Regional Emission Analysis using Travel Demand Models and MOVES-Matrix

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ABSTRACT

Travel demand models (TDM) are developed by Metropolitan Planning Organizations (MPOs) for analyzing regional travel patterns but are often used to prepare activity inputs for use with the U.S. Environmental Protection Agency's (EPA) MOtor Vehicle Emission Simulator (MOVES) emissions model for air quality conformity analysis. This latter application requires modelers to either prepare multiple MOVES runs for various scenarios, or to develop their own pre- and post-processors for emission modeling. Both approaches involve a cumbersome and time consuming process.

To reduce these demands on modelers time, a tool that automates both the processing of TDM outputs and produces the same results as using MOVES is highly desirable. In this study, tool was developed to automatically link TDM outputs with MOVES-Matrix to provide emissions estimates at both the link and overall inventory level. MOVES-Matrix is an emissions modeling tool that operates by iteratively running MOVES across all possible combinations of vehicle source-type, fuel, meteorology, operating conditions, and other parameters to create a multi-dimensional emission rate lookup matrix (*1*) to produce must faster outputs at runtime.

The Atlanta Regional Commission (ARC) TDM was used for this case study within metropolitan Atlanta area to demonstrate and validate the automated tool (*2*). For this purpose, conventional inventory-level emission modeling was first conducted using MOVES and these emission results were compared with results from the automated tool. Link-level emissions were similarly analyzed. The results indicate that the automated tool produces emission results very close to those using MOVES, while significantly reduce the running time. The tool can thus be beneficial to conformity analysis, as well as other environment applications, such as hot spot analysis and dispersion modeling.

Keywords: Travel Demand Model, MOVES-Matrix, Emission Inventory, Link-level emission

1. INTRODUCTION

Transportation conformity is required by the Clean Air Act section 176(c) to ensure that federal funding and approval are given to highway and transit projects that are consistent with ("conform to") the air quality goals established by a state air quality implementation plan (SIP). Transportation activities may not cause new air quality violations, worsen existing violations, or delay timely attainment of the national ambient air quality standards *(3)*. These regulations establish the link between air quality planning and transportation planning and each Metropolitan Planning Organization (MPO) must make a positive conformity determination for regional transportation plans (RTPs) and transportation Improvement Programs (TIPs). In this case, it is necessary to develop an approach for environmental assessment of those transportation plans.

The U.S. Environmental Protection Agency (U.S. EPA) developed MOtor Vehicle Emission Simulator (MOVES) to estimate emissions from on-road vehicles in the United States. The MOVES model is the approved regulatory emission model that must be applied to all recent transportation conformity analysis (unless a project-level conformity screening tool has been approved for use in the region). A recent survey on nearly 80 transportation and air quality agencies indicated that more than half of agencies already applied MOVES mainly for SIP or conformity study, and most of the other agencies were switching to or planning to applying MOVES *(4)*. MOVES serves three levels of emission analysis, including the national-level, regional-level and project-level. In regional-level analysis, MOVES works with travel activity information provided by travel demand model and other applicable data sources. Among the surveyed agencies, about half of them used TDM output and Highway Performance Monitoring System (HPMS) data to prepare regional travel activity data for MOVES, while most other agencies implemented either one of the two resources *(4)*.

However, the MOVES interface is complex and requires various input files to execute the program, which makes the emission analysis a cumbersome and time-consuming process. Establishing the linkage between TDM and MOVES is a resource-intensive process, which often requires that agencies hire outside consultants to script *ad hoc* software to translate TDM outputs into MOVES inputs, often known as air quality pre- or post-processors. For each transportation scenario that is assessed, a new set of MOVES inputs usually needs to be prepared, which makes MOVES difficult to apply in assessing large-scale transportation networks that experience dynamic changes in on-road fleet composition and operating conditions. Also, existing pre- or post-processors are normally designed for county (regional) level analysis and ultimately lead to regional inventory emissions instead of link-level emissions, limiting the capability to further apply emissions results to hot spot assessment or environmental justice analysis. For example, some MPOs post-process link-level TDM outputs into MOVES regional-level inputs, and the results obtained from MOVES are still emission inventories (*5, 6*). Nevertheless, link-level emissions for the whole region are possible to generate in MOVES project-level model. For example, Oregon and Texas DOTs have used MOVES project-level models to either generate emissions by link, or to apply customized duty-cycles (*7, 8*). Those studies do, however, require significant additional efforts in data preparation.

In this paper, we present a new tool establishing linkage between a multidimensional array of pre-run MOVES emissions rates, referred to as MOVES-Matrix, and an activity-based TDM. Two applications have been developed – an inventory-level module for regional conformity analysis, and a link-level module for hot spot assessment and environmental justice analysis. In the link-level module, the linkage can automatically process the link-level TDM output and supplementary data source through a Python program, and match the link-level travel activity with emission factors from MOVES-Matrix. The link-level emission outputs can be plotted for each hour of operation, and represent the spatial distribution of different pollutants. Also, for agencies who already developed MOVES inputs or do not have TDM link-level outputs for certain counties, an inventory-level module was developed to establish a linkage to process MOVES inventory inputs for emission inventories with applicable emission factors from MOVES-Matrix. This new tool allows for rapid assessment of transportation scenarios and related emissions impacts on a link-by-link basis, enabling further linkage to dispersion models and spatial analysis.

