Energy Use and Emissions Rate Modeling Applications

Executive Summary

The MOVES-Matrix 4.0 report presents a comprehensive solution to the computational challenges inherent in using the U.S. Environmental Protection Agency's (EPA) regulatory energy use and emissions model, MOVES 4.0.1, for large-scale and high-resolution transportation energy and emissions analysis. While MOVES 4.0.1 provides detailed, modal-based emission rate estimates that are ideal for project-level applications, its complexity and runtime requirements make it prohibitive for modeling expansive and dynamic roadway networks (such as that of the Atlanta, Georgia region). The MOVES-Matrix 4.0 framework addresses this gap by pre-generating trillions of emission rates through exhaustive MOVES executions across all combinations of input parameters, storing the results in structured databases (that can be queried directly and quickly), thereby eliminating the need for repetitive model runs during modeling applications.

MOVES-Matrix 4.0 builds upon prior versions (MOVES-Matrix 2014 and MOVES-Matrix 3.0), expanding its applicability to the latest MOVES 4.0.1 platform, while updating backend configurations to accommodate changes such as the migration to MariaDB (an open-source relational database) and updates to vehicle physics parameters used within the model. A key innovation lies in its design for supercomputing clusters, where the model was configured to run without root access in a self-contained environment. By leveraging Georgia Tech's Partnership for an Advanced Computing Environment (PACE) high-performance computing infrastructure, the research team executed over 180,000 MOVES runs per modeling region (each defined by unique fuel supply and inspection and maintenance (I/M) characteristics), covering combinations of calendar years, temperatures, relative humidity levels, and fuel scenarios. The deliverable is a highly detailed, multi-dimensional emissions database that can support any project-level or network-wide energy and emissions modeling task.

Each MOVES-Matrix sub-database contains energy and emissions rates indexed by critical vehicle and environmental parameters. The energy use and emission rates are stored in three forms: by average speed and facility type, by MOVES operating mode bin (OpMode), and by operating mode with fuel and engine technology distinctions. These variants support flexible integration with various modeling platforms, including regional travel demand models, traffic microsimulation outputs, or second-by-second monitored vehicle data. Because MOVES-Matrix stores the pre-computed, fully adjusted outputs from MOVES (including temperature, fuel, I/M, and on-road operation corrections), MOVES-Matrix returns identical results to traditional MOVES runs, but executing model implementation hundreds of times faster.

This research report further details the operational and technical architecture behind MOVES-Matrix 4.0's execution. This includes the automation of MOVES input file generation, batch job submission protocols, and database management processes. Georgia Tech's PACE environment (consisting of over 34,000 computing cores) enabled the team to compress what would normally require multiple decades of computations into a couple of weeks. The final system allows energy and emission rates to be accessed through Python scripts (or other user-specified interfaces) and is fully compatible with downstream tools used in emissions inventories, dispersion modeling, and exposure modeling, ensuring that applications will meet regulatory compliance.

Test runs verified MOVES-Matrix's computational and analytical equivalence to standard MOVES 4.0.1 runs. Using various fleet and environmental conditions, the team demonstrated that emission rates derived from the matrix were consistent within 0.0005% of those generated directly by MOVES (i.e., the only differences are rounding errors). The performance tests revealed a greater than 200 times speed increase across modeling scenarios, and these speed advantages unlock the feasibility for performing network-wide regional analyses and temporally resolved emissions analysis (e.g., for every hour of an entire year) that are intractable using the traditional MOVES user interface with conventional batch runs.

The benefits of MOVES-Matrix 4.0 are especially compelling in the context of modern, data-intensive transportation research. Its modular design allows users to rapidly assess the effects of shifting vehicle fleets, changing meteorological conditions, and dynamic traffic patterns (without ever re-running MOVES). MOVES-Matrix also supports advanced applications, such as regional dispersion modeling, population exposure assessment, and microenvironmental analyses. While the current release focuses on on-road running energy use and emission rates, extensions for other emissions processes (e.g., starts, evaporative emissions, and truck hoteling) are currently under development, building on earlier versions of the system.

Overall, MOVES-Matrix 4.0 represents a major advancement in high-resolution emissions modeling. MOVES-Matrix maintains full regulatory compliance with EPA standards while enabling large-scale and computationally intensive analyses to be conducted efficiently. Its open-source nature, scriptable interface, and compatibility with national modeling needs make it a fast and efficient modeling tool for agencies, researchers, and policymakers engaged in transportation and environmental planning.

Introduction

The MOtor Vehicle Emission Simulator (MOVES) model, developed by the U.S. Environmental Protection Agency (EPA) (*1*), represents a significant advancement in emission rate estimation compared to predecessor MOBILE series of models (*2*). MOVES excels in its ability to process high-resolution input data, particularly at the project level, and can provide energy use and emission rates for modal activity, representing energy use as a function of instantaneous (1 hertz (Hz)) speed and acceleration, and subsequent emission rates as a function of energy use. This capability makes MOVES highly compatible with various sources of big data for vehicle activity, including streaming machine vision data, smartphone location tracking, and traffic simulation modeling. The integration of MOVES with these high-resolution data sources enhances research efforts aimed at assessing the environmental impacts of transportation design and operation strategies. Furthermore, this compatibility significantly benefits microscale hot-spot analysis and near-road dispersion modeling for use in environmental impact assessment, by leveraging more representative vehicle activity data in both temporal and spatial dimensions. However, despite the significant improvements and model advantages, the MOVES interface is complex, and the structure of its input variables and algorithms can make analytical applications time-consuming and cumbersome.

