MOVES-Matrix for High-Performance Emission Rate Model Applications

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A Research Report from the National Center for Sustainable Transportation

Randall Guensler, Georgia Institute of Technology

Haobing Liu, Georgia Institute of Technology

Xiaodan Xu, Georgia Institute of Technology

Hongyu Lu, Georgia Institute of Technology

Michael Rodgers, Georgia Institute of Technology

National Center for Sustainable Transportation

Georgia Tech School of Civil and Environmental Engineering
College of Engineering

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School of Civil and Environmental Engineering, Georgia Institute of Technology

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EXECUTIVE SUMMARY

The MOtor Vehicle Emission Simulator (MOVES) model was developed by the U.S. Environmental Protection Agency (USEPA) to estimate emissions from on-road and off-road vehicles in the United States. The MOVES model represents a significant improvement over the older MOBILE series of modes, primarily because emission rates are now truly modal in nature. Emission rates are now a function of power surrogates, which depend on speed and acceleration. Traffic simulation model outputs and smartphone GPS data can provide second-by-second vehicle activity data in time and space, including vehicle speed and acceleration. Coupling high-resolution vehicle activity data with appropriate MOVES emission rates further advances research efforts designed to assess the environmental impacts of transportation design and operation strategies. However, the MOVES interface is complicated, and the structure of input variables and algorithms involved in running MOVES to assess operational improvements makes analyses cumbersome and time consuming. The MOVES interface also makes it difficult to assess complicated transportation networks and to undertake analyses of large-scale systems that are dynamic in nature.

The MOVES-Matrix system developed by the research team can be used to perform emissions modeling activities in a fraction of the time it takes to perform even one single individual MOVES run. The MOVES-Matrix approach involves running the MOVES model iteratively, across all potential input variable combinations, and using the resulting multidimensional array of pre-run MOVES outputs in emissions modeling. The research team configured MOVES to run on a distributed computing cluster, obtaining MOVES energy consumption and emission rate outputs for each vehicle class, model year, and operating condition, by calendar year, fuel composition (summer, winter, and transition fuels), local Inspection/Maintenance (I/M) program, meteorology, and other variables of interest. The team ran MOVES 146,853 times to generate the on-road emission rate matrices for Atlanta. More than 90 billion emission rates populate the primary output matrix, but implementation tools developed by the team generate matrix subsets for specific applications to speed up the analytical processes. In 2017-2018, the team developed MOVES-Matrix 2.0, which now integrates engine start, soak, evaporative, and truck hoteling emissions. The resulting emission rate matrices allow users to link emission rates to assess big data projects (such as regional emissions for emission inventory development) and to support near-real-time evaluations of changes in emissions for large, dynamic transportation systems. In the case study applications performed by the team, emission rate generation with MOVES-Matrix is 200-times faster than using the batch mode of MOVES graphic user interface in the same computer environment and the process predicts exactly the same emissions result.

Introduction

In the United States, the MOtor Vehicle Emission Simulator (MOVES) model (U.S. EPA, 2015a) provides significantly improved emission rates compared to the older MOBILE series of models (U.S. EPA, 2016a), primarily because MOVES emission rates are more modal in nature, better representing emissions as a function of instantaneous (1Hz) speed and acceleration. Project-level modeling with MOVES requires the highest resolution of input data. A variety of new fleet activity data are now available for use in emissions modeling in project-level, such as streaming machine vision data (Liu, et al., 2015), smartphone location tracking (Akanser, et al., 2015; Hilpert et al., 2011; Elango, et al., 2007), and traffic simulation modeling (Xu, et al., 2016b; Talbot et al., 2013; Anya et al., 2014). Coupling MOVES emission rates with various sources of big data for vehicle activity can further advance research efforts designed to assess the environmental impacts of transportation design and operation strategies. Hot-spot analysis and near-road dispersion modeling for environmental impact assessment also benefit from the use of more accurate vehicle activity data in both time and space aspects, and the application of high-resolution emission rates for on-road driving conditions. However, the MOVES interface is complicated, and the structure of input variables and algorithms involved in running MOVES to assess operational improvements makes such analyses cumbersome and time consuming.

The MOVES interface makes it difficult to assess complicated transportation networks and to undertake analyses of large-scale systems that are dynamic in nature. For example, The Atlanta Regional Commission (ARC) Travel Demand Model network includes 74,500 roadway segment links (and the new ABM15 model employs more than 202,000 links). It is nearly impossible to perform emissions modeling for a dynamic network of this size using individual MOVES emission rates for each link, especially when fleet composition and on-road operating conditions change dynamically over the course of a day. On a typical personal computer (PC), depending on the pollutant types to be modeled, MOVES requires around 10-30 seconds to process emissions for one link for a unique fleet and operating condition. To obtain the composite emission rates for 1,000 roadway links in Atlanta, where the fleet composition and operating conditions vary every hour on every road segment, and where temperatures and humidity values vary by hour of day and month, and for the three Atlanta fuels (summer, winter, and transition), nearly 32 million individual MOVES runs would be required. It would take ten years to run on a typical PC, considering 1,000 road segments, with operations of each hour across 24 hours, in 21 temperature bins scenarios (10-110 F in 5F bins), 21 humidity bins scenarios (0%-100% in 5% bins), and 3 fuels supply scenarios (summer, winter, and transition fuel supply), which sums to 31,752,000 individual MOVES runs. Admittedly, the number of runs required for these cases are exaggerated, because there are many shortcuts that can be taken to reduce the number of runs required. For example, many runs yield the exact same emission output across certain temperature or humidity ranges, as they are insensitive to several pollutant types. In most cases, it is also impractical to run emissions with 10 F during the summer. However, modeling every operating condition described above is still impractical. A high-performance modeling approach is needed to assess large-scale dynamic networks. Yet, regulations require that the latest approved regulatory model (i.e., MOVES 2014a) be used in all transportation and air quality planning and assessment work (U.S. EPA, 2015a).

Previous studies have focused on optimizing model run speed for regulatory emissions models. For example, Guensler et, al. (2004) ran MOBILE6, the predecessor of MOVES model, tens-of-thousands of times to generate a matrix of emission rates (known as MOBILE-Matrix) by road class, fleet composition, fuel, inspection and maintenance (I/M), temperature, etc., for Georgia, and applied emission rates in conformity analysis and CALINE4 dispersion model routines. The emission matrix developed for MOBILE6 facilitated rapid analysis via scripts (Guensler, et al., 2004). With the release of the more advanced MOVES model as replacement of MOBILE series models, Liu and Frey (2012) developed a simplified MOVES model called MOVES-Lite, based on the ratio of operating mode bin as the cycle adjustment factor, and the results were within 5% of MOVES outputs.

To improve modeling efficiency, but at the same time ensure that regulatory requirements for use of MOVES are met, the research team developed MOVES-Matrix. The MOVES model was run hundreds of thousands of times to generate an emission rate lookup matrix for all combinations of MOVES input variables. That is, the same concept of iterative model processing and matrix generation was applied to MOVES as it was to the MOBILE model more than 20 years ago (Guensler, et al., 2004; Guensler, et al., 2000; Guensler and Leonard, 1995). The MOVES-Matrix emission rates described in this paper can be queried for any analytical purpose that can be conducted by MOVES, without ever having to launch MOVES or transfer MOVES modeling output files into the analyses. Obtaining regulatory approval for any modeling approach is predicated on the approval of the U.S. Environmental Protection Agency (U.S. EPA), which requires that the latest MOVES model must be employed. The research team has demonstrated any modeling approach in which MOVES-Matrix is applied yields exactly the same emission rates as MOVES when run for the same conditions. As demonstrated in this paper, MOVES-Matrix is simply the comprehensive set of outputs from the MOVES model; hence, applications of MOVES-Matrix emission rates yield exactly the same results as MOVES.

MOVES Background

Historically, regulatory emissions models, such as the MOBILE series of models, defined emissions as a function of average speed, essentially irrespective of acceleration (Beardsley, 1997; Guensler 1993). In the MOVES model, emissions are now defined 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, which better reflects acceleration and speed impacts on work and engine load (U.S. EPA, 2016b). The U.S. EPA's MOVES model employs a "binning" approach in modeling emissions for different on-road fleets and on-road operating conditions, where on-road activities that falls into the same operating mode bin receives the same emission rate for a given vehicle type and set of environmental condition. In MOVES, driving cycles (speed-acceleration activity) can be decomposed into operating mode bins and modeled as a function of time spent operating in each bin. This design enables MOVES to provide common emission rates for all modeling scales (macroscale, mesoscale, and microscale) (U.S. EPA, 2016b).

MOVES requires refined input data, including meteorology, calendar year, fuel type, I/M program elements, traffic volume, operating speed, fleet age distribution and vehicle type distribution (U.S. EPA, 2015b). Baseline emission rates for specific operating modes are also adjusted in the model to account for the impacts of temperature, humidity, fuel composition, vehicle aging, and other factors on the emission rates. Figure 1 below presents the process flow for on-road emissions modeling with MOVES.

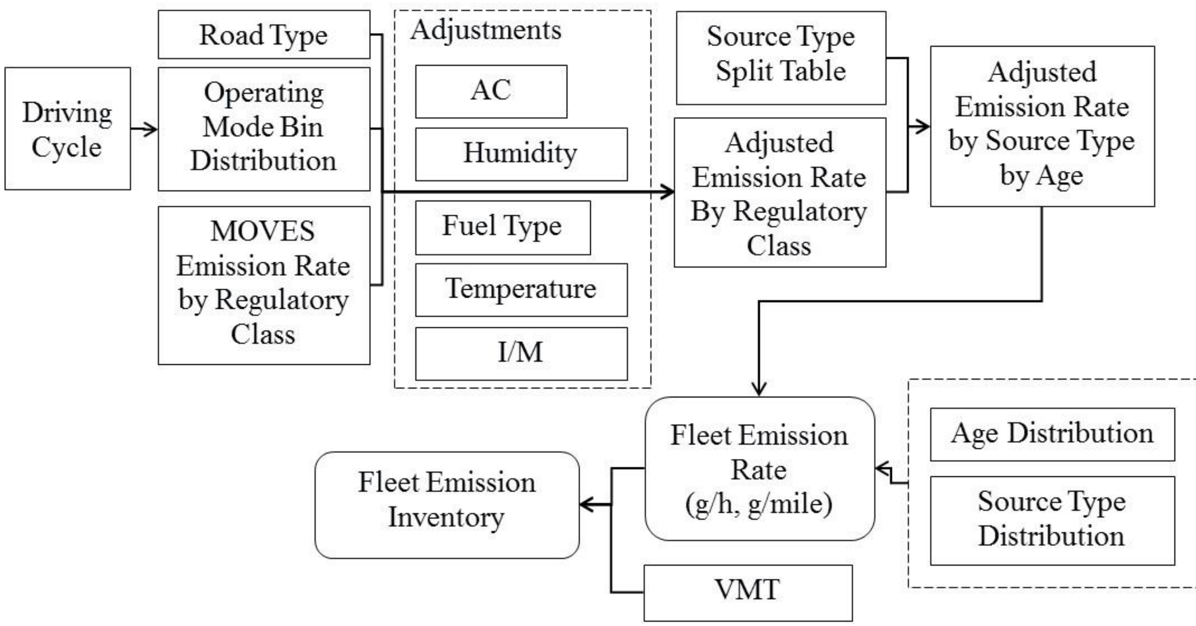


Figure 1. MOVES Data Processing Overview

Because emissions are a function of the energy required to move the vehicle, which depends upon power demand, vehicle weight, and on-road operating conditions, the MOVES model employs surrogates for engine load: vehicle specific power (VSP) for light-duty vehicles, and scaled tractive power (STP) for heavy-duty vehicles. VSP and STP are a function of vehicle speed, acceleration, and vehicle mass. Second-by-second VSP and STP are calculated as shown in equation (1) (U.S. EPA, 2016a):

$$\mathrm{VSP(STP)_t\ (kW/tonne)} = \left(\frac{A}{M}\right)v_t + \left(\frac{B}{M}\right){v_t}^2 + \left(\frac{C}{M}\right){v_t}^3 + \left(\frac{m}{M}\right)(a_t + g * \sin\theta_t)v_t \qquad (1)$$