2. METHODOLOGY

There are basically two approaches to apply MOVES for a conformity study, which include the inventory approach and emission rate approach *(9)*. By adopting the inventory approach, mass emissions are estimated using total vehicle mile traveled (VMT), a speed bin distribution and other supplemental input files. By adopting the emission rate approach, emissions rates for running emissions and engine starts, etc. are estimated independently. Using this approach, emissions estimates are derived by matching the travel activities with corresponding emission rates under specific speed, road type and vehicle composition conditions. Regardless of which approach applied, the same group of input files are required *(4)*:

- Fleet composition, including MOVES vehicle source type and model year distributions;
- Regional travel activities, including VMT distributions by HPMS vehicle type, month, day and hour adjustment factors, road type distributions, ramp fraction, daily vehicle starts and average speed distributions;

- Scenario inputs, including meteorology, inspection and maintenance (I/M) programs, and fuel.

By adopting the inventory approach, modelers can achieve rapid assessment of emission inventories by directly deploying MOVES software without developing any specific post processors. The regional activity inputs are often prepared by post-processing and aggregating the regional travel demand model outputs to obtain applicable vehicle miles traveled (VMT), volume, and distributions in MOVES input format (*5*, *10*). These results can show the mass emissions for the region and percentage of changes under different scenarios. However, this approach only yield emission inventory outputs, and the link-level emissions and spatial visualization are unavailable through this method. For analysis of different scenarios, separate input files need to be prepared and MOVES needs to be re-launched.

Adopting the emission rate approach can help address several limitations of using inventory approach, and provide modelers with great flexibility in model development at the cost of increasing complexity. Using this approach, users have to prepare many fewer MOVES runs, but each run requires more supporting data. This approach achieves a more detailed emission output, generally at the link or travel analysis zone (TAZ) level. This approach normally requires the user to initially estimate emission rates using MOVES under selected scenarios, then match the travel activity information (VMT by road type, speed bin, source type and model year) with applicable emission rates for that specific road type, speed bin, source type and model year (*11*). The link-level or TAZ-level emission output can be mapped to visualize the spatial distribution of pollutants, and further applied for air quality assessment. However, there are no free and standardized connections to MOVES to post-process emission rates into link-level or TAZ-level emissions, and developing such a connection requires a considerable understanding of MOVES modeling structure and regional activity features to avoid estimation errors.

In this study, an advanced emission modeling approach is described for regional emission analysis by using MOVES-Matrix. In MOVES-Matrix, MOVES 2014 is run 153,846 times, iterating across all combinations of vehicle source-type, fuel, environmental, ~~average speeds~~operating mode bins, and other parameters, and the modeled emission rate outputs are stored in a huge multi-dimensional array so that the emission rates can be used in other analyses without re-running MOVES (*1*). With proper scripting, users can extract MOVES emission rates from MOVES-Matrix and obtain the exact same emission results as MOVES. In the advanced emissions modeling approach, activity estimates are derived from the regional travel demand model and properly processed using the recommended modeling approaches provided by USEPA (*9*, *12*). This approach bypasses the time-consuming process for running MOVES emission rates by agencies, and the uniform format helps to simplify the assessment for both inventory model and emission rate models, while achieving the same results. The details of modeling approach are provided in following sections.

Methodology Overview

TDMs are typically developed by a metropolitan planning organization (MPO) to output hourly traffic volumes and applicable on-road operating conditions, generally through post processing the model results. Here we describe a modeling process, currently being implemented, for coupling a typical TDM output and MOVES-Matrix emission rates.

In this approach, a research boundary (time, location and duration) is designated first for running the TDM and MOVES-Matrix, and all the analysis are conducted within this domain. The methodology includes three preliminary steps, which include: 1) preparing regional inputs within TDM modeling range; 2) generating MOVES-Matrix under all possible regional conditions; 3) matching regional activity outputs either in link-level or inventory-level from TDM and applicable emission rates from MOVES-Matrix. The work flow is shown in diagram below. For this demonstration only on-road emissions are considered. Other emission necessary for conformity study, such as start and evaporative emissions will be analyzed through other on-going projects.