The MOVES interface presents significant challenges for use in assessing complex transportation networks and conducting analyses of large-scale, dynamic systems. For example, the Atlanta Regional Commission (ARC) Travel Demand Model network encompasses 149,969 roadway segment links *(3*), and performing emissions modeling for such a vast, dynamic network using individual MOVES runs for each link becomes virtually impossible in terms of computation loads, especially when fleet composition and on-road operating conditions vary across hours of the day. To illustrate the scale of the challenge, modeling a subset of 1,000 roadway links would require nearly 32 million individual MOVES runs, if analysts wanted to account for hourly variations in fleet composition, operating conditions, temperatures, and relative humidity across 24 hours, 21 temperature scenarios (10 to 110° F in 5° F bins), 21 humidity scenarios (0% to 100% in 5% bins), and 3 fuel supply scenarios (summer, winter, and transition). On a typical personal computer (PC), a single MOVES run takes approximately 10 to 30 seconds to model energy use and emissions for a single link (depending on the pollutants and processes being modeled); hence, it would take approximately ten years to finish the millions of runs for these 1,000 roadway links. While shortcuts can reduce the number of required runs (e.g., removing redundant runs that produce identical outputs for certain temperature or humidity ranges), modeling every possible operating condition remains impractical. Consequently, a high-performance modeling approach is essential for assessing large-scale dynamic networks. Regulations mandate the use of the latest approved regulatory model (i.e., MOVES 4.0.1) in all transportation and air quality planning and assessment work (*1, 4*). This regulatory requirement underscores the need for a solution that maintains compliance while significantly enhancing computational efficiency.

Several efforts have been made to optimize run speed for regulatory emissions models. For example, Khan, Wei, and Frey (2018) developed MOVES-Lite, a simplified version of MOVES 2014a that uses operating mode (OpMode) bin proportions as cycle adjustment factors (*5*). MOVES-Lite achieves predictions within plus or minus 2% for energy use and most pollutants (up to plus or minus 8% for carbon monoxide) compared to MOVES, while operating approximately 600 times faster. In a different approach, the Coordination Research Council implemented MOVES 2014a on Amazon Web Services (AWS) to leverage cloud computing capabilities (*6*). However, subsequent versions of MOVES (MOVES3 and MOVES4) were not configured to run on cloud platforms.

To enhance modeling speed while ensuring compliance with regulatory requirements, the Georgia Tech research team developed MOVES-Matrix 2014 (*7*) and MOVES-Matrix 3.0 (*8*). The MOVES model was executed hundreds of thousands of times to iterate across all combinations of MOVES input variables (i.e., MOVES run specifications and user-supplied input data), and the energy use and emission rate results were stored as look-up matrices (no "optimization" or adjustment to the output). This concept of iterative model processing and matrix generation builds upon previous applications to the MOBILE model (*9–11*).

In this research, the team applied the same conceptual design as MOVES-Matrix 2014 and MOVES-Matrix 3.0 to the latest MOVES version (MOVES 4.0.1), implementing a series of significant script updates required to accommodate MOVES model changes, such as migration to MariaDB (an open-source relational database) and internal model updates to the source type physics procedures. The resulting MOVES-Matrix 4.0 energy use and emission rate matrices can be queried for any analytical purpose typically conducted by MOVES, eliminating the need to launch MOVES or transfer its output files into analyses. Because the matrix is generated through iterative MOVES 4.0.1 runs, MOVES-Matrix 4.0 produces the same exact energy use and emission results as MOVES 4.0.1 and therefore application results, as will also be demonstrated in this report.

MOVES-Matrix Generation

The MOVES interface is complex and preparing the input files to properly characterize specific emission scenarios requires extensive labor. Running the MOVES application is also time-consuming, as energy use and emission calculations are performed independently for each MOVES model run, which starts with base emission rates and applies various correction factors (e.g., temperature, humidity, fuel properties), without optimization or reuse of previously calculated results. This lack of computational efficiency, combined with MOVES' general structure, makes it difficult to use for large-scale transportation networks (with spatial and temporal variability in on-road fleet composition and operating conditions that affect the magnitude of the correction factors). The research team configured MOVES 4.0.1 for execution on supercomputing clusters to pre-run MOVES across all possible combinations of input variables. The resulting outputs are stored as lookup matrices that can be queried to provide MOVES energy use and emission rates for any calendar year, fleet composition, on-road operating conditions, environmental conditions, etc. The MOVES-Matrix application generates link results identical to MOVES without the need to run MOVES directly.

MOVES Background

MOVES defines energy use and emissions as a function of speed and vehicle-specific power (VSP) for light-duty vehicles, or speed and scaled-tractive power (STP) for heavy-duty vehicles. Second-by-second VSP and STP are calculated using factors of vehicle speed, acceleration, road grade, vehicle mass, and various resistance factors (road load coefficients), as shown in Equation 1.

$$\mathrm{VSP(STP)_t}\ (\mathrm{kW/metric\ ton}) = \left(\frac{\mathrm{A}}{\mathrm{M}}\right)\mathrm{v_t} + \left(\frac{\mathrm{B}}{\mathrm{M}}\right)\mathrm{v_t}^2 + \left(\frac{\mathrm{C}}{\mathrm{M}}\right)\mathrm{v_t}^3 + \left(\frac{\mathrm{m}}{\mathrm{M}}\right)(\mathrm{a_t} + \mathrm{g} * \sin\theta_\mathrm{t})\mathrm{v_t} \quad (1)$$

where $\mathrm{v_t}$ is the velocity at time t (meters per second (m/sec)), $\mathrm{a_t}$ is acceleration at time t (m/sec^2), θ_t is road grade (radians or degrees), g is acceleration due to gravity (9.81 m/sec^2), m is vehicle mass (metric ton), A is rolling resistance (kW-sec/m), B is rotating resistance and quadratic portion of the aerodynamic drag (kW-sec^2/m^2), C is aerodynamic drag (kW-sec^3/m^3), M (metric ton) in VSP is the fixed mass factor for the source type (metric ton) which equals to vehicle mass (i.e., $\mathrm{M} = \mathrm{m}$ for VSP calculations), and M in STP is the scaling factor to scale STP ranges to within the same range as VSP (metric ton).