Where:

v_t=velocity at time t (m/sec)

a_t=acceleration at time t (m/sec^2)

θ_t=road grade (radians or degrees, as needed in sin calculation algorithms)

g=gravitational acceleration (9.81 m/sec^2)

m=vehicle mass (tonnes)

M=fixed mass factor for the source type (tonnes)

A=rolling resistance (kW-sec/m)

B=rotating resistance (kW-sec^2/m^2)

C=aeodynamic drag (kW-sec^3/m^3)

M in VSP=fixed mass factor for the source type (tonnes), m=M for VSP calculations

M in STP=scaling factor to scale STP ranges to within the same range as VSP (tonnes)

The MOVES model uses a binning approach in emissions modeling. VSP and STP bins are established for three types of operations: braking, idle, and cruise-acceleration. Bins for cruise-acceleration are further separated into three average speed groups (0-25 mph, 25-50 mph, 50+ mph), and then into VSP ranges within each average speed group. Higher VSP and STP values within specific operating speed ranges are linked with higher fuel consumption rates, CO_2 emission rates, and criteria pollutant emission rates. **Error! Reference source not found.**Figure 2 below describes and defines each MOVES running operating mode bin (opMode bin) by speed and VSP ranges, and presents an example of the MOVES CO_2 emission rates for model year (MY) 2016 passenger trucks in each operating mode bin. High speeds, moderate accelerations at high speed, and hard accelerations at moderate or high speed push on-road activity into higher VSP bins, which then use higher fuel consumption and emission rates in energy and emissions calculations.

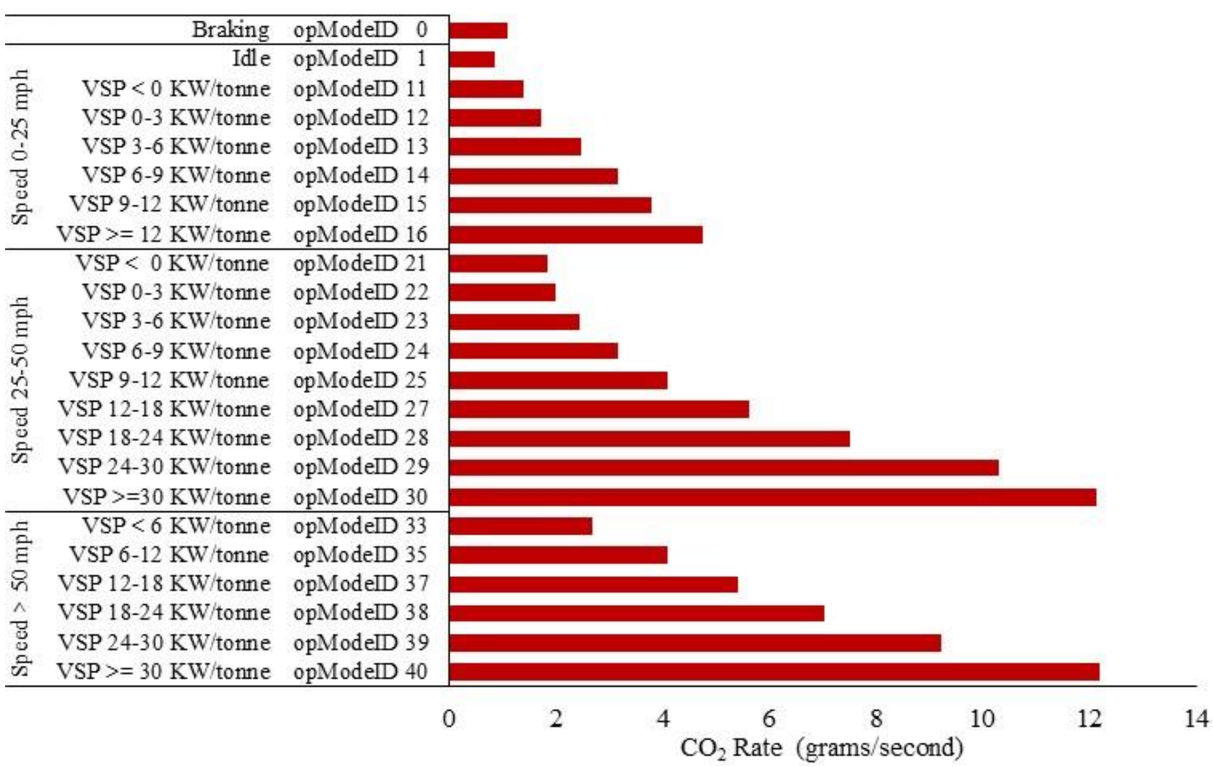


Figure 2. Definitions of Running Operating Mode Bins and Example CO_2 Emission Rates for Passenger Trucks (MY 2016)

MOVES-Matrix Conceptual Approach

Because emissions are a complex function of many locally-dependent variables, and because MOVES integrates a number of aggregation functions for use in emission estimation at state and county levels, the interface is complex and requires numerous inputs to properly characterize any specific emission scenario modeled by a user. A lot of labor is required to prepare MOVES input files. In addition, running MOVES is time consuming, because the model always begins by calculating base emission rates and adjusts the rates using various correction factors for temperature, humidity, fuel property, etc. This also makes MOVES difficult to use for large-scale transportation networks that experience dynamic changes in on-road fleet composition and operating conditions that affect corrections factors during the day.

MOVES-Matrix is composed of the outputs from a tremendous number of MOVES model runs. The basic process is to run MOVES across all variables that affect output emission rates, where each iteration yields pollutant emission rates for: a specific vehicle source type (vehicles represented in the run are a specific type of vehicle), a specific model year (age group), a specific operating, a single calendar year, other applicable regional regulatory parameters (fuel properties, I/M program characteristics), and a specific temperature and humidity condition. After conducting hundreds of thousands of runs, users can query the resulting MOVES emission rate matrix (MOVES-Matrix) and obtain the exact same MOVES emission rates obtained from any single MOVES model run, without ever having to launch MOVES again, or transfer MOVES outputs into the analyses.

Figure 3 below provides an overview of MOVES-Matrix application process. Users first identify the subset of the MOVES-Matrix they need, by specifying calendar year, fuel month, and meteorology data. Then, the user can access each cell that contains an emission rate for a specific vehicle class and model year from MOVES-Matrix and weight each emission rate by on-road activity to assemble the on-road fleet emission rate. Because the weighting process is exactly the same as used in MOVES to generate a fleet composite emission rate for a link, the MOVES-Matrix process yields exactly the same emission rates as a direct MOVES run, but in a fraction of the time to use it.

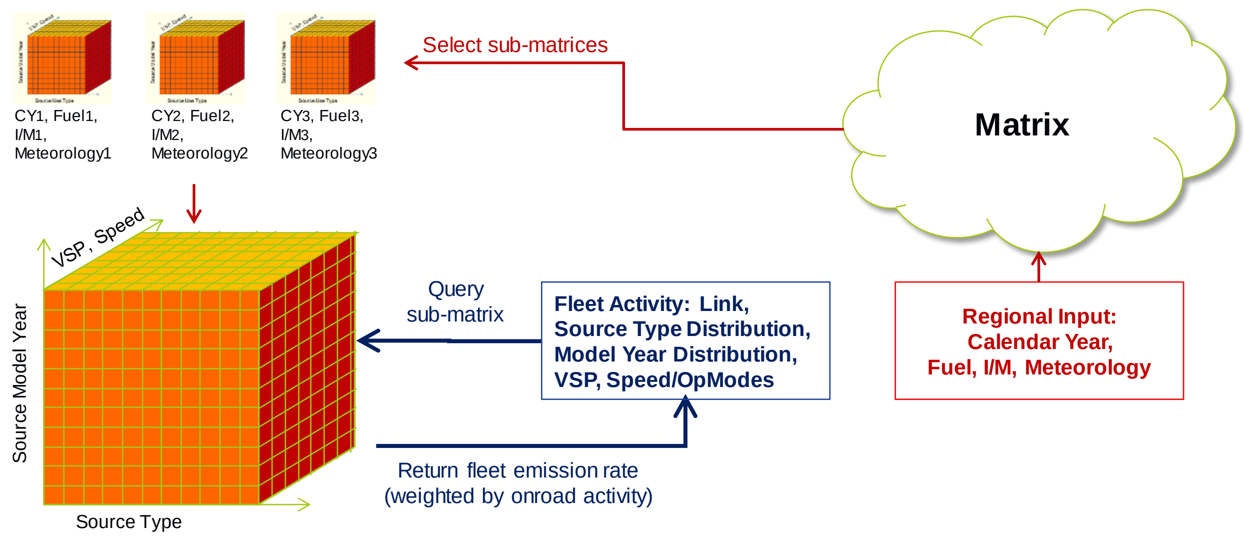


Figure 3. MOVES-Matrix Application Process Flow

Figure 4 shows the emission rate assembly process for MOVES-Matrix. Because each iterative MOVES run used to generate the matrix already performed the complex emission rate calculations and adjustments for temperature, humidity, fuel composition, I/M program, etc., MOVES-Matrix already contains cells representing the corrected emission rates. For the user, applying MOVES-Matrix is significantly faster than running MOVES. In fact, the MOVES-Matrix fleet emission rate assembly process is so fast, that it opens the door to using the matrix emission rates for large-scale and real-time emission estimation.

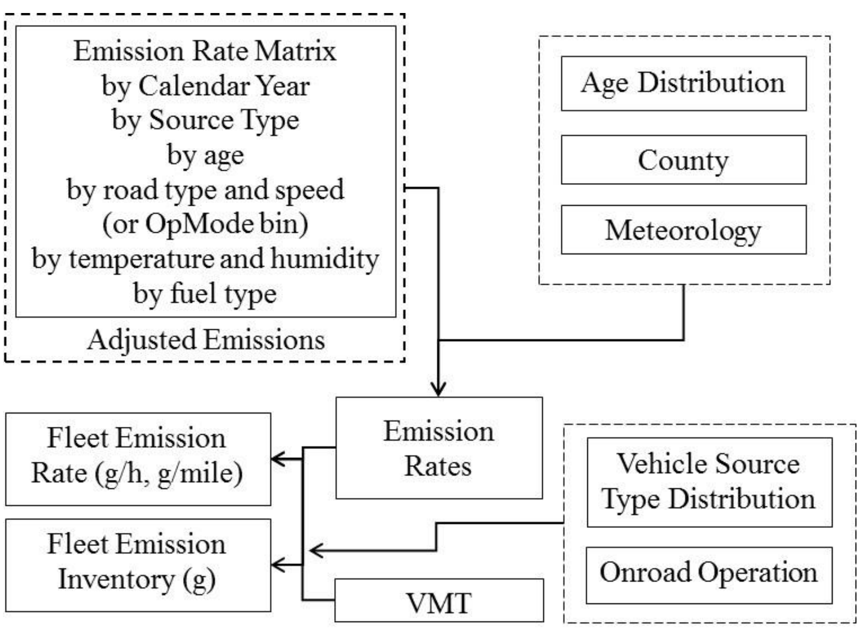


Figure 4. MOVES-Matrix Data Processing Overview

MOVES-Matrix – On-road Emissions Development

To develop the MOVES-Matrix emission rate database for a region of interest, a total of 30,429 MOVES runs are prepared by the research team (calendar years 2010-2025, 2030, 2035, 2040, 2045, 2050; winter, summer, and transition fuel months, 10F-110F temperatures in 5F intervals, 0%-100% relative humidity in 5% intervals). Five times the number of runs is required to generate emission rates for 1F intervals, but the team has concluded that the marginal benefit is not very high for doing so. The team developed the MOVES-Matrix model in three steps:

1) Develop the set of input files to support iterative MOVES runs across all relevant input variables
2) Run the MOVES input files in an advanced computing cluster to obtain multi-dimensional emission rates outputs
3) Develop algorithms and a MOVES-Matrix user interface that can be used to pull applicable emission rates from the matrix for use in
    a. Regional emissions inventory modeling
    b. Traffic simulation modeling
    c. Corridor-monitored second-by-second activity analysis
    d. Microscale dispersion modeling

In addition to csv input tables, each MOVES modeling run employs an import xml file and an execution mrs file. For each MOVES input element representing a single transportation link, the user can assign a specific calendar year, fuel month, temperature, humidity, I/M settings, source type distribution, model year distribution, and fuel type distribution. In running a single link in MOVES, we noted that MOVES can output disaggregated emission rates for each vehicle source and model year type (13 source types × 31 model years) and fuel types (gasoline, diesel, CNG, etc.) within a link that has specified operating conditions, in about the same time that it takes to generate a single aggregated emission rate for the link. Hence, we obtain 403 (13 × 31) source type emission rates for every single MOVES run. Not only are fewer runs required, a significant reduction in modeling time also accrues from not having to launch the model as frequently. Table 1 outlines the model inputs used to create on-road MOVES-Matrix.