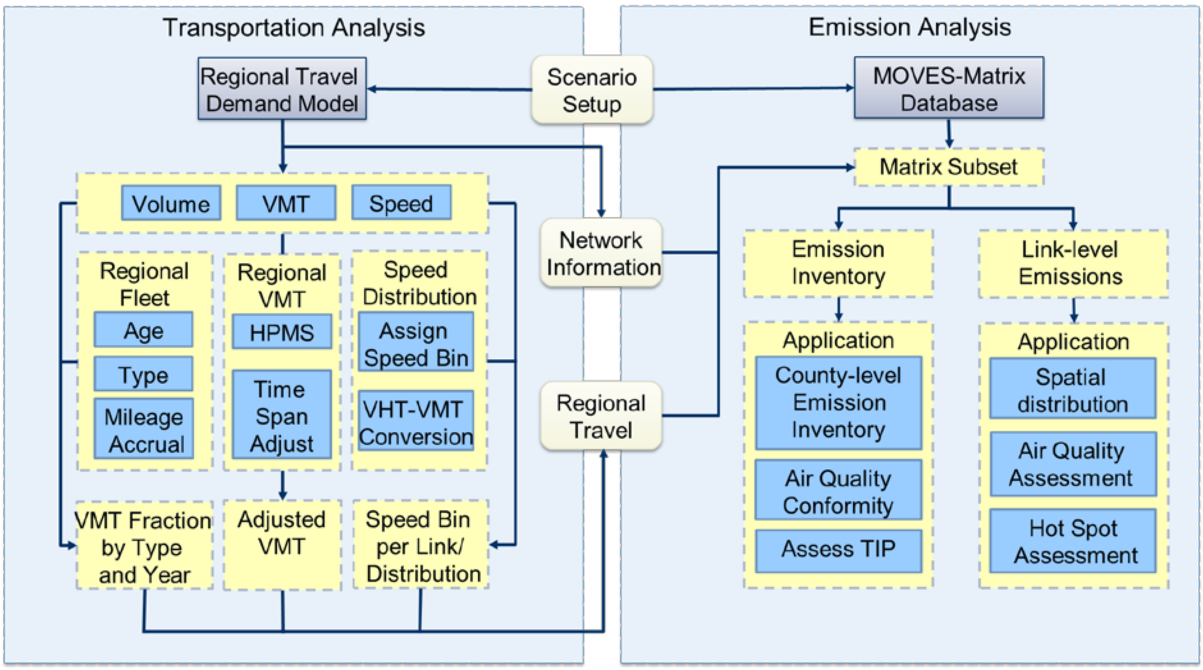


Figure 1. Work Flow of Proposed Method

Regional Model Inputs

As discussed above, three different inputs are required for a MOVES-based regional emission analysis, which include regional fleet composition, travel activities and other scenario inputs.

According to conformity study requirements, the input data should be prepared for a single investigated year, aggregated by hours and apply to all possible fuel-vehicle type combinations (*12*). For on-road emissions, the emission inventory is derived from the product of hourly VMT and corresponding emission rates for that specific road type, source type, model year and speed bin where the VMT is generated. The methodology of preparing input files under conformity study requirements is introduced in the following sections.

Local fleet composition

MOVES represents vehicle fleet features using 13 vehicle source type and 31 applicable model years (age 0~30 from investigated calendar year) (*13*). Agencies can prepare the vehicle composition with data from the MOVES default database, from state motor vehicle registration data (e.g., motorcycles, passenger cars, passenger trucks, light commercial trucks), or from other possible resources like local transit agencies, bus companies, and refuse haulers (*9*). It has been previously demonstrated that vehicle fleet composition can have significant impact on emission results, and these inputs should be well calibrated to represent local conditions *(14, 15).*

The design of MOVES only allows one vehicle source type composition per scenario, which means that users must run MOVES for each fleet condition to be considered. However, with the advantages provided by MOVES-Matrix, the vehicle composition can be prepared for individual zones, road types and TAZs. In this study, vehicle compositions by road type were prepared for the investigated counties. For each road type, the vehicle type distribution was represented by a three-dimensional matrix, with source type, model year, and fraction of population as the three axes. The road type was as a reference, and was be applied during post-processing of TDM outputs.

Furthermore, individual vehicles with different vehicle types and/or model years may have significantly different probability to be present in the roadway network due to vehicle owner’s preferences. In this case, the vehicle population distribution is usually not equivalent to the VMT fraction by vehicle types and model years, and mileage accrual of different types and model years should be considered to project the vehicle population distribution into VMT distribution for post-processing TDM output. In MOVES, VMT is represented by HPMS vehicle type. A relative mileage accumulation rate (RMAR) in combination with source type populations and age distributions is used to distribute the total annual miles driven by each Highway Performance Monitoring System (HPMS) vehicle type to each source type and age group, and this rate only varies by calendar year. The VMT data is assigned to different source types and model years by multiplying RMAR factors within a HMPS vehicle type *(12)*. The final VMT by source type and model year is calculated using the following equation:

$$VMT_{t,a} = \frac{f_{t,a}^{POP} \times RMAR_{t,a}}{\sum_{t \in C_h} f_{t,a}^{POP} \times RMAR_{t,a}} VMT_h \quad (1)$$

Where,

t – source type,

a – model year,

h – HMPS vehicle type,

C_h- the set of source types included in HMPS vehicle type h,

$RMAR_{t,a}$ - relative mileage accumulation rate for source type t and model year a,

$f_{t,a}^{POP}$-population fraction of source type t and model year a.

For link-level emission analysis, the VMT variables in equation above can be replaced by VMT fractions of all links to speed-up the emission estimation process, as an aggregated VMT fractions can be obtained for any VMT. The VMT fraction by source type and model year are used to obtain aggregated emission rates, and multiplied by hourly VMT for that specific link under specific average speed and road type.

Regional Travel Activity

The TDM outputs include three components for emission analysis, which include hourly VMT, road type and average speed. However, that information cannot be directly used as emission model inputs for two reasons: 1) the TDM is usually run for an annual average day or weekday condition, while high emission often occurs during one season and under high congestion level (e.g. the highest NO_X emissions often occur hot summer afternoons); 2) the VMT in most TDM outputs is populated by theoretical models, which may be different from actual on-road conditions. In this case, specific time-span and VMT adjustments should be conducted on VMT outputs. Average speed should also be processed to obtain the speed bin distribution to match the corresponding emission rates from MOVES. The roadway facility type from TDM outputs should also be assigned with a MOVES road type ID, and while applicable, the ramp in the modeled network should be differentiated ramps from the highway segments.

The TDM outputs are processed to prepare inventory-level and link-level emission model inputs respectively in MOVES format. For inventory model inputs, the road type, VMT and average speed are post-processed into vehicle type VMT, VMT fractions by road type, and vehicle hour traveled (VHT) fractions by speed bin. Time-span adjustment factors (month, day, hour) are stored in separate tables. Any required traffic adjustments, such as HPMS adjustment factors, will be applied through pre-processing of VMT outputs. For link-level model inputs, each link has a road type, VMT and average speed with adjustment factors applied directly to the individual links.