The MOVES model employs a "binning" approach, categorizing on-road activity into operating mode (OpMode) bins, based on speed and VSP/STP combinations. These OpMode bins are established for braking, idle, and cruise-acceleration operations, with the latter further divided by speed and VSP/STP ranges. Higher VSP and STP values within specific speed ranges generally correspond to higher fuel consumption and emission rates, as shown in Figure 1.

MOVES4 applies a series of post-processing adjustments to the base emission rates to reflect real-world variability in environmental and operational conditions, as illustrated in Figure 2. Base emission rates by regulatory class are weighted by on-road operations (represented through MOVES operating mode distributions by facility type and vehicle class) into source use hours by vehicle source type and model year. These adjustments account for the impacts of air conditioning usage, ambient temperature, and relative humidity on vehicle emissions and energy consumption, as well as the effects of fuel properties and Inspection and Maintenance (I/M) programs. All adjustments are pollutant-specific and implemented as scaling functions or multiplicative factors applied to emission rates prior to fleet-level aggregation. This modeling approach enables MOVES to generate consistent and representative emission estimates across multiple spatial and temporal scales, including macro-, meso-, and microscale applications.

MOVES4 includes significant updates to MOVES3 source type physics parameters for VSP/STP configurations (*12*, *13*). In MOVES 2014, the VSP and STP parameters (A, B, C, m, and M) varied by source type and model year, with only 22 parameter sets (*14*). MOVES3 and MOVES4 dramatically expanded this to 206 parameter sets, introducing an additional layer of categorization by regulatory class (embedded in the "SourceUseTypePhysics" table of the MOVES database). The SourceUse hours are generated by disaggregating Vehicle Miles Traveled (VMT), not only by source type and model year, but also by regulatory class (as VSP/STP parameters vary across regulatory classes), based on a default distribution table embedded in the "SampleVehiclePopulation" table of the MOVES database. This distribution is applied uniformly for all model runs, regardless of specific county characteristics, meteorological conditions, time of day, day of the week, etc. The present MOVES interface does not allow customized distributions of regulatory classes (*15*).

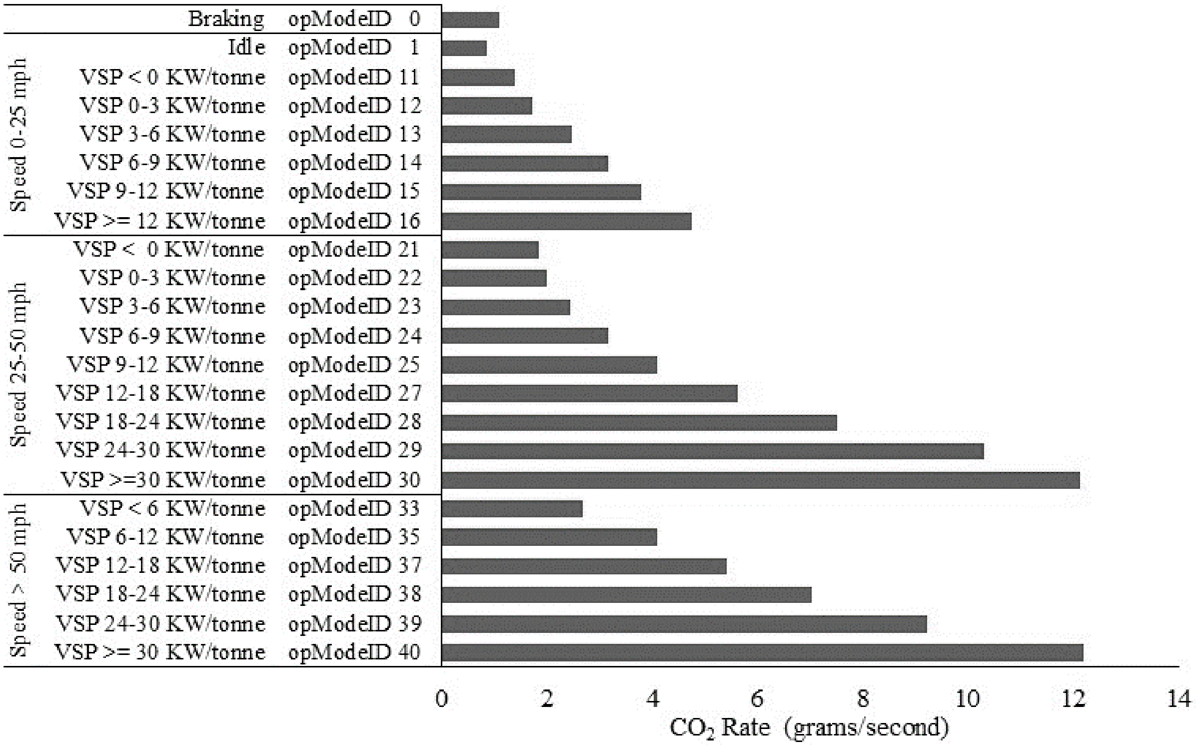

Figure 1. MOVES OpMode and Sample Carbon Dioxide (CO_2) Emission Rates by OpMode (*7*)