Table 1. Content of Input File for Each On-road MOVES Run

Input	Description
Link	23 links with each assigned operating mode bin Set volume for each link as 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 each source type
Source type	Uniform source type distribution (1/13 for each source type) for each link
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 5º F-bin interval, 23 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 2010-2025, 5-year intervals in 2030-2050, input in xml and mrs file.

MOVES Configuration in PACE (Partnership for an Advanced Computing Environment)

The research team has priority access to the Partnership for an Advanced Computing Environment (PACE) high performance computing (HPC) cluster. PACE is a collaboration between Georgia Tech faculty and the Office of Information Technology, and was established for the primary purpose of providing an environment for distributed, high-performance computing. Participating researchers can benefit from the large-scale computing and storage infrastructure, which is organized in the forms of shared queues and distributed computational runs. Dedicated technical services are provided to manage the hardware and software infrastructure for the cluster. Users submit jobs to PACE from a few select head nodes and the cluster assigns jobs to available cores. On its largest shared queue, PACE manages around 35,000 cores, with 90 terabytes of memory, 2 petabytes of online commodity storage, and nearly 300 terabytes of high-performance scratch storage. The largest queue that the research team can currently access has 202 nodes with 8,200 cores. PACE nodes (each machine is called a node) are divided into two types:

- Head Node – All PACE users have access to head nodes, which are used to launch jobs. No computations are performed on head nodes.

- Cluster Node – Cluster nodes run the actual jobs. A user has access to a particular cluster node only during the time the user's job is running on the cluster.

When a MOVES job is launched on a cluster machine, the scripts first install MOVES on the machine by unzipping the MOVES source files on the disk. The script then proceeds to install a thin version of MYSQL server by unzipping its files onto the disk, and starts the SQL server on an available port. MOVES command line java processes are then launched to create input and output database files respectively (for iterations). The output files are zipped and stored on PACE persistent storage. More details on launching MOVES in PACE can be found in Liu et al., (Liu et al., 2016).

Depending on the application and research scope, MOVES-Matrix can be constructed for different input variable resolutions. Table 2 listed two typical sizes of MOVES-Matrix (i.e., with temperature of 1F interval and 5F interval), and corresponding amount of time to generate MOVES-Matrix using PACE. It takes 20 days to generate emission rates of MOVES-Matrix on the PACRE system at 1F temperature resolution (given the number of dedicated nodes that the research team is allowed to access). The preparation time for MOVES-Matrix on PACE at 5F temperature intervals can be as short as 4 days. However, MOVES-Matrix generation on larger and faster shared distributed computing platforms (such as those operated by the Department of Energy) could be performed in a matter of hours (depending upon resources allocated).

Table 2. Time for Generating MOVES-Matrix

MOVES-Matrix Size	Time to Prepare
30,429 files - 21 calendar years × 3 fuel months × 23 temperature bins (0-110 F with 5F interval) × 21 humidity bins (0-100% with 5% interval)	4 days
146,853 files - 21 calendar years × 3 fuel months × 111 temperature bins (0-110 F with 1F interval) × 21 humidity bins (0-100% with 5% interval)	20 days

MOVES-Matrix Structure and Algorithm Design

On-road MOVES-Matrix for a modeling region is generated from 30,429 MOVES runs (21 calendar year * 3 fuel months * 23 temperature bins * 21 humidity bins = 30,429). The scripts repeated MOVES runs where each parameter in Table 1 was incremented, and each run yield emission rates output applicable to:

- Given calendar year
- Regional regulatory parameters (fuels properties and I/M program)
- Specific temperature and humidity
- Specific operating condition
- All air pollutants

- All source types
- All model years (age group)

To support varied levels of detail for on-road fleet composition and operating conditions that may be available to modelers, the research team designed MOVES-Matrix to enable the use of the following three operating input modes.

- **Operating Mode Distribution.** Users can provide operating mode distribution for operations.
- **Average Speed and Facility Type.** Users can provide average speed and road type (arterial vs. freeway) as inputs, in which case emission results are a function of internal MOVES default driving cycles. A database of MOVES default operating mode distributions was pre-generated by average speed (0.1 mph interval and facility type). If average speed and facility type is used as input, the specific operating mode distribution is selected from the default database as the operation input.
- **Driving Schedule.** Users can provide a driving schedule (speed-time trace) for on-road operations. If the user specifies a second-by-second driving trace to describe on-road vehicle activity, VSP/STP for each second is calculated and then converted to operating mode bin**Error! Reference source not found.**. The operating mode distribution is then calculated by aggregating operating mode bin of each second for each vehicle source type in each link.

Figure 5 summarizes the process for generating operating mode distributions.

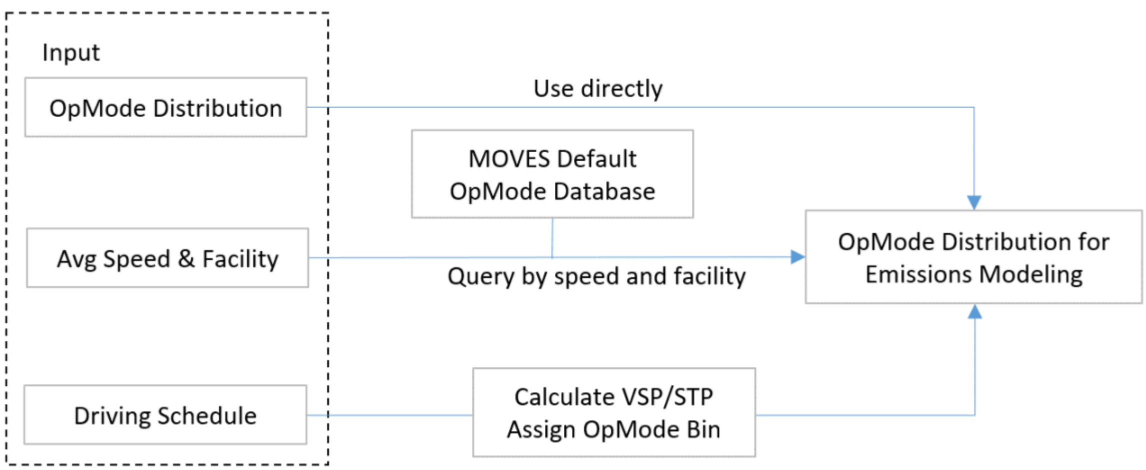


Figure 5. Process Flow from Operation Input to Operating Mode Distribution

The MOVES-Matrix application consists of three modules: 1) input, 2) emission database, and 3) output. Input modules are created for each of the three operating input modes described above. In designing MOVES-Matrix, it was important to first assess model user habits. Real-world applications of MOVES for emission inventory development or project-level conformity analyses currently use a variety of simplification approaches to limit the number of MOVES runs that will be required. For example, analysts often assume that fleet composition does not vary (using a default regional registration mix for model years and technology groups) with heavy-duty truck fractions quantized in specific percentages by road class (0% or 1% on certain local roads and arterials and 3% or 5% on certain freeways). Planning inventories may also assume a single temperature, humidity, and fuel supply. Every time another transportation scenario needs to be assessed, a new set of emission rates applied with new meteorology or fuel scenario generally needs to be developed from MOVES and connected with the activity data.

To support typical applications, in each region, the MOVES-Matrix emission database was grouped into 30,429 (or 146,853 if 1-degree temperature is applied) sub-matrices, with each sub-matrix storing emission rates for all source types, all source model years, all operating mode bins, for one specific calendar year, one fuel month, one temperature, one relative humidity, one fuel supply (by year, month), and one I/M strategy (by year). This way, a small subset of emission rates can be extracted from the matrix based on the user's year, month, and meteorology inputs. This structure helps support emission control strategy analysis, given that users tended to assume a single temperature, humidity, and fuel, when exploring the impacts of strategies on traffic activity and emissions. Using a sub-matrix is significantly faster than extracting data from the comprehensive MOVES-Matrix array.

After the sub-matrix of emission rates is identified and accessed, the emission rate processing is the same as used by MOVES in project-level modeling. The emission rates in the sub-matrix are connected to vehicle activity data through MOVES-Matrix algorithms. MOVES-Matrix weights the emission rates from individual source types to generate the composite emission rate. The weighting combines on-road vehicle activity, as defined by combined source type and model year distribution (newer vehicles typically represent a larger share of the on-road fleet than older vehicles) and the amount of activity by operating mode bin to calculate a composite emission rate for each link. The emission rate weighting function is as follows in equation (2) and (3).

$$\text{Fleet ER} = \sum_{\text{ST}} \sum_{\text{MY}} \sum_{\text{OM}} \text{ST\%} \times \text{MY\%}_{\text{ST}} \times \text{OM \%}_{\text{ST,MY}} \times \text{ER}_{\text{ST,MY,OM}} \qquad (2)$$

$$\text{TEM} = \text{VMT} \times \text{Fleet ER} \qquad (3)$$

Where:

Fleet ER: fleet comprehensive emission rate.

VMT: vehicle miles traveled.

TEM: total emissions

ST: vehicle source type

MY: model year

OM: operating mode bin

$ST\%$: proportion of one source type (source type distribution input)

$MY\%_{ST}$: proportion of one model year by one source type (age distribution input)

$OM\%_{ST,\ MY}$: time proportion of one operating mode bin by one source type and one model year

$ER_{ST,MY,OM}$: emission rate of one source type, model year, and operating mode bin.

MOVES-Matrix 2.0 – Off-Network Emissions Development

In addition to the running exhaust, the team has also expanded MOVES-Matrix to include emissions from off-network modes, i.e., engine starts, truck hoteling, evaporative sources, brake/tire wear. MOVES-matrix development for these processes is presented in Xu, et al. (2018a). A case study was conducted for the metropolitan Atlanta, GA to verify the feasibility of using this expanded version of MOVES-Matrix and to ensure that the approach obtains the exact same results as applying MOVES directly (Xu, et al., 2018b; Xu, et al., 2017). The travel activity inputs come from regional travel data generated by the Atlanta Regional Commission's activity-based travel demand model. The emission results from MOVES-Matrix are compared to MOVES output to verify the equivalence of this approach.