Other Scenario Inputs

Other input used for on-road emission estimation include fuel, I/M program, retrofit data and meteorological data. For meteorology data, a 24-hour temperature and humidity profiles are defined for each investigated month. Users can either choose MOVES defaults or prepare their own data for fuel, I/M and retrofit program for their scenarios according to the MOVES guidance provided by USEPA (*12*). The scenario inputs are used to generate MOVES-Matrix for the entire investigated region, and if certain inputs are not available, the MOVES default are applied instead.

MOVES-Matrix Setup

MOVES-Matrix can be prepared using the MOVES default scenario or EPA approved I/M and fuels across all possible meteorology inputs by taking the advantage of the powerful computational ability of a computer cluster at Georgia Tech (*1*). Because MOVES has been run for all possible iteration, the user can call for the applicable MOVES emission rate in MOVES-Matrix from other operations and obtain the exactly the same emission output that MOVES provides without ever having to launch MOVES again or transfer MOVES outputs into the analyses. As MOVES-Matrix is storing emission rates that have already been adjusted by MOVES for meteorology, fuel, I/M, etc., MOVES-Matrix actually does no modeling calculations at all. In this study, MOVES-Matrix was used in conjunction with the travel demand model to demonstrate that the modeling approach yields the same emissions as direct MOVES runs, but with significant time savings.

In this study, the emission rates by average speed bin were prepared using the following method. As the emission results are a function of internal MOVES default driving cycles. the research group first ran the MOVES 2014 in county-level, and obtained the MOVES default operating mode distributions generated from driving cycles embedded in MOVES model. The default operating mode distribution was specified by source type, road type, average speed bin, and model year group. Noticed that two groups of operating mode distribution would be generated in for county-level application, since MOVES actually deploys separate VSP/STP parameters for fleet older than 2013 and fleet newer than 2013 respectively. Given the specific scenario (i.e., calendar year, month, temperature, humidity), the emission rates by operating mode bin in MOVES-Matrix are extracted, and merged with pre- and post-2013 operating mode fractions separately to obtain the emission rate in time scale by each source type and average speed bin.

$$\text{Aggregated emission rate by source type, road type, and avg speed bin} = \sum_{two\ MY\ group\ (pre-\&\ post-2013)} \sum_{opmode\ bins} \text{emission rate} \times \text{op mode fraction} \quad (2)$$

With the emission rate for each speed bin, road type and source type, the emissions can be estimated by matching the regional activities with applicable emission rates. The average speed bins and road types (e.g. arterial vs. freeway) are exported as operational data from the TDM for emission inputs. The fleet composition can come from multiple sources as discussed above. To calculate emissions, users need only link their regional travel outputs, including facility type, link average speed, and fleet composition with the applicable Matrix emission rates as discussed in the next section. More details on setup, implementation and application of MOVES-Matrix can be found in Guensler et al., (*1*).

In this study, a ramp emission rates matrix was also prepared as they are handled differently from freeways or non-freeways. Instead of driving schedules, ramp operation is described in the current MOVES version as an operating mode distribution that reflects the power demand expected from ramp operation associated with each connected average highway speed (in total of 16 speed bins) for each of the source types. These operating mode distributions represent the fractions of time spent in each operating mode bin for each source type by average speed of the highway that the ramp is connected to. The ramp operating mode distribution can be found in the "RoadOpModeDistribution" table in the MOVES database.

The ramp operating mode distributions from the "RoadOpModeDistribution" table were used in running MOVES in project-level mode, and to generate ramp emission rates by source type, model year, and speed bin, with those operating mode distributions applied. The emission rates were scaled in unit of grams (or kJ for energy use) per operating hour per vehicle. In MOVES, similar to the description of highway activity, ramp activity is also described as total operating hours. The total emissions from ramp operations can be easily obtained by multiplying total operating hours with ramp emission rate in grams-per-hour, and weighted by all source types and model years.

Emission Analysis

The emission analysis for link-level and inventory-level inputs is different in structure because the inventory-level inputs strictly follows MOVES format, while the link-level input can be processed with more flexibility in order to reduce computation time. A diagram below shows the difference between the two types of analysis.