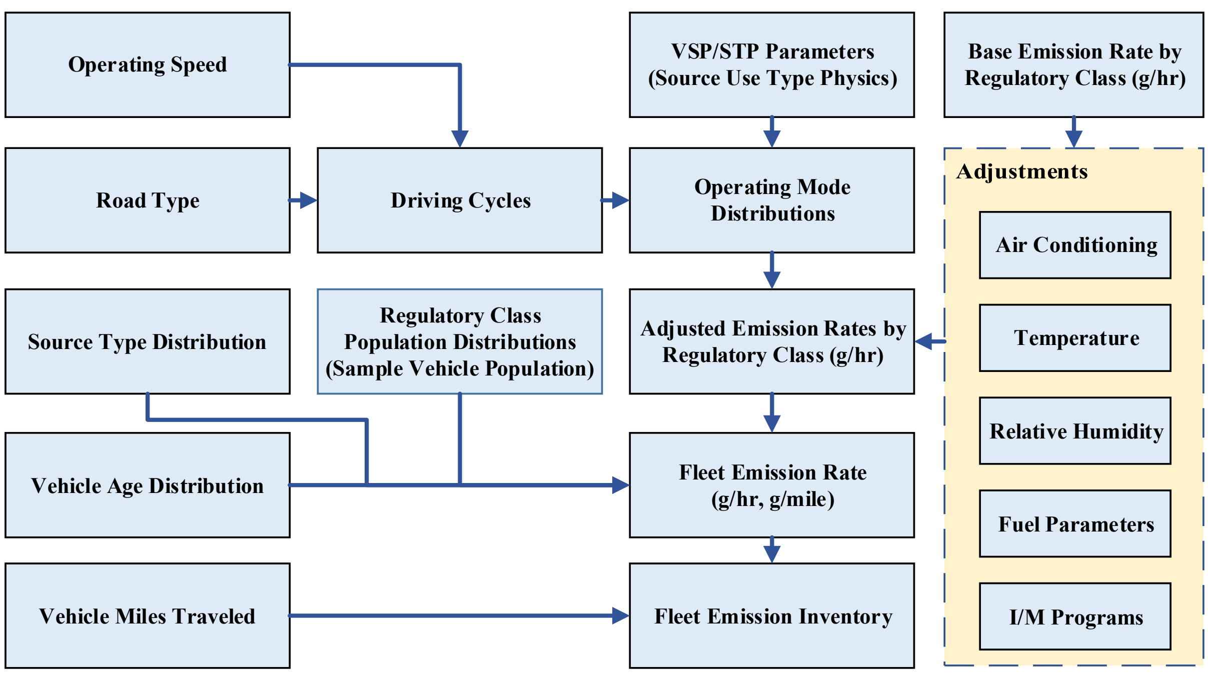

Figure 2. Flow Chart of MOVES On-road Running-Exhaust Modeling

MOVES-Matrix 4.0 Conceptual Design

MOVES-Matrix 4.0 is an extensive lookup table, comprising MOVES outputs developed by iteratively running MOVES 4.0.1 across all combinations of variables that affect emission rates. Each MOVES run generates a pollutant emission rate for a specific combination of vehicle source type, model year, vehicle fuel type, on-road operating condition (average speed and road type with default MOVES driving cycles, or a single on-road VSP/STP operating mode bin), calendar year, temperature, relative humidity, and other applicable regional regulatory parameters (fuel properties, I/M program characteristics). The resulting MOVES-Matrix can be queried to obtain the exact same emission rates that would be produced by any MOVES model run, without the need to launch MOVES or transfer its outputs into subsequent analyses.

To develop the MOVES-Matrix emission rate database for each region of interest (defined by fuel specifications and I/M programs), the research team prepares a total of 181,818 MOVES runs (26 calendar years × three months × 111 temperature bins × 21 humidity bins), with each run makes up a sub-matrix of a unique combination of calendar year, month, temperature, and relative humidity. These runs cover calendar years 2015 to 2035, 2040, 2045, 2050, 2055, 2060; summer, winter, and transition fuel months; temperatures from 0 to 110 degrees in one-degree intervals; and relative humidity from 0% to 100% in 5% intervals.

To support varied levels of detail for on-road fleet composition and operating conditions that may be available to modelers, the research team prepared three MOVES-Matrix variants as shown in Table 1. A complete matrix database per region includes more than 5.8 trillion energy use and emission rate records.

1) Matrix by Operating Mode (OpMode-Matrix): each sub-matrix provides more than 1.8 million energy use and emission rates by vehicle source type, model year, pollutant type, and operating mode bin.

2) Matrix by Operating Mode and by Fuel (OpMode&Fuel-Matrix): each sub-matrix provides more than 5.0 million of energy use and emission rates by vehicle source type, model year, fuel type, engine tech, pollutant type, and operating mode bin.

3) Matrix by Average Speed and by Facility Type (Speed-Matrix): each sub-matrix provides more than 25.2 million of energy use and emission rates by vehicle source type, model year, pollutant type, facility type, and average speed.

Table 1. MOVES-Matrix Variants

MOVES-Matrix Variant	Key Fields to Identify Sub-Matrix	Key Fields to Identify Emission Rate in Sub-Matrices
Average Speed and Facility Type Matrix (Speed-Matrix)	Calendar year, month, temperature, humidity	Vehicle source type, model year, pollutant type, facility type, speed
Operating Mode Matrix (OpMode-Matrix)	Calendar year, month, temperature, humidity	Vehicle source type, model year, pollutant type, operating mode bin
Matrix of Operating Mode and Fuel (OpMode&Fuel-Matrix)	Calendar year, month, temperature, humidity	Vehicle source type, model year, fuel type, engine tech, pollutant type, operating mode bin

For all variants of MOVES-Matrix generation, the energy use and emission rate processing include three main steps:

1) Developing the set of input files and run specification (RunSpecs) files to support MOVES runs across all relevant input variables;
2) Running the MOVES input files in an advanced computing cluster to obtain multi-dimensional emission rates outputs;
3) Designing algorithms and a MOVES-Matrix user interface that can be used to pull applicable emission rates from the matrix for use in regional emissions inventory modeling, traffic simulation modeling, corridor-monitored second-by-second activity analysis, and microscale dispersion modeling.