The emission inventory analysis in MOVES can be described as applying applicable emission rates to specific vehicle activities across an entire vehicle population (across source types, or "Stype" in Equation (4)), for the given set of environmental conditions, fuel specifications, etc. Similar to the on-road modeling, the relationship among the three elements can be illustrated using the following equation (4):

$$\text{Emissions} = \sum_{\text{Stype}=\text{i}}^{\text{n}} (\text{activity by OpMode fraction} \times \text{em rate by OpMode bin}) \quad (4)$$

For all processes, the vehicle population is defined by the MOVES source type population and vehicle age distribution, and these distributions may differ spatially and temporally across transportation network links. For example, drivers tend to use newer vehicles on freeway commutes (Khoeini and Guensler, 2014; Granell, et al., 2002). Most users prepare the fleet input based on locally derived data, typically regional vehicle registration data, or some combination of local data with MOVES default distribution (Porter et al., 2014).

In MOVES project-level analysis, vehicle activities and emission rates are differentiated by various emission processes. The MOVES project-level processes and activities covered by this study are listed in Table 3. In MOVES, the relevant vehicle activities consist of vehicle miles travelled (VMT), source hours, hoteling hours, and number of engine starts. The instantaneous operating condition for certain activities is represented by operating mode, where activity falls onto one of a series of operating mode bins (OpMode Bins) in MOVES. Although refueling emissions depend on fuel/energy consumption, because total energy consumptions can be estimated from running exhaust, engine start, and hoteling, refueling emission can be ultimately counted as a by-product of other emitting processes and linked to stationary source activities (fueling stations). The tank vapor venting process (diurnal evaporation) is not included in this case study because we applied the MOVES project-level approach. Diurnal evaporation is estimated using in the MOVES county-level model, as it requires 24-hour profiles for vehicle operations and ambient temperatures, while MOVES project-level model only allows single-hour scenario input.

Table 3. MOVES Project-level Processes and Activity (U.S. EPA, 2015b)

Process ID*	Process Name	Specific Activity	OpMode Bin	OpMode Bin ID*
1	Running Exhaust	VMT	Vehicle Specific Power (VSP)/Scaled Tractive Power (STP) bin	0-40, 300
2	Start Exhaust	Number of engine start	Soak time bin	100-108
9	Brake Wear (PM only)	VMT	VSP/STP bin, brake wear stopped	0-40, 501
10	Tire Wear (PM only)	VMT	Average speed bin	400-416
11	Evap Permeation	Source hour	Hot/cold soak and operating	150-151, 300
13	Evap Fuel Leaks	Source hour	Hot/cold soak and operating	150-151, 300
15	Crankcase Running Exhaust	VMT	VSP/STP bin	0-40, 300
16	Crankcase Start Exhaust	Number of engine start	Soak time bin	100-108
17	Crankcase Extended Idle Exhaust	Hoteling hours	Extended idling	200
18	Refueling Displacement Vapor Loss	Energy consumption	See process 1, 2, 90, 91	
19	Refueling Spillage Loss	Energy consumption	See process 1, 2, 90, 91	
90	Extended Idle Exhaust	Hoteling hours	Extended idling	200
91	Auxiliary Power Exhaust	Hoteling hours	hoteling diesel auxiliary	201

**The ID numbers in the Table 1 are defined by the U.S. EPA for MOVES; details can be found at: (https://www.epa.gov/moves/moves-algorithms).*

The approach taken to prepare MOVES-Matrix for various emissions processes (Xu, et al., 2018a) was essentially the same as previously performed to generate running exhaust emission rates (Liu et al., 2016). The MOVES project-level model was run iteratively across all possible combinations of temperature and humidity, for a specific I/M program and set of fuel specifications, to generate the matrix of emission rates per source type, model year, unit of activity, and operating mode bin. The emission rates in MOVES-Matrix for each process are in the form of grams of emissions or joules of energy consumption per unit of activity, by operating mode.

The major task in this study was to develop the iteration methodology used to prepare emission rates for each emission process, and to develop the output matrices of emission rates for the various processes. The methodology for each emitting process was different, so each process is explored in more detail in the following sections. To simplify the analysis, some of the emitting processes were combined when they shared the same activity inputs. The five categories of emitting processes are listed in the Table 4.

Table 4. Emission Process Category in this Study

No.	Category	Process	Activity
1	Running emissions	Running exhaust, crankcase running exhaust, brake wear, tire wear	VMT
2	Start emissions	Start exhaust, crankcase start exhaust	Number of engine starts
3	Hoteling emissions	Extended idle exhaust, auxiliary power exhaust, and crankcase extended idle exhaust	Hoteling hours
4	Evaporative emissions	Fuel permeation, fuel leaks	Source hours
5	Refueling emissions	Refueling displacement vapor loss, refueling spillage loss	Combination of 1, 2, 3

Running Emissions Modeling Regime

In MOVES, running operations refer to operation of internal-combustion engines after the engine and emission control systems have stabilized at operating temperature (U.S. EPA, 2015b). The running exhaust is estimated based on vehicle VMT or vehicle hours travelled (VHT) with respect to different speeds. As shown in previous section, the VMT is further-partitioned by speed and vehicle specific power (VSP) for light-duty vehicles or scaled tractive power (STP) for heavy-duty vehicles. In MOVES, running emissions are contributed from running exhaust and crankcase running exhaust. In addition, particulate matter from brake wear and tire wear emissions can be included in the running emission package, because they essentially share the same inputs as running exhaust. To account for running emissions, the following inputs are prepared for vehicle activities:

- **Link data**: The link-level VMT, average speed, and road grade are required inputs.
- **VMT fractions**: The VMT fractions by source type and model year should be prepared to properly-partition total VMT by vehicle population.
- **Operating mode fractions**: Users need to employ at least one of the following three on-road operating conditions to generate opMode fractions: average speed, operating mode distribution, or second-by-second vehicle speed trace.

MOVES-Matrix is prepared for all four running processes, in emission-per-hour by individual source type, model year and operating mode bin (0-40, 300, 400-416, and 501). For each process, VHT is calculated from VMT and average speed. Then, emissions are estimated by multiplying VHT by source type, model year, and OpMode Bin with corresponding emission rates and then summing emissions by link.

Start Emissions Modeling Regime

Vehicle emission rates are elevated for the first few minutes after an engine is started (Weilenmann, et al., 2009). The vehicle activity data needed for estimating engine start emissions include the number, location, and time of engine starts. Start exhaust and crankcase start exhaust can be considered as start emissions as they both use the number of starts as their major activity. To properly-account for start emissions, the following inputs should be prepared for estimating start activities:

- **Number of engine starts by zone:** Engine starts occur at the origin location of trip origin-destination pairs. In this case, the number of starts can be prepared for pre-defined traffic analysis zones (TAZs) in a travel demand model, neighborhood zones, or for an entire region.
- **Start fractions by vehicle population:** The start fractions by source type and model year are prepared to partition the number of starts by vehicle population.
- **Soak time distribution:** Users prepare the soak-time distribution by time of days and vehicle type. The parking durations at different times of day can vary significantly as a function of trip chaining and previous activities.

MOVES-Matrix is prepared for the two start processes (start and crankcase) in grams-per-start by individual source type, model year, and soak time bin. For each process, emissions are estimated by multiplying number of starts by source type, model year, and OpMode Bin with corresponding emission rates for each zone.

Hoteling Emissions Modeling Regime

In MOVES, "hoteling" is defined as any long period of time during which truck drivers sit in their vehicles during mandated driver break periods (U.S. EPA, 2015c). Hoteling emissions are only available for long-haul combination trucks (MOVES source type ID = 62). Extended idling, auxiliary power exhaust and crankcase idling exhaust are considered as they occur during total hoteling hours. To properly-account for truck hoteling emissions, the following inputs should be prepared for estimating hoteling activities:

- **Hoteling hours:** Hoteling hours are required for calculating hoteling emissions.
- **Truck population:** The long-haul combination truck population by model year should be prepared to properly-represent fleet composition.
- **Extended idle/auxiliary power hour fraction:** The fraction of extended idling or idling with APU units is used to partition hoteling hours for individual processes.

MOVES-Matrix is prepared for three hoteling processes, in grams of emission per hoteling hour by model year for long-haul combination truck. For each process, the hoteling emissions are estimated by multiplying hoteling hours by model year, hour fraction of process with corresponding emission rates.

Evaporative Emissions Modeling Regime

A significant portion of unburned fuel evaporates from vehicles all the time. Evaporative processes occur during vehicle refueling, while parked, and while driving, and contribute to a large portion of gaseous hydrocarbon emissions from gasoline vehicles (U.S. EPA, 2014). Evaporative processes are different from exhaust emissions because they do not directly involve combustion. Although refueling emissions are included in MOVES evaporative emissions, refueling losses employ different vehicle activity inputs and should be modeled as a stationary source activity. To properly-account for evaporative emissions, following inputs should be prepared for estimating evaporative activities.

- **Source hours operating and parked:** Source hours operating (SHO) and source hours parked (SHP) should be prepared by zone. SHO can use the on-road VHT in running emissions, and SHP can share the same zonal information as engine start.
- **Vehicle population:** Vehicle operation and parking should be tracked by source type so that source hours of operating and source hours of parking can applied respectively.
- **Soak time distribution:** Users should prepare the fractions of hot soak and cold soak to split the service hours of parking.

MOVES-Matrix is prepared for two evaporative processes (vehicle operating and parked), in emissions per source hour, by source type, model year, for hot/cold soak and operating. For each process, emissions are estimated by multiplying source hours by model year, hour fraction of process with corresponding emission rates.

Refueling Emissions Modeling Regime

Refueling emissions refers to the displaced fuel vapors and fuel spillage when liquid fuel is added to the tank at a gas station (U.S. EPA, 2014). Refueling emissions are estimated from the total volume of fuel dispensed (gallons); hence, refueling losses are a function of energy consumption. As energy consumption of all vehicles are estimated from running, engine start, and hoteling process, the refueling emissions are allocated to fuel consumed in on-road driving activity, engine start activity and truck hoteling activity. The activities for refueling emissions include VMT, number of engine starts and truck hoteling hours.

The model inputs required for each category of emissions are summarized in Table 5. Although refueling emissions are calculated in this case study, they will not be used in comparative analysis later in the paper because refueling emissions are better represented in a stationary source emissions inventory given that the emissions actually occur at the refueling location.

Table 5. Summary of Model Inputs for Different Emission Process

No.	Category	Population inputs	Vehicle activity inputs	Emission rates
1	Running emissions	Link volume; VMT fraction by source type and model year;	Link VMT, average speed; Average grade; STP/VSP bin fraction	Emission rates per hour by source type, model year and VSP/STP bin
2	Start emissions	Vehicle population by source type and model year	Number of engine starts by zone; Soak time distribution	Emission rates per start by source type, model year and soak time bin
3	Hoteling emissions	Long-haul combination truck population by model year	Hoteling hours; Hour fraction for individual process	Emission rates per hoteling hour by model year
4	Evaporative emissions	VMT fraction by source type and model year; Vehicle population by source type and model year	SHO and SHP; Soak time distribution	Emission rates per source hour by source type, model year and soak time bin/ operating
5	Refueling emissions	See 1, 2 and 3	See 1, 2 and 3	See 1, 2 and 3

Benefits of MOVES-Matrix

Figure 6 below compared MOVES with MOVES-Matrix in terms of overall working mechanisms. MOVES starts with a set of baseline emission rates, and these baseline emission rates are adjusted during each run before they are connected to activity data. MOVES-Matrix stores adjusted emission rates for all scenarios, and for the scenario of interest. MOVES-Matrix filters the emission rates for the specific scenario, rather than doing adjustment calculations.