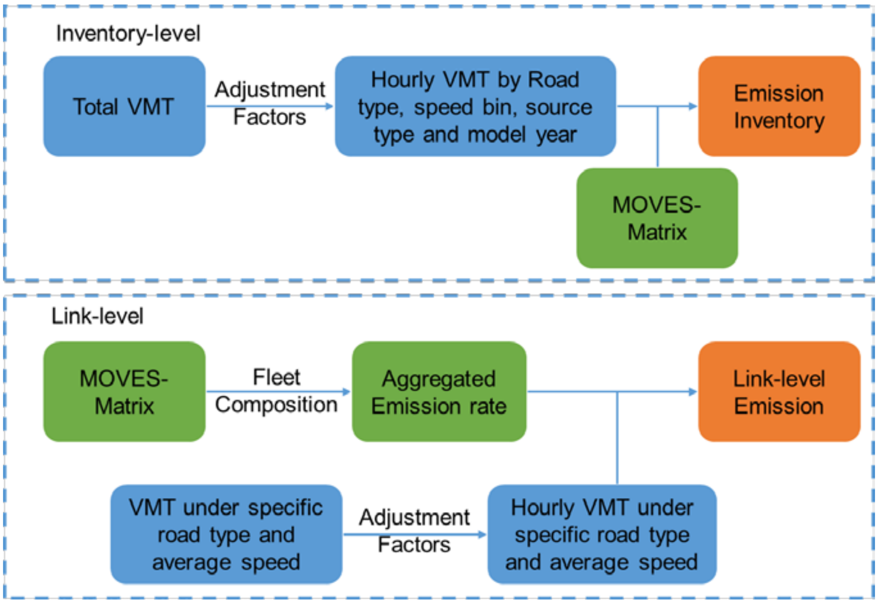


Figure 2. Work Flow of Proposed Method

Figure 2 shows that the inventory-level analysis first post-processes total VMT and other output distributions from the TDM, and applies MOVES-Matrix as the last step. No post-processing is needed after applying emission rates, which is the same as the MOVES inventory model algorithm. Basically, the inventory model simply replaces the MOVES software with MOVES-Matrix, and users can directly apply MOVES input files. The link-level analysis applies MOVES-Matrix first, and post-processing is conducted on both emission rates and link-level inputs. A link record will be visited only once during a single investigated hour.

3. AN ATLANTA CASE STUDY

The Atlanta Regional Commission (ARC) is the MPO for the metropolitan Atlanta, GA area. The ARC Travel Demand Model generates regional travels by using an activity-based model for the 20-county non-attainment area (*2*). Coordinated Travel-Regional Activity-Based Modeling Platform (CT-RAMP) is implemented in the travel demand model system to facilitate the regional activity forecasting with 30-minute resolution. The generated activities are sub-divided into trips based on the origin and stop information, and allocated to links within the local transportation networks during five different time periods (early morning, morning peak, mid-of-day, PM peak and evening). These activity estimates are used as the source for estimating emission distribution on the network through linkage to emission estimation tools.

In this study, the ARC TDM model was used as a case study to estimate on-road emissions with the proposed method, and to validate the emission analysis process conducted on both the inventory and link-level. The MOVES input files and run specification files used for conformity analysis of 20-county non-attainment area were used as inputs for inventory-level model analysis, and the results between applying MOVES and MOVES-Matrix were compared. The link-level TDM network output was used for obtaining link-level emissions, and analyzing the spatial and temporal distribution of emissions within the entire 20-county non-attainment area.

In order to compare the emission results using MOVES and using proposed method, the same analysis domain and calendar year 2017 were applied for emission analysis. The 20-county non-attainment area is divided into 13 county I/M program counties (represented by Fulton County) and 7 additional ring counties without I/M program (represented by Bartow County). The 8-hour Ozone is measured by VOC and NO_X in a hot summer scenario, while $PM_{2.5}$ is measured by total $PM_{2.5}$ on an annual condition.

Inventory-level Emission Modeling

The inventory-level emission modeling with MOVES-Matrix apply the MOVES2014 inputs generated from TDM outputs and other data source (ARC, 2016). A summary table of inventory model inputs is shown below.

Table 1. The MOVES Inventory Inputs

Section	Name	Description	Data Source
Local Fleet	Source type population	Vehicle population by 13 MOVES source type	Regional vehicle registration data
	Age fraction	Vehicle population fraction by model years for each source type	Regional vehicle registration data
Regional Travel Activity	Vehicle type VMT	VMT by HMPS vehicle type	Post-processed TDM output
	Road type VMT fraction	VMT fraction by road type for each source type	Post-processed TDM output
	Speed bin distribution	VHT fraction by road type, source type and hour ID	Post-processed TDM output
	Month adjustment factors	VMT adjustment factors by month for each source type	MOVES default
	Day adjustment factors	VMT adjustment factors by weekday/weekend for each source type, road type and month ID	MOVES default
	Hour adjustment factors	VMT adjustment factors by hour for each source type, road type, month ID and day ID	Post-processed TDM output
	Ramp fractions	VHT fraction of ramp for selected	Post-processed

		road type	TDM output
Other Scenario Inputs	Meteorology	Temperature (°F) and Humidity (%) by hour	Regional meteorology data
	I/M program	Regional I/M program for 13- county area	Regional I/M program
	Fuel	Fuel supply, formulation, usage fraction and Alternate Vehicle Fuels & Technologies (AVFT) strategy	Regional fuel information

Notice that the speed bin distribution applied fraction of VHT instead of VMT as MOVES required. The VHT distributions for each hour, each road type and each source type should be converted to VMT fractions by the following conversion equation:

$$f_v^{VMT} = \frac{f_v^{VHT} \times M_v}{\sum_{v \in V} f_v^{VHT} \times M_v} \quad (3)$$

Where,

v is the speed bin,

V is the set of all speed bins,

M_v is the medium speed of speed bin v,

f_v^{VHT} is the VHT fraction of speed bin v,

f_v^{VMT} is the VMT fraction of speed bin v.

In this case, the vehicle type VMT can be partitioned by source type, model year, road type and speed bin with following equation:

$$VMT_{t,a,r,v} = VMT_h \times \frac{f_{t,a}^{POP} \times RMAR_{t,a}}{\sum_{t \in C_h} f_{t,a}^{POP} \times RMAR_{t,a}} \times f_r^{VMT} \times f_m^{VMT} \times \frac{f_d^{VMT}}{N_d} \times f_{hr}^{VMT} \times f_v^{VMT} \quad (4)$$

Where most variables use same definition as equation (1) and (2). For other variables,

r is the road type ID,

m is the month ID,

d is the day ID (2 for weekend and 5 for weekday),

hr is the hour ID,

N_d is the number of days in selected month,

f^{VMT} is the VMT fraction.