Table 2 outlines the model inputs used to create MOVES-Matrix by operating mode.

Table 2. Model Input Files for One OpMode-Matrix Run (MOVES-Matrix by Operating Mode)

Input	Description
Link	23 links with each assigned operating mode bin (running-exhaust) Volume per link: 13 (source types) ×31 (model years) = 403
Age distribution	Uniform age distribution (1/31 for each age group from age 0 to 30 years) for all source types
Source type	Uniform source type distribution (1/13 for each source type) for all links
I/M strategy	Default from MOVES, determined by calendar year (CY) and region
Fuel supply	Default from MOVES, determined by calendar year, month and region: • November to March: winter fuel • April and October: transition fuel • May to September: summer fuel
Fuel formulation	Default from MOVES, determined by fuel supply
Fuel usage fraction	Default from MOVES
Alternative fuel technology (AVFT)	Default from MOVES
Meteorology	Temperature: 0-110º F with 1º F-bin interval, 111 bins in total Humidity: 0%-100% with 5%-bin interval, 21 bins in total
Operating mode distribution	Single 100% fraction of a specific operating mode bin for each link.
Year	Each year in 2015-2035, 5-year intervals in 2040-2060; input in xml and mrs file

Executing MOVES 4.0.1 via Cluster Computing

The team adapted MOVES 4.0 for cross-platform use on the Partnership for an Advanced Computing Environment (PACE) at Georgia Tech (*16*) (Red Hat Enterprise Linux 9.0, (RHEL9)) without requiring root access. This was achieved by manually configuring MOVES 4.0 and its dependencies (e.g., MariaDB, Java, and Go) in a user-space, self-contained setup. Starting from RHEL9, the libraries of libtinfo.so.5.9, libncurses.so.5 and libncurses.so.5.9 also need to be installed to support MariaDB. The Go components of external generator and external calculator were compiled under RHEL7 environment before job submission to the clusters. As the MOVES main process requires the use of specific ports (*15*), each job is submitted to a separate computing node on PACE.

When a MOVES 4 job is launched on a cluster node, the MOVES-Matrix scripts:

1. Install prerequisite database components through binary installation of MariaDB (without root access)
2. Import the MOVES database (i.e., movesdb20240104 for MOVES 4.0.1) (*15*)
3. Install Java® (if Java 17 is not installed on clusters)
4. Install MOVES 4.0.1
5. Modify configuration files accordingly, specifying working directories for MOVES and MariaDB
6. Launch MOVES command line Java® processes to create input and output database files

The file sizes and generation time of MOVES-Matrix varies across resolution and variants, depending on the application and research scope. The research team has priority access to the Phoenix cluster on PACE, which consists of 34,816 cores and 1,395 nodes. Generating emission rates for all variants of MOVES-Matrix with one-degree temperature resolution takes 31 days. In contrast, the preparation time for MOVES-Matrix by operating mode (OpMode-Matrix) with a five-degree temperature interval can be as quick as 4.5 days.

MOVES-Matrix Applications

Figure 3 provides an overview of the MOVES-Matrix application process. Users begin by identifying the sub-matrix that is needed (by calendar year, fuel month, and meteorology data). They then access each cell containing an emission rate for a specific vehicle type and model year from MOVES-Matrix and weight these rates by on-road activity to reassemble the fleet emission rate. This weighting process is identical to that used in MOVES to generate a fleet composite emission rate for a roadway link, so that MOVES-Matrix yields the exact same emission rates as a direct MOVES run, but in a fraction of the time. Because each MOVES run has already performed the complex emission rate calculations and adjustments for temperature, humidity, fuel composition, I/M program, etc., MOVES-Matrix simply contains these resulting emission rates. For users, MOVES-Matrix provides the same MOVES modeling results at a significantly lower time and labor cost, thus enabling large-scale and real-time emissions modeling.