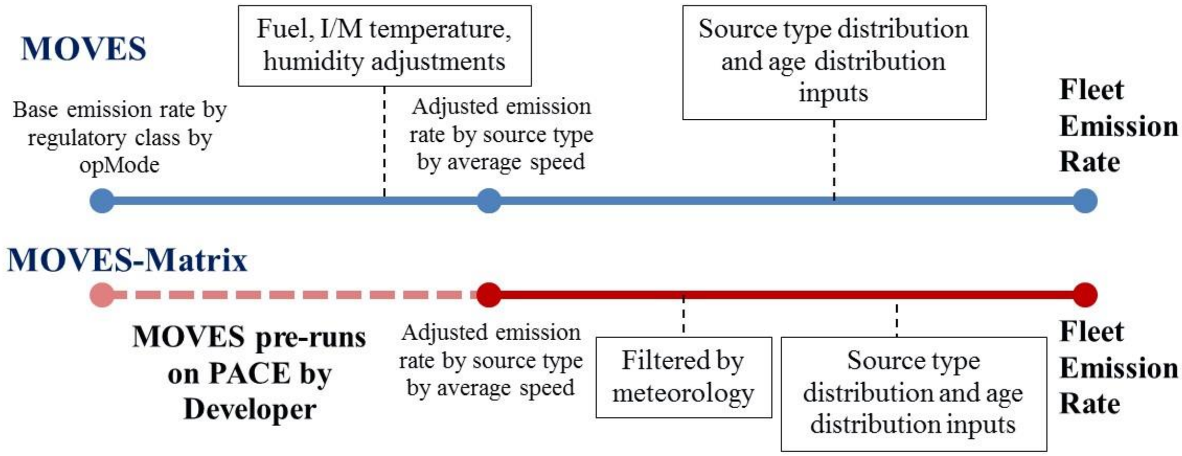


Figure 6. MOVES vs. MOVES-Matrix Working Mechanism

Four design characteristics contribute to the accuracy and fast processing speed of MOVES-Matrix more efficiently:

- MOVES-Matrix emission rates are employed directly from MOVES runs performed by the research team. There are no code modifications, no correction factors, and no approximations involved, which ensure that the emission results obtained from MOVES-Matrix are exactly the same as those generated by the MOVES model directly.
- MOVES-Matrix allows users to assess impacts of changes in on-road operating conditions and on-road fleet composition. Rather that running MOVES again, MOVES-Matrix employs emission rates that have already been adjusted by fuel, meteorology and I/M strategy. No further MOVES calculations are needed. The matrix structure also facilitates sensitivity analysis of MOVES algorithms without having to run MOVES again.
- In MOVES-Matrix, the emission rates database is pre-organized by calendar year, fuel specification, I/M program, temperature, and humidity. Hence, the emission rate sub-matrix is ready to be applied to specific scenarios of interest. This significantly increases the speed of emission rate generation processes.
- MOVES-Matrix is open source and collaborative. Python, Java, Perl, or any other scripting language can be used to link MOVES-Matrix emission rates with travel demand models, traffic simulation, monitored data, and dispersion models.

MOVES-Matrix Performance Test

On-road Emissions Verification

To demonstrate the effectiveness and efficiency of on-road MOVES-Matrix, the researchers developed a set of comparative test runs to compare the performance of MOVES-Matrix with the MOVES batch mode for emission rate values and run speeds. Table 6 below listed the iteration variables and increments for the test runs.

Table 6. The Input Variables for Scenario Development

Variable	Values
Region	Atlanta, Buffalo, Washington D.C., Denver, and Seattle
Calendar year	2014, 2018, and 2022
Temperature and humidity	July for summer, and January for winter
Source type distribution	2014, 2018, and 2022
Vehicle age distribution	2014, 2018, and 2022
Operating Condition	MOVES default driving cycle, user-specified driving cycles, and user-specified opMode distributions

For every one of the five regions: Atlanta, Buffalo, Washington D.C., Denver and Seattle, 18 scenarios are developed as combinations of calendar years, humidity and temperatures, source type distributions, vehicle age distributions, and operating conditions, as shown in Table 7. Therefore, in total, 18 (scenarios) ×5 (regions) = 90 scenarios are developed.

Table 7. The 18 Scenarios for Each Region

ID	Calendar Year	Month	Temperature (°F)	Humidity (%)	Age Distribution	Source Type Distribution	Operating Condition*
1	2014	Jul.	80	60	2014	2014	v
2	2014	Jul.	80	60	2014	2014	d
3	2014	Jul.	80	60	2014	2014	o
4	2018	Jul.	80	60	2018	2018	v
5	2018	Jul.	80	60	2018	2018	d
6	2018	Jul.	80	60	2018	2018	o
7	2022	Jul.	80	60	2022	2022	v
8	2022	Jul.	80	60	2022	2022	d
9	2022	Jul.	80	60	2022	2022	o
10	2014	Jan.	45	60	2014	2014	v
11	2014	Jan.	45	60	2014	2014	d
12	2014	Jan.	45	60	2014	2014	o
13	2018	Jan.	45	60	2018	2018	v
14	2018	Jan.	45	60	2018	2018	d
15	2018	Jan.	45	60	2018	2018	o
16	2022	Jan.	45	60	2022	2022	v

ID	Calendar Year	Month	Temperature (°F)	Humidity (%)	Age Distribution	Source Type Distribution	Operating Condition*
17	2022	Jan.	45	60	2022	2022	d
18	2022	Jan.	45	60	2022	2022	o

**: The operating conditions are represented by letters. The letter "v" stands for default MOVES driving cycle, "d" stands for user-specified driving cycle, and "o" stands for user-specified opMode distributions.*

Link Input

For each scenario, two different links are calculated, including a restricted highway link and an unrestricted highway link. The restricted highway link is to represent the uncongested traffic condition of freeway, while the unrestricted highway link is to represent the congested traffic condition of arterial. Table 8 provides the information for the links.

Table 8. The Input Link Information

Link ID	Road Type	Volume (veh/h)	Speed (mph)	Length (mile)
1	Restricted Highway	1200	55	10
2	Unrestricted Highway	600	20	5

Source Type Distribution and Model Year Distribution Input

The used source type distributions are link-specific, and three different sets of source type distributions are used for the three calendar years. All the 13 source types are used, with the distributions obtained from Atlanta Travel Demand Model operated by Atlanta Regional Commission. The source type distributions are shown in Table 9. National default vehicle age distributions are used for the calendar years of 2014, 2018, and 2022 (U.S. EPA, 2018).

Table 9. The Input Source Type Distributions for Calendar Years of 2014, 2018, and 2022

Link ID	Source Type ID	Source Type	2014	2018	2022
1	11	Motorcycle	2.89%	2.99%	3.09%
1	21	Passenger Car	45.39%	47.03%	48.66%
1	31	Passenger Truck	31.16%	32.25%	33.34%
1	32	Light Commercial Truck	7.83%	8.16%	8.49%
1	41	Intercity Bus	0.01%	0.01%	0.01%
1	42	Transit Bus	0.04%	0.05%	0.05%
1	43	School Bus	0.37%	0.41%	0.44%
1	51	Refuse Truck	0.29%	0.22%	0.14%
1	52	Single Unit Short-haul Truck	6.66%	4.93%	3.19%
1	53	Single Unit Long-haul Truck	0.28%	0.21%	0.13%
1	54	Motor Home	1.27%	0.94%	0.61%
1	61	Combination Short-haul Truck	1.78%	1.31%	0.85%
1	62	Combination Long-haul Truck	2.04%	1.51%	0.99%
2	11	Motorcycle	3.93%	3.92%	3.91%
2	21	Passenger Car	45.59%	45.47%	45.35%
2	31	Passenger Truck	36.23%	36.11%	35.98%

Link ID	Source Type ID	Source Type	2014	2018	2022
2	32	Light Commercial Truck	9.05%	9.07%	9.09%
2	41	Intercity Bus	0.01%	0.01%	0.01%
2	42	Transit Bus	0.03%	0.03%	0.03%
2	43	School Bus	0.28%	0.29%	0.30%
2	51	Refuse Truck	0.08%	0.09%	0.09%
2	52	Single Unit Short-haul Truck	2.89%	3.02%	3.15%
2	53	Single Unit Long-haul Truck	0.12%	0.13%	0.13%
2	54	Motor Home	0.73%	0.76%	0.80%
2	61	Combination Short-haul Truck	0.53%	0.53%	0.54%
2	62	Combination Long-haul Truck	0.53%	0.58%	0.63%

Operating Conditions

All three different operating conditions are examined in the verification process: average speed and facility type, OpMode distribution, and second-by-second driving traces. For user-specified driving cycles, two different driving cycles are used to represent the two links. The driving cycle of the restricted highway link represents the uncongested traffic operations, with an average speed of 55 mph, while the driving cycle of the unrestricted highway link represents the congested traffic operations, with an average speed of 20 mph. The time sequences of the speeds of the two driving cycles are as shown in Figure 7.

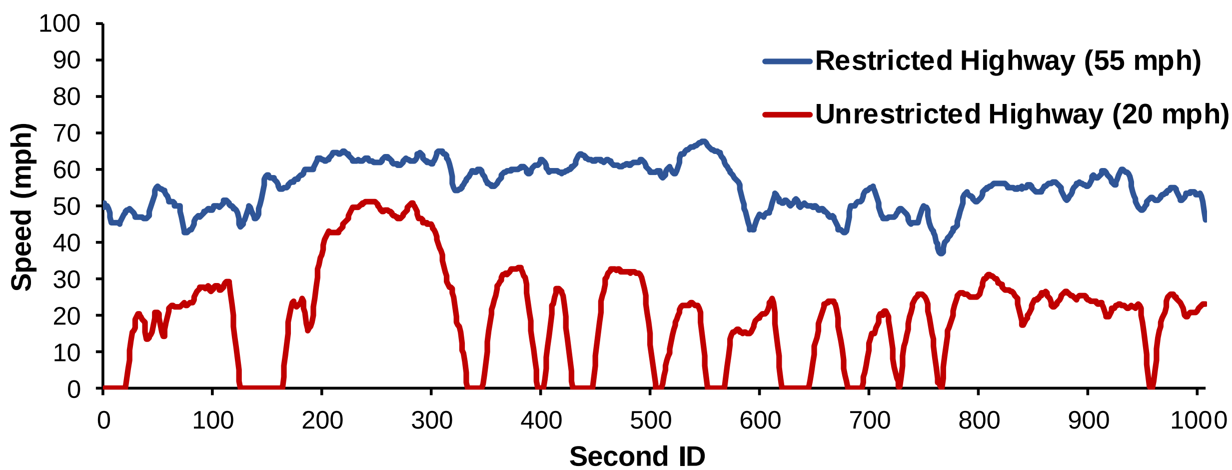


Figure 7. Speed vs. Time Traces of User-specified Driving Cycles

For user-specified opMode distributions, two sets of opMode distributions are used to represent the two links, as shown in Figure 8.

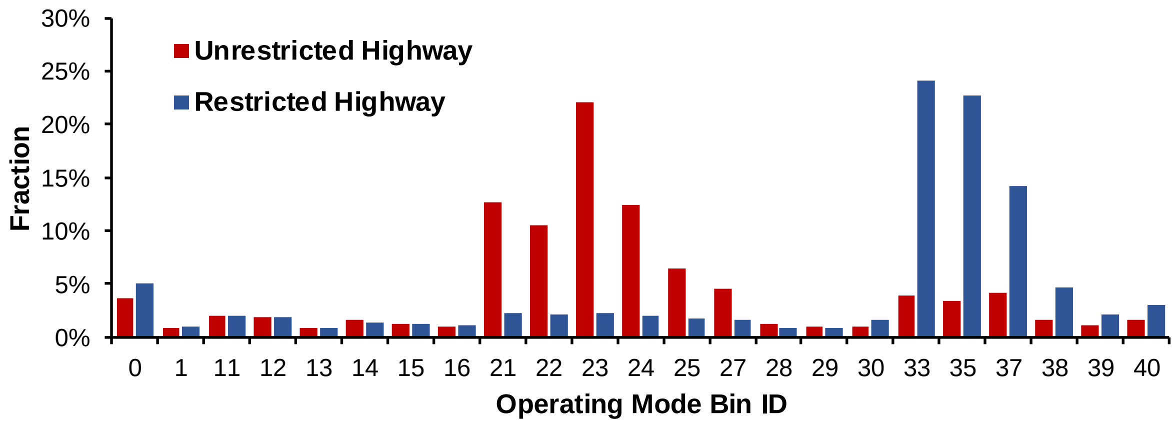


Figure 8. Operating Mode Bin Histograms for User-specified opMode Distributions

MOVES and MOVES-Matrix Launch

MOVES is run in batch mode to obtain the results for the 90 scenarios. Setting up MOVES for batch mode runs starts with the establishment of the input databases in MySQL, by calling the command line Java processes. Then, MOVES runs are also launched by command line Java processes to generate outputs. The time consumed to establish the databases and run the tasks are recorded by batch commands. The results of the MOVES runs are exported by SQL commands to be compared with those of MOVES-Matrix.