The meteorology, fuel and I/M program were used to prepare MOVES-Matrix for the 7-county and 13-county areas respectively. The on-road emission rates and ramp emission rates were both represented by unit emissions per hour as the base unit. For each applicable hour ID, one MOVES-Matrix output record was generated from the database, with each record including source type, model year, road type, speed bin and emission rate. The partitioned VMT is matched to applicable emission rates to obtain the emission inventories. The VMT for restricted and unrestricted roadway are treated differently due to ramp emissions on restricted highway segments, and following equations were used:

$$E_{unr} = \sum_{all\ \ t,a,v} \frac{VMT_{t,a,r,v}}{M_v} \times e_{t,a,r,v}^{on-road} \qquad (5)$$

$$E_{res} = \sum_{all\ \ t,a,v} \frac{VMT_{t,a,r,v}}{M_v} \times [e_{t,a,r,v}^{on-road}\left(1 - f_{ramp}\right) + e_{t,a,r,v}^{ramp} \times f_{ramp}] \qquad (6)$$

Where most variables use same definition as equation (1), (2) and (3). The other variables are:

E_{unr} – emission inventory for unrestricted roadway,
E_{res} – emission inventory for unrestricted roadway,
e – emission rate,
f_{ramp}-the operating time fraction (VHT fraction) of ramp.

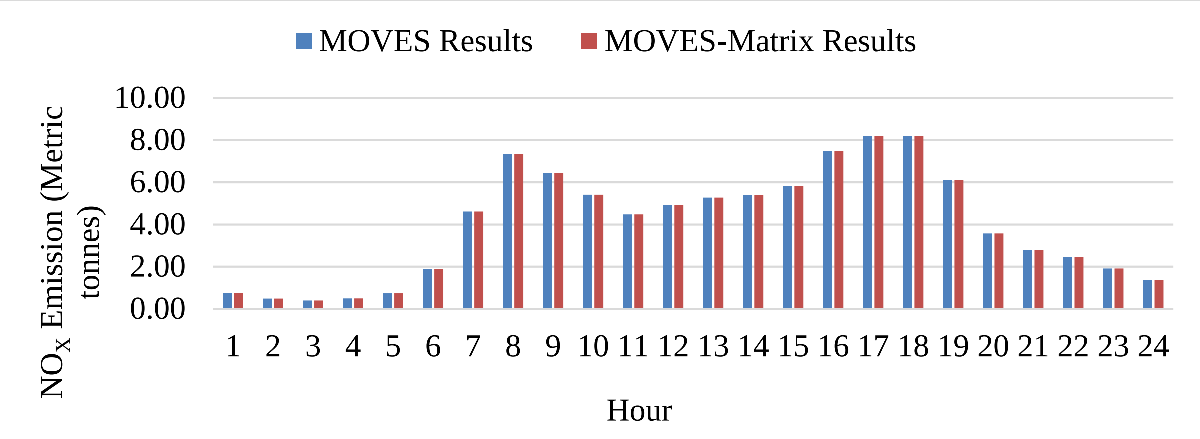
With the same MOVES input provided by ARC, the 4 different scenario were run both in MOVES and in tool developed for this study. A summary of results is provided in table below.

Table 2. The Inventory-model Outputs

Scenario	13 Inspection/Maintenance counties			7 ring counties		
Tool	MOVES 2014	MOVES-Matrix	Difference	MOVES 2014	MOVES-Matrix	Difference
Run time (min)	8	1.07	-86.6%	7	1.07	-84.7%
NO_X (tonne/day)	71.72	71.72	0.0%	24.84	24.84	0.0%
VOC (tonne/day)	11.32	11.32	0.0%	3.80	3.80	0.0%
Scenario	13 non-attainment counties $PM_{2.5}$			7 ring counties $PM_{2.5}$		
Tool	MOVES 2014	MOVES-Matrix	Difference	MOVES 2014	MOVES-Matrix	Difference
Run time (min)	18	1.07	-94.1%	15	1.07	-92.9%

$PM_{2.5}$ (tonne/day)	2.36	2.36	0.0%	0.66	0.66	0.0%

From the table above we can see, the linkage between TDM output and MOVES matrix can significantly reduce execute time, while generated the exactly the same on-road emissions as MOVES 2014. Also, a 24 hour on-road NO_X emission profile and $PM_{2.5}$ emission profile were plotted for the 20-county area derived from two tools, the result is shown in graph below.