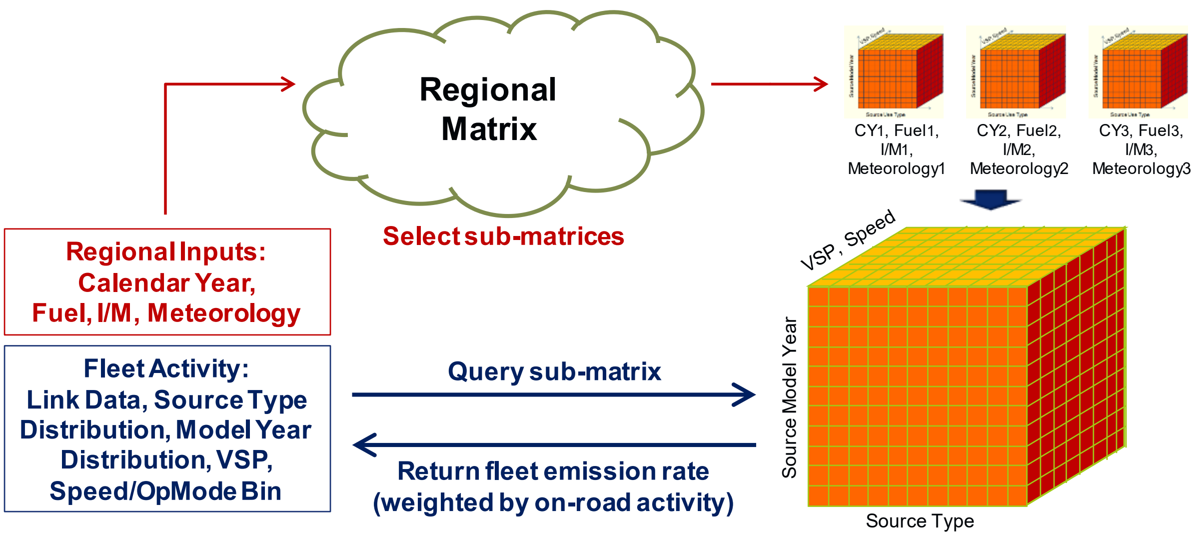

Figure 3. Overview of MOVES-Matrix Application

Query and Assembly of MOVES-Matrix Rates

The MOVES-Matrix emission database for each region is organized into 181,818 sub-matrices. Each sub-matrix stores energy use and emission rates for all source types (including fuel types and engine techs for OpMode&Fuel-Matrix), model years, and on-road operations (average speed or operating mode bins) for a specific combination of calendar year, fuel month, temperature bin, relative humidity bin, fuel supply, and I/M strategy. This structure allows users to extract a small portion of rates based on customized inputs to reduce data retrieval time (compared to searching the full MOVES-Matrix), which is particularly beneficial for emission control strategy analysis, when users often assume constant temperature, humidity, and fuel composition.

Once the appropriate sub-matrix is accessed, the energy use and emission rate processing algorithms mirror those used by MOVES 4.0.1 in project-level modeling. These algorithms weight the energy use/emission rates from individual source types to generate a composite energy use/emission rate. MOVES-Matrix 4 algorithms break down vehicle activity by source type and model year into regulatory classes, then aggregate back to operating mode distributions, based on the distributions defined in the sample vehicle population table. For user-specified driving cycles, second-by-second VSP/STP is calculated for each source type, model year, and regulatory class (based on the latest source type physics parameters). These values are then converted to operating mode bins and aggregated to operating mode distributions for each vehicle source type in each link. The emission rate weighting function is described in Equation 2 and Equation 3.

$$\mathrm{Fleet\ ER} = \sum_{\mathrm{ST}} \sum_{\mathrm{MY}} \sum_{\mathrm{OM\ (V\&F)}} \mathrm{ST\%} \times \mathrm{MY\%}_{\mathrm{ST}} \times \mathrm{OM\ (V\&F)\%}_{\mathrm{ST,MY}} \times \mathrm{ER}_{\mathrm{ST,MY,OM\ (V\&F)}} \tag{2}$$

$$\mathrm{TEM} = \mathrm{VHT(or\ VMT)} \times \mathrm{Fleet\ ER} \tag{3}$$

where $\mathrm{Fleet\ ER}$ is the fleet comprehensive energy use and emission rate (grams/mile or grams/hour), TEM is the total energy use and emissions, VHT is the vehicle hours traveled (used if $\mathrm{Fleet\ ER}$ is in grams/hour), VMT is the vehicle miles traveled (used if $\mathrm{Fleet\ ER}$ is in grams/mile), ST is the vehicle source type, MY is the model year, OM is the operating mode bin, $\mathrm{V\&F}$ is the average speed bin and facility type, $\mathrm{ST\%}$ is the proportion of one source type (from source type distribution input), $\mathrm{MY\%}_{\mathrm{ST}}$ is the proportion of one model year by one source type (from age distribution input), $\mathrm{OM\ (V\&F)\%}_{\mathrm{ST,MY}}$ is the time proportion of one operating mode bin (or proportion of average speed bin and facility type) by one source type and one model year (from operating mode distribution input or drive schedule), and $\mathrm{ER}_{\mathrm{ST,MY,OM\ (V\&F)}}$ is the energy use and emission rate of one source type, model year, and operating mode bin.

MOVES-Matrix Verification and Performance Test

To demonstrate the effectiveness and efficiency of MOVES-Matrix, the research team developed a set of test runs to its performance with the MOVES batch mode in terms of energy use and emission rate results and run speeds. Table 3 lists the iteration variables and increments for these test runs. All three variants of MOVES-Matrix were verified: 1) Speed-Matrix verified using default driving cycles embedded in MOVES, 2) OpMode-Matrix verified using user-specified operating mode distributions, and 3) OpMode-Matrix verified using user-specified driving cycles. The test comprised 4,050 runs, each covering 14 links representing various average speeds or operating conditions, and five pollutant types per run, resulting in a total of 283,500 emission results.

Table 3. Iteration Scenarios for Test Runs

Variables	**Iteration Increment**	**Number of Iterations**
Facility type	Freeway, Local	2
Fleet (MY & type)	Freeway fleet, Local fleet	
Calendar Year	2015-2055 in 5-year interval	9
Fuel month	January (winter), April (transition), July (summer)	3
Temperature	20-100 F in 20 F interval	5
Humidity	20-100% in 20% interval	5
Operation input	Average speed, OpMode distribution, Driving cycle	3
Total Scenarios (Number of Runs): 2×9×3×5×5×3		**4,050**
Number of links in each run	Average speed: 5-70 mph in 5-mph interval OpMode distributions: 5-70 mph in 5-mph interval with each applied with operating mode distribution Driving cycles: 14 links with each applied with a customized second-by-second driving schedule	14
Total Number of Link Scenarios: 4,050×14		**56,700**
Pollutant type	THC, CO, NO_X, $PM_{2.5}$, CO_2	5
Total Number of Emission Results: 56,700×5		**283,500**

Because MOVES is the official model for use in regulatory analyses, it is crucial that MOVES-Matrix generate the exact same results as running MOVES directly. The comparison of the emission rate results shows that MOVES-Matrix 4.0 outputs are within 0.0005% of the traditional MOVES model results obtained with the conventional batch mode of MOVES 4.0.1 (see Figure 4). Any potential round-off errors associated with the weighting calculations in MOVES are insignificant.