MOVES-Matrix and MOVES share the same input files for meteorology, fleet composition, link information, and driving cycles. The opMode distribution file is also prepared for MOVES-Matrix to represent the same user-specified opMode distributions with MOVES. The 90 scenarios are setup in MOVES-Matrix batch mode. The results are exported as csv files after running the Python scripts. The running time of the Python scripts are recorded so that they can be compared with MOVES. The team has scripted the setup of MOVES and MOVES-Matrix to employ automatic verification procedures.

Results Comparison

For all 90 scenarios, the outputs for MOVES and for MOVES-Matrix are exported. The results for energy consumption and the emissions of the pollutants (CO, CO_2, NO_x, THC, VOC, $PM_{2.5}$ and PM_{10}) are compared to obtain the relative differences. The maximum relative difference across all 90 scenarios is 0.00046%, which for all practical purposes can be ignored. The relative difference results from the different precision of the outputs. MOVES only keeps six significant digits for the final outputs, while MOVES-Matrix keeps all output digits. A comparison of the modeled results clearly demonstrates that MOVES-Matrix and MOVES generates the exact same results.

MOVES takes 6325.7 seconds (approximately 1 hour and 45 minutes) to establish the databases and finish all the runs, while MOVES-Matrix takes only 32.2 seconds. There is a 200 times improvement of performance to use MOVES-Matrix. That is, MOVES-Matrix can finish the emissions computation tasks 200 times faster than using MOVES in batch mode. The fast calculation speed of MOVES-Matrix provides a user platform that can be employed with newer and bigger datasets, such as INRIX GPS data, traffic simulations, smartphone data, etc., and supports dynamic, real-time emission modeling.

Off-Network Emissions Verification – Atlanta Case Study

The Atlanta, GA metropolitan region serves as a case study for emissions from all MOVES processes. The team used the Atlanta Regional Commission's Travel Demand Model (ARC, 2012) to populate most of the model inputs. The emission results were analyzed for speciation profiles, temporal distributions, and spatial distributions. Finally, a verification of MOVES-Matrix was performed to demonstrate that the emission results generated from MOVES-Matrix were exactly the same as using MOVES directly.

The ARC's TDM estimates regional vehicle activity using their activity-based model (ABM) for the 20-county non-attainment area (ARC, 2012). The model forecasts regional travel activity at 30-minute resolution, and predicts trips and link-level network travel. The model covers 5,981 transportation analysis zones (TAZs) and 74,500 roadway network links in the 20-county metropolitan area, with detailed land use and road characteristic information. In this study, the vehicle activities from ARC's TDM model were applied in estimating spatial and temporal emission distributions on the network using a linkage to MOVES-Matrix. The preparation of vehicle population, vehicle activity, and emission rate inputs will be introduced in the following sections.

Vehicle Population Input

Regional vehicle registration data provide the vehicle population by source type and model year. The MOVES default relative mileage accumulation rate (RMAR) was used to project vehicle population composition into VMT fraction by source type and model year. The vehicle distribution was simplified to be uniform across the entire region. However, in areas where high-resolution fleet composition data may be available, any number of sub-regional or local fleets could be applied to freeways and arterials, zones, or even individual links. The MOVES-Matrix approach provides flexibility to implement any fleet composition tracked by the user.

Vehicle Activity Input

The ARC's TDM outputs were post-processed to obtain the vehicle activity inputs for emission modeling. If the data or fraction was not available through ARC's output, the MOVES default data or fraction was applied as a surrogate.

- **Link data**: Link-level VMT and average speed were readily available from TDM output, and directly applied in the modeling process.
- **Average grade**: Average grade was assumed to be zero (0) for all the links. However, new modeling tools are now available to integrate road grade directly into MOVES-matrix operations (Liu, et al., 2018).

- **VSP/STP bin composition**: The MOVES default VSP/STP bin distribution was used.
- **Number of engine starts**: Total number of engine starts was trip production by TAZ in TDM model; derived by processing the trip output file.
- **Soak time distribution**: The MOVES default soak time distribution was used.
- **Hoteling hours**: Hoteling hours were assumed to be a set portion of total heavy-duty truck VHT using the MOVES default hoteling hour fraction.
- **Hoteling process hour fraction**: The MOVES default fraction was used.
- **Source hours operating**: SHO was the same as link-level VHT derived from VMT and average speed.
- **Source hours parked**: SHP was derived based on number of vehicles parked by TAZ, calculated as total vehicle population minus vehicles in operation.

The regional default fuel and I/M program were used to prepare MOVES-Matrix. The matrices were prepared for all 13 emissions processes. Based on these modeling runs, the overall emissions composition and the estimated temporal and spatial distributions of HC and $PM_{2.5}$ are presented below. The number of MOVES runs needed for developing MOVES-Matrix for Atlanta, with 21 calendar years × 3 fuel months × 111 temperature bins (0-110 F with 1F interval) × 21 humidity bins (0-100% with 5% interval) is 1,909,089. With number of runs for each process listed below:

- Running exhaust: 146,853
- Start exhaust: 1,174,824
- Evaporative emissions: 293,706
- Hoteling emissions: 293,706
- Other emissions can be added to current runs, no additional runs needed

Currently, the research team has access to 202 computing nodes with 8,200 cores, which can run one scenario per one week. In this study, MOVES-Matrix was used for a typical summer weekday in 2017.

Emissions Verification

To verify off-network emission modeling integration, results from MOVES-Matrix were compared to results using MOVES 2014a directly. The verification was conducted for a large subset of transportation network links and hours. For the on-network portion of emissions (including process IDs 1, 9, 10, 15, part of 11, 13, 18, 19), 200 links were randomly selected from the network during for first hour verification. The comparison between MOVES and

MOVES-Matrix results are shown in

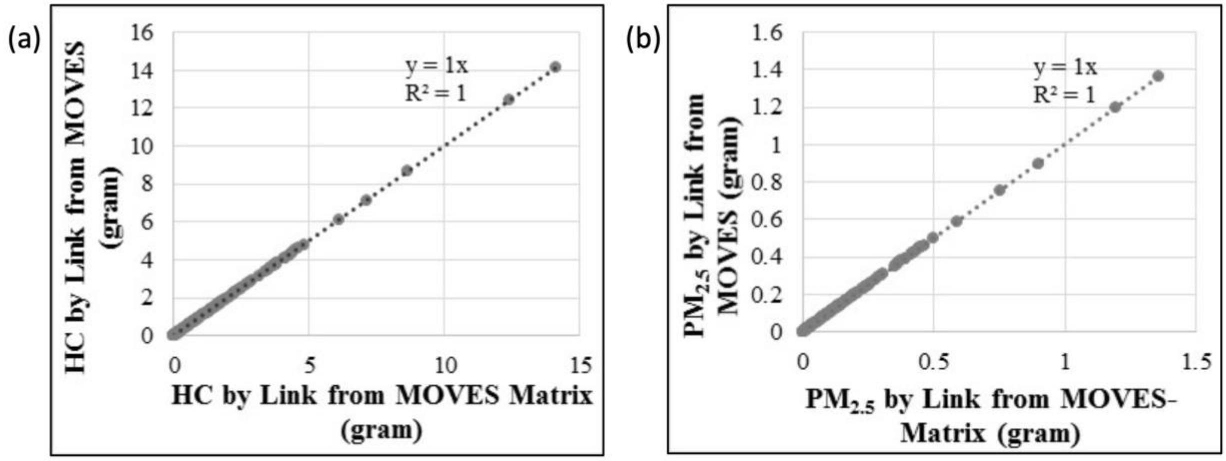


Figure 9. The emissions from network resources estimated by MOVES-Matrix for evaporation, brake wear, tire wear, and crankcase emissions from running processes are exactly the same as the MOVES results. For the off-network portion of emissions (including process ID 2, 16, 17, 90, 91, part of 11, 13, 18, 19), the first hour of data was used for verification. The comparison between MOVES and MOVES-Matrix results are shown in

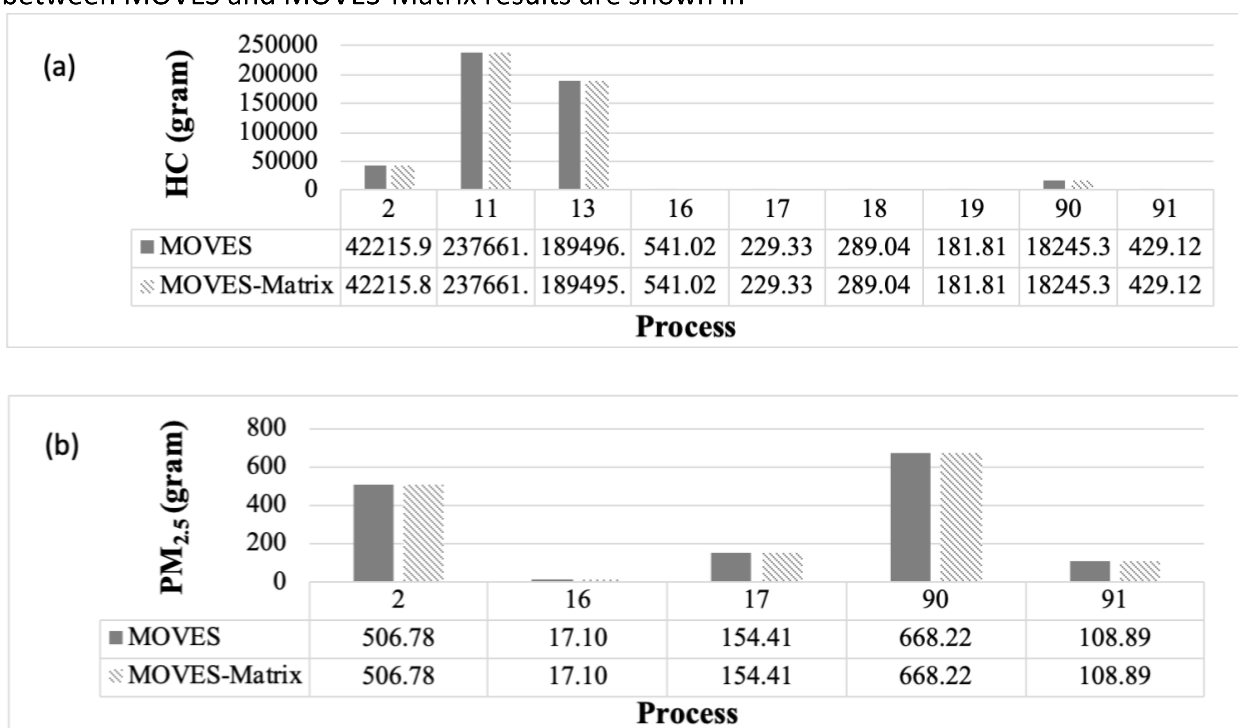


Figure 10.