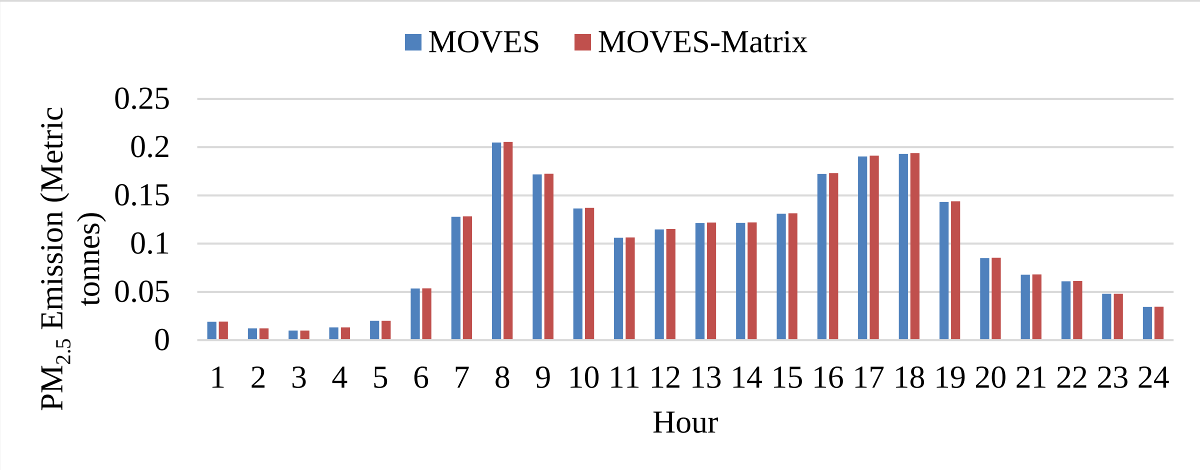


Figure 3. 24-hour on-road NO_X emission and $PM_{2.5}$ emission profile

The figure above demonstrates that the linkage developed in this study can produce exactly the same emission profile as MOVES. In this case, it is fairly reasonable to claim that the tool developed in this study can produce a close approximation of MOVES results, while providing significant time-savings.

Link-level Emission Modeling

The link-level emission modeling post-processed the emission rates from MOVES-Matrix and TDM outputs, and this post-processing can be conducted in a flexible manner according to the form of inputs prepared by the user. In this study, the link-level ARC TDM network outputs were used for emission analysis, and the results may not be exactly the same as the inventory models due to following reasons: 1) the VMT from link-level model does not exactly match the total VMT used in inventory model; 2) the inventory model applied a consistent distribution for the entire region, while the actual traffic volume and VMT could be significantly skewed (e.g. Interstate highways have significantly high vehicle throughputs and average speed); 3) the on and off ramp are processed separately from highway segments; 4) the emission rate for each speed is applied instead of a speed bin for higher accuracy. The facility type from the TDM outputs can indicate if the roadway belongs to a ramp segment, and the ramps can be marked by applying a special road type ID. This prevented use of the freeway speed distributions for ramp segments and eliminated potential estimation bias.

With proposed method in this study, each link has a single VMT, road type, average speed, adjustment factor, and is multiplied by an aggregated emission rate link-by-link. First, the aggregated emission rates by speed bin and road type were calculated by aggregating emission rates by speed bin, road type, source type and model year, and VMT fraction by source type and model year. The equation for calculating this aggregated emission rates e_{agg} is shown below.

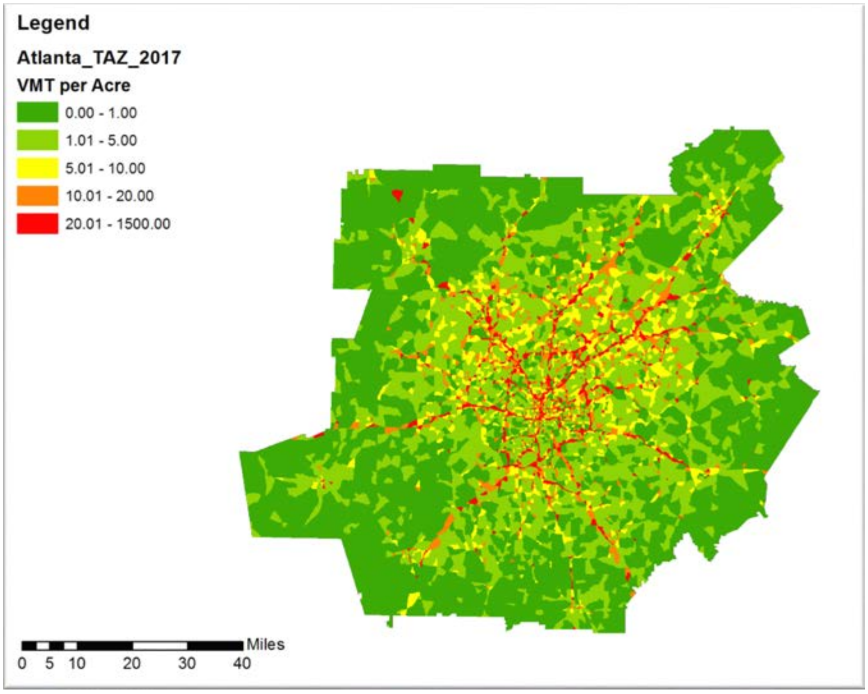
$$e_{agg} = \sum_{all \;\; t,a} f_h^{VMT} \times \frac{f_{t,a}^{POP} \times RMAR_{t,a}}{\sum_{t \in C_h} f_{t,a}^{POP} \times RMAR_{t,a}} \times e_{t,a,v,r} \qquad (7)$$

Where f_h^{VMT} is the VMT fraction by HPMS types prepared for each road type respectively. The VMT fraction by HMPS types is partitioned into VMT fraction by source type and model year by deploying the RMAR factors. Next, the monthly adjustment factors for road type r was also calculated by aggregating the VMT fractions by source type and model year of road type r, and the monthly adjustment factors by source type f_m^{VMT}:

$$f_r^{VMT} = \sum_{all \;\; t,a} f_h^{VMT} \times \frac{f_{t,a}^{POP} \times RMAR_{t,a}}{\sum_{t \in C_h} f_{t,a}^{POP} \times RMAR_{t,a}} \times f_m^{VMT} \; for \;\; all \;\; a \;\; and \;\; all \;\; r \qquad (8)$$

The aggregated emission rates were populated for road segments and ramps respectively, and stored in separate lookup tables. Since the VMT fractions by HPMS type $f_{h,r}^{VMT}$ were prepared for all road types, the vehicle compositions by road type should also be different, which is more detailed assignment than in the inventory model.