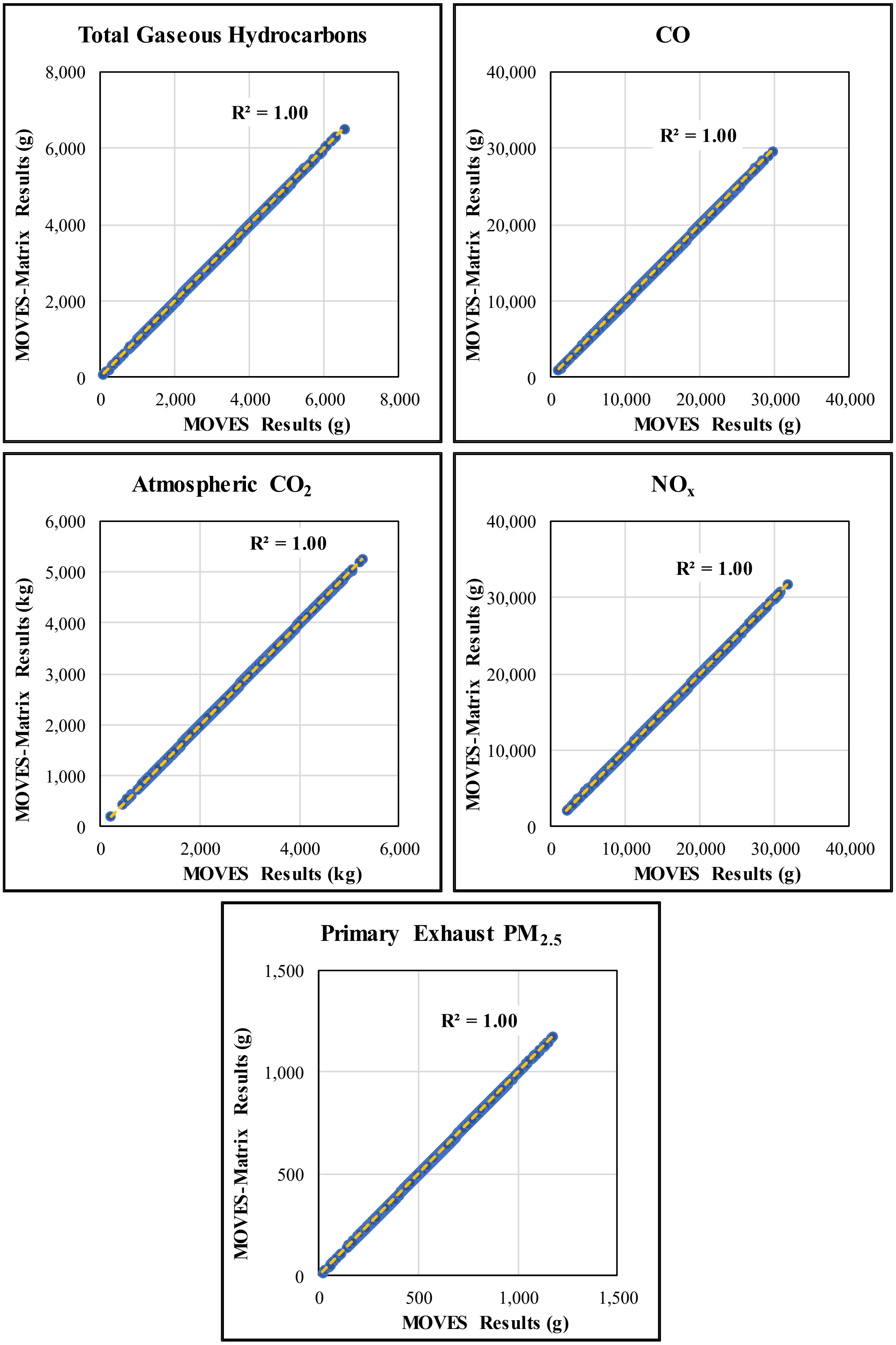

Figure 4. MOVES-Matrix 4.0 Verification Results by Pollutant

Both models were run on the same computing node with an Intel® Xeon® Gold 6226 central processing unit (CPU) at 2.70 gigahertz (GHz), RHEL 7 64-bit, and six gigabytes of Random Access Memory (GB RAM). Based on identical data inputs, the research team recorded the total run time, including input loading time and model calculation time, for all three methods in both MOVES batch mode and MOVES-Matrix. As shown in Table 4, MOVES-Matrix significantly outperformed MOVES batch mode in terms of computational efficiency, running more than 200 times faster than MOVES.

Table 4. MOVES and MOVES-Matrix Model Run Time Comparison

Model	Process	Method (total runs = 4,050)					
		Average Speed (1,350 runs)		OpMode Distribution (1,350 runs)		Driving Cycle (1,350 runs)	
		Time (hour)	Speed (sec/link)	Time (hour)	Speed (sec/link)	Time (hour)	Speed (sec/link)
MOVES	Load Input	3.83	0.73	4.13	0.79	4.23	0.81
	Calculation	207.40	39.50	153.12	29.17	192.23	36.62
	Total	211.23	40.23	157.25	29.95	196.46	37.42
MOVES-Matrix	Load Input	0.78	0.15	0.16	0.03	0.54	0.10
	Calculation	0.07	0.01	0.03	0.01	0.16	0.03
	Total	0.85	0.16	0.19	0.04	0.70	0.13
Ratio of Run Time (MOVES Batch Mode/MOVES-Matrix)		249		828		281	

Benefits of MOVES-Matrix 4.0

MOVES-Matrix stores pre-adjusted emission rates for all scenarios and simply filters the appropriate emission rates rather than performing adjustment calculation, which allows MOVES-Matrix to achieve significantly faster processing times compared to MOVES but still generates the same output. Four design characteristics contribute to the accuracy and fast processing speed of MOVES-Matrix:

1. Direct MOVES-derived energy use and emission rates: MOVES-Matrix emission rates are obtained directly from MOVES runs (no code modifications, correction factors, or approximations). The energy use and emission results from MOVES-Matrix are identical to those from the MOVES model.