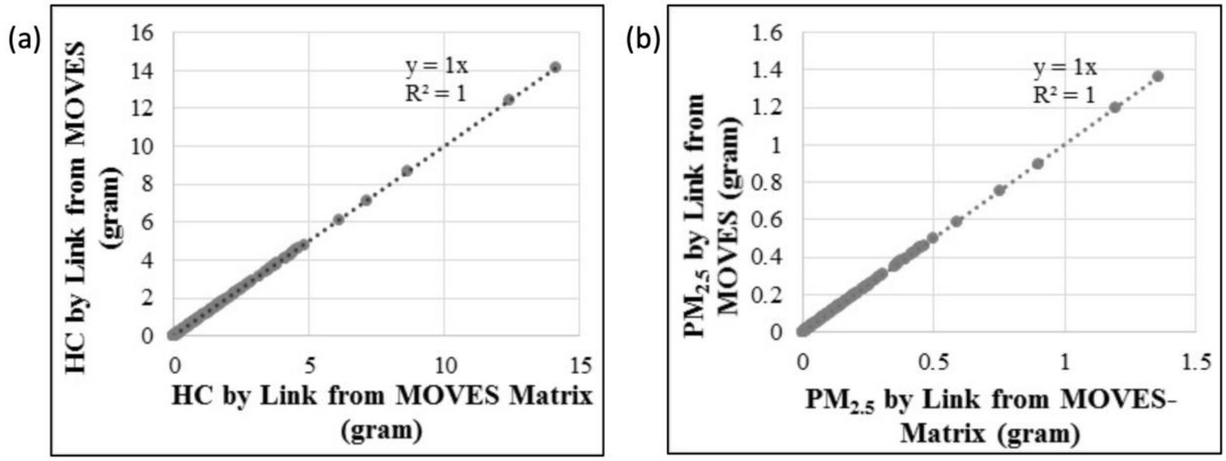
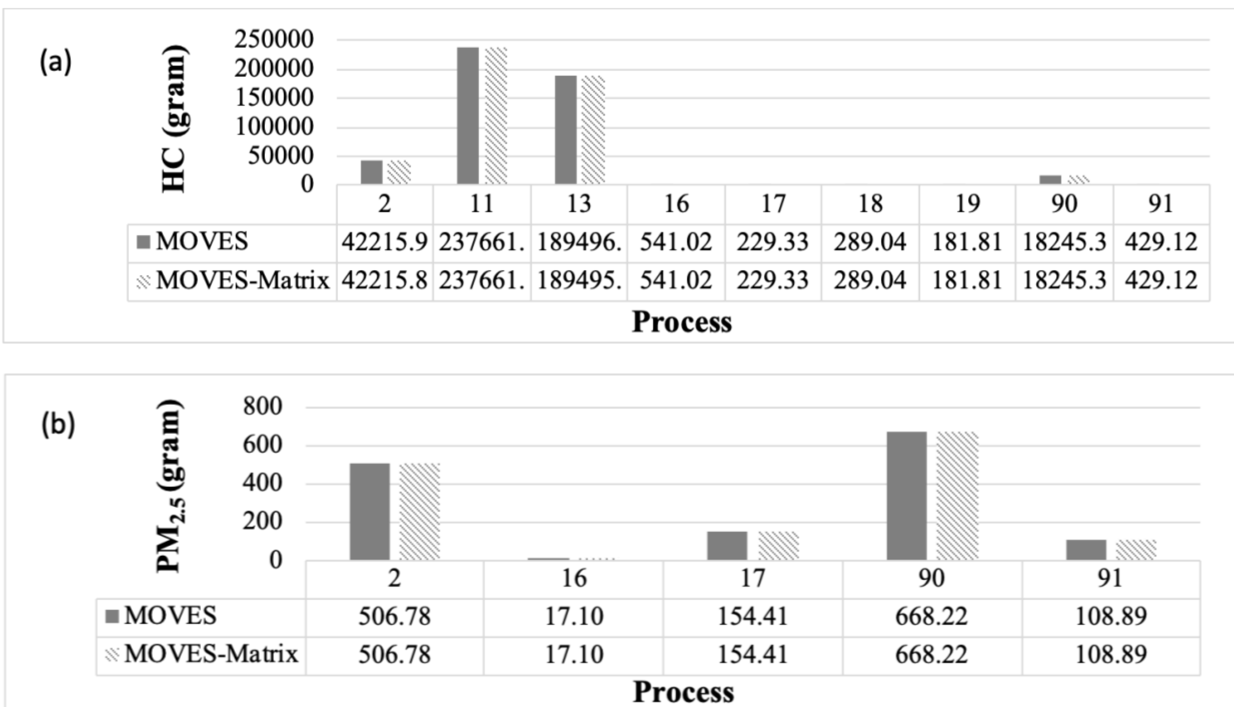


Figure 9. Comparison between MOVES and MOVES-Matrix results for (a) HC and (b) $PM_{2.5}$ for an On-network Subset



(a)	2	11	13	16	17	18	19	90	91
MOVES	42215.9	237661.	189496.	541.02	229.33	289.04	181.81	18245.3	429.12
MOVES-Matrix	42215.8	237661.	189495.	541.02	229.33	289.04	181.81	18245.3	429.12

(b)	2	16	17	90	91
MOVES	506.78	17.10	154.41	668.22	108.89
MOVES-Matrix	506.78	17.10	154.41	668.22	108.89

Figure 10. Comparison between MOVES and MOVES-Matrix Results for (a) HC and (b) $PM_{2.5}$ for Off-network Sources

As expected, because the emissions in the matrices were derived from individual MOVES runs, the emissions from MOVES runs and MOVES-Matrix runs are the same. Hence, the MOVES-Matrix process generates exactly the same regional emission inventory estimations as when using MOVES directly. The team plans to implement additional verification efforts on the PACE distributed computing server farm to verify MOVES-Matrix for all links, all hours, and all pollutants.

Other Applications

The research team has implemented MOVES-Matrix in a variety of emission modeling research efforts, including the assessment of: emissions impacts of an HOV-to-HOT lane conversion (Xu, et al., 2017a), transit eco-driving (Xu, et al., 2017b), benefits of transit deadheading reduction (Li, et al., 2016), individual vehicle emission modeling (Guensler, et al., 2017), MOVES sensitivity analysis (Liu, et al., 2015), near-road dispersion modeling (Liu et al., 2017), connections with travel demand model (Xu, et al., 2016a), and connections with Vissim® microscopic simulations (Xu, et al., 2016b). For each assessment, the research results demonstrated that the results from MOVES-Matrix were the same as using MOVES directly. Figure 11 shows four examples of MOVES-Matrix applications in connection with Atlanta Travel Demand Model (TDM), microscopic traffic simulation modeling (Vissim®), individual vehicle emission modeling, and dispersion modeling with AERMOD.

For regional-scale scenarios involving large numbers of roadway links (74,500 links in Atlanta), the research team recommends that users manage fleet composition by road type and traffic analysis zones (Xu, et al., 2016a). Link speeds and volumes can be obtained from travel demand models, and/or dynamic traffic assignment. MOVES-Matrix supports batch mode processing and enables multi-task runs, just as MOVES does. Each task specifies a single calendar year, meteorology, fuel supply, and fleet model year distribution. At the link level, links that have the same fleet composition can be grouped in the same task, allowing users to obtain emission rate for all speeds and for fleet compositions for multiple calendar years and meteorology scenarios. These emission rates can then be mapped back to specific links based on traffic analysis zone, and link speed, and multiplied by link volumes to obtain fuel consumption and mass emissions for each link. The research team is currently implementing a MOVES-Matrix connection with the Atlanta Regional Commission's travel demand model, which will serve as a guide for MOVES-Matrix application in regional scale.

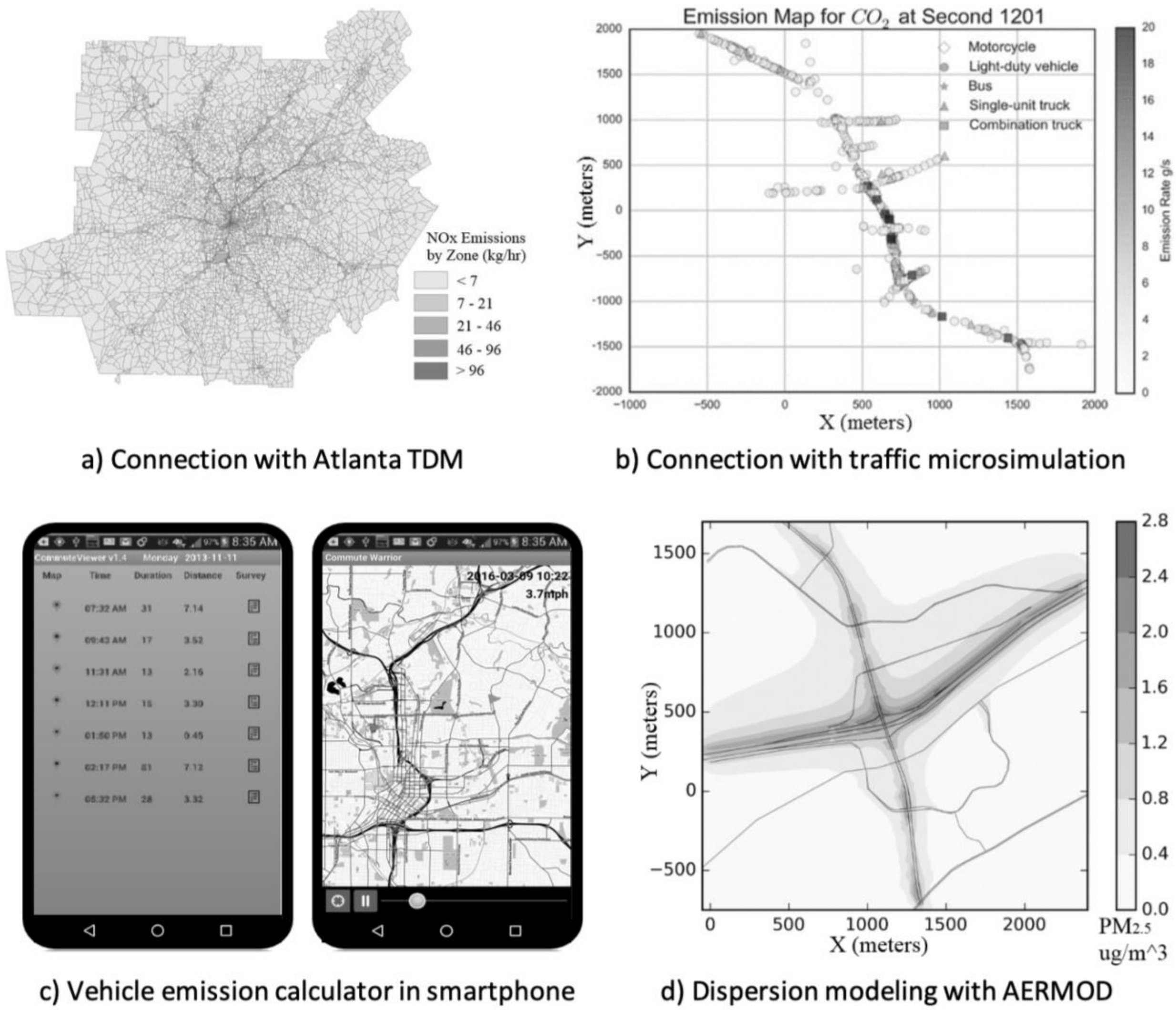


Figure 11. Examples of MOVES-Matrix Applications

For project-level emission analysis, users can link MOVES-Matrix emission rates with traffic simulation model outputs. The simulated vehicle driving traces (second-by-second speed vs. time) for individual vehicles yield second-by-second on-road operating conditions (which translate to speed and VSP bin) that can be linked with operating mode emission rates in the MOVES-Matrix. For example, the research team linked MOVES-Matrix with Vissim® microsimulation software and predicted emissions as a function of Vissim®-simulated second-by-second vehicle trajectories (Xu, et al., 2016b). To accomplish the linkage, a local fleet composition (fleet composition for 13 source types and their on-road model year distributions) is developed for use in the Vissim® simulation and in emissions modeling. The Vissim® model is coded and calibrated to represent on-road traffic conditions. A Component Object Model (COM) interface is applied to collect network information and second-by-second speed profiles for the simulated vehicles on the network. Second-by-second vehicle traces data are post-processed to obtain second-by-second operation mode bins. Finally, the applicable MOVES-Matrix operating mode bin emission rates (by county, fuel formulation, I/M strategy, and meteorology) are pulled from the MOVES-Matrix emission rate table. Emission results are calculated by matching the operation conditions for each vehicle-second in the simulation model with applicable MOVES-Matrix emission rates for the vehicle source type, model year, operating mode bin, and pollutant.