Since the ARC TDM divided a simulated day into 5 time periods, the hourly VMT were prepared by applying MOVES default hour adjustment factors. As the TDM link-level outputs are generated from a typical weekday, the day adjustment factors were not applied in this model. For each hour of operation, the link-level inputs were screened individually, with VMT under specific, time period, road type and average speed was distributions chosen and then multiplied by adjustment factors an aggregated emission rate. The link-level emissions were populated for the TDM network, and then aggregated results by TAZ for the AM peak period. These results for July are shown in figure 4 below. The total computation time for a 24-hour period, 20-county area network with 73,730 links and 4 selected pollutants was 5.4 minutes.



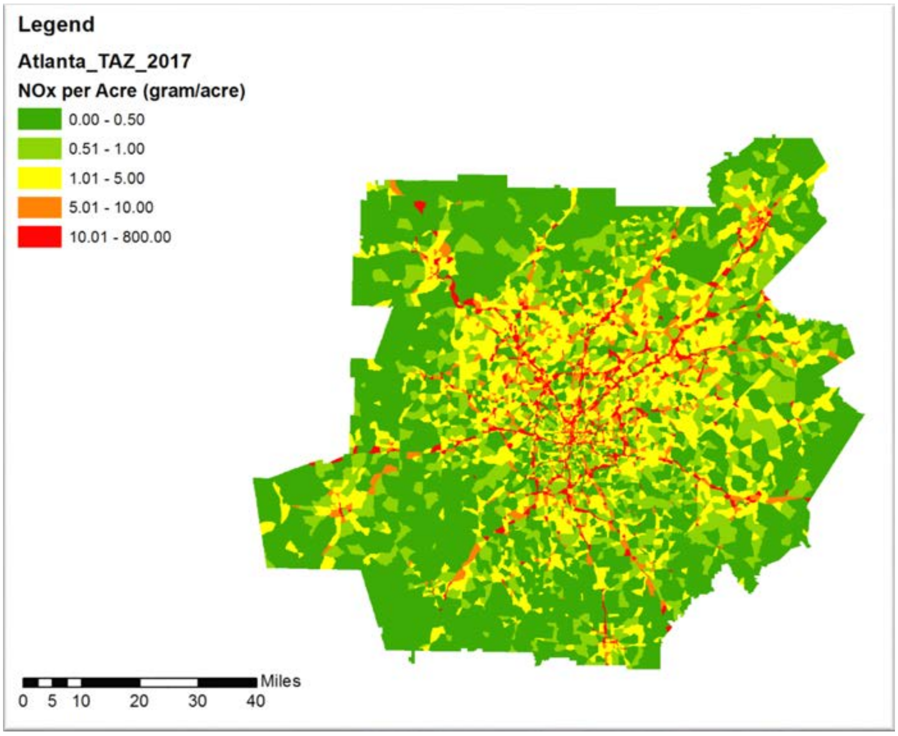


Figure 4. The VMT and NO_X emissions per Acre by TAZ (8:00 AM – 9:00 AM)

From the figure above we can see that the distribution of unit NO_X emissions have the similar pattern to the distribution of VMT. The area around interstate highways 85, 75 and

285, as well as downtown Atlanta are significantly darker (greater emissions) than other areas. These emission results derived from link-level TDM and MOVES-Matrix linkage relatively represent the real world conditions, and meet expectations regarding regional emissions distributions.

In this case, the linkage of these models can greatly help researchers obtaining emission distribution throughout the region, and are beneficial for further air quality analysis. For example, MOVES-Matrix can be connected with both TDMs and dispersion models and all the processes can be automated. A high-performance dispersion modeling system based on MOVES-Matrix and distributed computing cluster has been demonstrated (*16*), that produces receptor modeling results more than two orders of magnitude faster than the normal procedures based on MOVES Graphical User Interface (GUI), CALINE4 and/or AERMOD atmospheric dispersion modeling system.

4. CONCLUSION

In this study, MOVES-Matrix was applied to replace MOVES2014 in a regional emission modeling application. A tool to allow automatic linkage between TDM outputs, other regional data and MOVES-Matrix was developed for achieving rapid assessment of emission inventories and link-level emissions. A case study on 20-county non-attainment Atlanta Area was conducted to validate the proposed tool. The results indicate that the proposed tool can produce emission inventories that closely approximate those using MOVES, while significantly reducing run time.

A link-level emission analysis was also conducted with these TDM network outputs, and the resulting emission distributions are consistent with regional travel patterns. These link-level emissions can be further applied in hot spot assessment and dispersion modeling as necessary. This process is extremely rapid compared to traditional methods. Total computation time for a 20-county area and for a 24-hour period of about five minutes. Thus, with proper scripting to adjust to link-level output from a specific TDM model, this tool can achieve rapid assessment of regional emission distribution.

However, there are several limitations of this study which should be addressed through further research efforts. First, the study only investigated the on-road emissions. Cold and warm start; extended idling, running losses and evaporative emissions all need to be further explored to fulfill a complete conformity analysis. Also, local data should be applied to refine the vehicle composition and mileage increment, and improve the accuracy of emission analysis. Finally, potential application of emission inventories and link-level emission populated by this tool should be further explored, and practical procedures should be provided for various applications, such as dispersion modeling.

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