2. Efficient energy use and emission modeling: MOVES-Matrix directly employs emission rates pre-adjusted for fuel specification, meteorology, and I/M programs, which allows users to assess impacts of changes in on-road operating conditions and fleet composition without repeatedly running MOVES. This structure also facilitates sensitivity analysis of MOVES algorithms.
3. Pre-organized database: Sub-matrices of energy use and emission rates are structured by calendar year, fuel specification, I/M program, temperature, and relative humidity. This pre-organization makes energy use and emission rates readily applicable to specific scenarios of interest, significantly increasing the speed of the emission assignment process.
4. Open-source and collaborative design: MOVES-Matrix is open-source, and it allows scripts in Python, C/C++, Java, SQL, or other languages to link MOVES-Matrix energy use and emission rates with travel demand models, traffic simulation, monitored data, and dispersion models.

MOVES-Matrix 4.0 was completed and verified against MOVES 4.0.1 in July 2024; applied case study applications of the model are still forthcoming. However, the model output structure for applications is identical to that of MOVES-Matrix 2014 which has been extensively applied across a variety of transportation and environmental studies. MOVES-Matrix can be easily coupled with vehicle activity analysis (*17–19*) by importing second-by-second vehicle operations, and can be used to model the emissions from individual vehicles (*20*). MOVES-Matrix can also be applied to a variety transportation models, such as travel demand models (*21*), and microscopic traffic simulation models (*22*), or applications of emissions modeling that require high-efficient model performance such as sensitivity assessment (*23*, *24*). MOVES-Matrix is highly-desirable for regional-scale dispersion analysis (*25–29*), providing high-performance computations that can deal with thousands of links in large-scale networks, variations in meteorology, and high-resolution sources for traffic operations. MOVES-Matrix 4.0 was developed for on-road running exhaust only, while MOVES-Matrix 2014 also supports rapid analyses of engine starts, truck hoteling, evaporative sources, brake/tire wear (*30*). The team is working on incorporating this feature into MOVES-Matrix 4.0 for off-network modeling.

The development of MOVES-Matrix 4.0 began in early 2024, with initial implementation covering Fulton County, Georgia. Based on the inventory of fuel specifications and I/M programs across the United States, there are 23 fuel regions and 86 I/M scenarios implemented across the 3,228 counties, resulting in 120 unique fuel and I/M program combinations (as shown in Table 5). This implies that by preparing 120 MOVES-Matrix 4.0 runs, all scenarios in every county across the United States can be covered. With each full set of scenarios of Opmode-Matrix taking approximately 4.5 days to run on the PACE cluster (at 5-degree temperature intervals), a national implementation of MOVES-Matrix 4.0 is feasible, with more computing time and/or a larger number of cores.

Table 5. Fuel Specification and I/M Programs in MOVES2014b, MOVES3 and MOVES4

MOVES Version	Number of Fuel Specifications	Number of I/M Programs	Number of Regions
MOVES2014b	22	89	117
MOVES3	23	87	122
MOVES4	23	86	120

The Georgia Tech team is preparing to expand MOVES-Matrix 4.0 coverage to meet any user's needs. With support from the National Center for Sustainable Transportation (NCST), the team is preparing matrices for other modeling regions as requests are received. Each MOVES-Matrix package includes the database of sub-matrices, a Python script to query and assemble the energy use and emission rates to users' applications, and documentation describing the database and its usage. NCST support allows the team to continually maintain the MOVES-Matrix scripts and notify users of any updates.

Conclusions

This study introduces MOVES-Matrix 4.0, a high-performance emission modeling system that can assemble any desired energy use and emissions rate for from pre-generated MOVES 4.0.1 energy use and emission rate outputs, eliminating the need for conducting MOVES modeling runs on the fly. Scenario tests demonstrated that MOVES-Matrix completes emissions computation tasks more than 200 times faster than running MOVES in batch mode, while producing the exact same results. Key benefits of MOVES-Matrix include:

1. Direct use of MOVES emission rates without modifications, correction factors, or approximations.
2. Organization of energy use and emission rates into sub-matrices that align with typical project-level emissions analysis assumptions, allowing rapid assessment of changes in on-road operating conditions and fleet composition.
3. High modeling efficiency based on query and assembly of energy and emission rates without the need to launch actual MOVES runs.
4. Compatibility with various scripting languages (Python, C/C++, Java, etc.) and with travel demand models, simulation models, monitored vehicle data, and dispersion modeling, and open-source availability for all users.

MOVES-Matrix 4.0 stores unmodified MOVES outputs and generates exactly same results with MOVES 4.0.1. The research team is currently updating the online sensitivity analysis tool (developed for MOVES-Matrix 2014) that will allow users to implement energy use and emission analysis online without having to run MOVES 4.0, and additional improvements to support off-network modeling access to MOVES-Matrix 4.0 results.

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Data Summary

As described in this report, the team configurated and pre-run EPA's MOVES's model to generate gigantic lookup matrices of MOVES4 energy use and emission rates.

Products of Research

The resulting energy and emission rate matrices are public domain and can be found at https://zenodo.org/records/15497651.

Data Format and Content

The format and content of the MOVES-Matrix data sets are documented in the NCST MOVES-Matrix overview and training documents at https://github.com/gti-gatech/moves_training/.

Data Access and Sharing

The MOVES-Matrix data are open source and can be downloaded and freely shared from the link provided above.

Reuse and Redistribution

The MOVES-Matrix data are open source can be downloaded, used, and freely redistributed using the link provided above.