MOVES-Matrix also makes it easy to link monitored on-road operating conditions, such as observed driving traces collected by smartphone apps. The development of MOVES-Matrix has simplified the use of large scale of traffic activity data in emission modeling, as is currently being demonstrated in a Department of Energy ARPA-E project (DOE, 2015; Guensler, et al., 2017) in Atlanta, making real-time MOVES energy consumption and emissions modeling feasible.

The research team has also applied MOVES-Matrix to individual vehicle modeling to predict second-by-second fuel consumption and emissions, and incorporated the emissions modeling approach into the *Commute Warrior*® Android® app, to predict real-time fuel consumption and emissions given second-by-second speed data concurrently collected by the smartphone GPS. When a vehicle make, model, and model year is chosen by the user, the vehicle source type by MOVES is identified from a lookup table and the applicable VSP vehicle parameters are identified for VSP calculations. The subset of corresponding emission rates for the vehicle source type (associated with vehicle make and model), fuel type, model year, is extracted from MOVES-Matrix and downloaded to the app for all operating mode bins, temperatures, and humidity combinations likely to be experienced by the user. When a vehicle speed trace is recorded in the *Commute Warrior*® app, second-by-second VSP is calculated as a function of source-type dynamics parameters (i.e., rolling resistance, rotating resistance, and aerodynamic dragging coefficients), speed, acceleration, and road grade. The operating mode bin for each second (given the VSP and speed values) and the applicable second-by-second fuel use and emission rates are assigned for the operating mode bin, temperature, and humidity specified.

The system also allows researchers to directly assess strategies designed to change individual travel behavior to increase efficiency, and evaluate the potential impacts of major transportation design and operation strategies. Energy and emission analysis tools coupled with simulation supports near-real-time predictions, and feedback to travelers to support more efficient decision-making. Users can track fuel economy, carbon footprint, and emissions, and playback vehicle speed and fuel consumption rates along trip routes, and generate trip summary reports by time period or trip purpose.

The team has also successfully linked MOVES-Matrix with dispersion models for transportation conformity and hot-spot analyses. The MOVES-Matrix connection with the AERMOD and CALINE4 models are automated using Python scripts (Liu et al., 2017). At the beginning of each model run, the system extracts a sub-matrix containing emission rate and energy consumption rates applicable to the scenario of interest. This extraction from MOVES-Matrix is based on the calendar year and month of the analysis, and the temperature and humidity range of the analysis. Hourly emission rate data can be calculated through MOVES-Matrix based on hourly traffic volume, on-road operating speeds and meteorology, and can be aggregated to any applicable time-scale for specific National Ambient Air Quality Standards (NAAQS) (U.S. EPA, 2016c). The fleet average emission rate and meteorology data then serves as the emission rate input for CALINE4 and AERMOD modeling. Static input parameters can be prepared in advance, including link geometry, geographic data, and receptor coordinates and normally do not change within any single analysis. Because the MOVES emission rates outputs are contained in MOVES-Matrix, and no approximations or corrections are employed, the emission results from the MOVES-Matrix, and the modeled air pollutant concentration are exactly the same as the traditional applications of MOVES model and dispersion models recommended by U.S. EPA (U.S. EPA, 2013), with 200 times faster speed. This means that the MOVES-Matrix model obtains the same results as the standard regulatory dispersion analysis with significant efficiency.

MOVES-Matrix Outreach and Availability

Over the past year, the Georgia Tech NCST team has continued to generate billions of MOVES emission rates, and has provided MOVES-Matrix support for emission analysis to universities, research institutes, and government agencies. The team updated Vermont Matrix for Dr. Britt Holmen and Dr. Lisa Aultman-Hall at the University of Vermont for teaching and emission analysis. The team prepared a Denver, CO region MOVES-Matrix for Dr. Paul Chinowsky in CEE and the Department of Mechanical Engineering at the University of Colorado at Boulder. The team prepared MOVES-Matrix for use in Seattle, WA, Buffalo, NY, and the States of Iowa and Virginia for Dr. Shauna Hallmark and Georges Bou-Saab at Iowa State University. The Ph.D. Dissertation research and emission analysis in Iowa will employ vehicle activity data from the SHRPII naturalistic driving study. The team has also prepared Atlanta MOVES-Matrix for Dr. Roger Wayson at AECOM, and David Kall at FHWA, for MOVES sensitivity analysis.

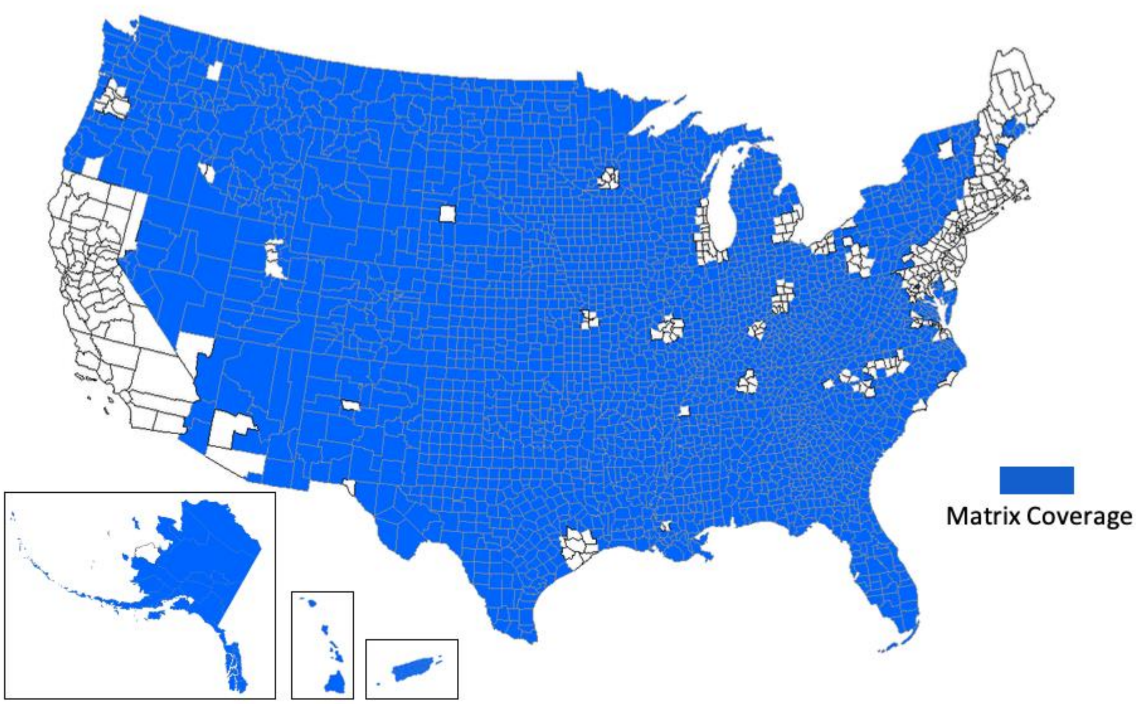


Figure 12 illustrates the regions for which MOVES-Matrix outputs have been prepared to date (California uses a different modeling tool). Texas is now complete. The research team met with USEPA staff in Ann Arbor in May 2018 and provided a complete overview of NCST research findings.

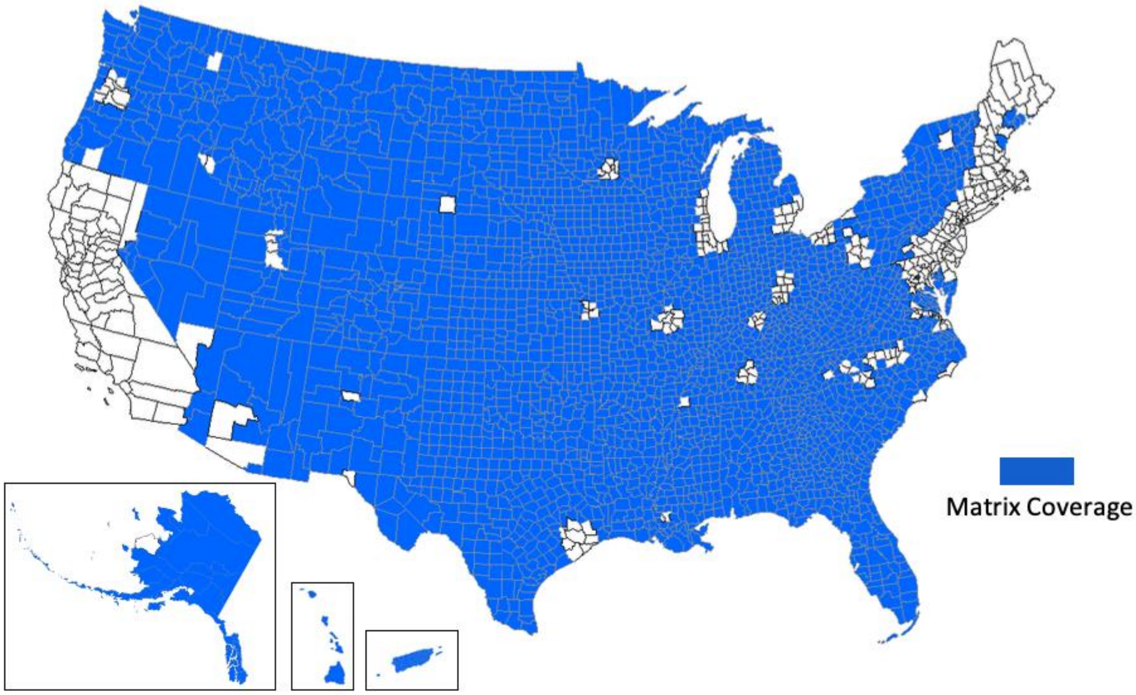


Figure 12. Current MOVES-Matrix Coverage Area

Conclusions

This study introduced the MOVES-Matrix modeling approach; a high-performance emission modeling system that uses big data of emission rates pre-generated by MOVES, rather than performing MOVES modeling runs on-the-fly for transportation scenarios of interest. Each MOVES-Matrix array for a modeling region is constructed from thousands of MOVES runs. The scenario runs demonstrate that MOVES-Matrix can finish the emissions computation tasks over 200 times faster than using the MOVES batch mode and the results are exactly the same. In addition to its high-performance in calculation speed, we believe there are also other benefits below in applying MOVES-Matrix:

- MOVES emission rates are employed directly in MOVES-Matrix (there are no code modifications, no use of correction factors, nor any approximations employed).
- In project-level emissions analysis, users typically assume a single temperature, humidity, and fuel, and estimate the emissions impact of the changes in vehicle operations and fleet composition. Hence, the data are organized into sub-matrices that fit the users' work scheme, allowing users to conveniently and quickly assess impacts of changes in on-road operating conditions and fleet composition.
- MOVES-Matrix emission rates can be operationalized in Java, Python, Perl, or any similar scripting program to link MOVES emission rates with travel demand models, simulation models, monitored vehicle data, and dispersion modeling.
- Because the emission database of MOVES-Matrix is composed of MOVES outputs, and the model achieves the exact same results as the MOVES, the research team believes that the model is ready for regulatory review and approval.
- MOVES-Matrix is an open source system that anyone can use.
- The research team has also recently developed an online version of MOVES-Matrix that will allow users to implement online emission analysis (and sensitivity analysis) online without ever having to run MOVES.

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