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# Development of a Simplified Version of MOVES and Application to Iterative Case Studies

**Extended Abstract #12818**

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## INTRODUCTION

Accurate emission factors and inventories are the foundation of air quality management.[1] On road vehicle emission factor models are based on vehicle characteristics, vehicle dynamics (e.g., speed and acceleration), and, in some cases, road infrastructure (e.g., road grade).[2] Travel demand models (TDMs) and traffic simulation models (TSMs) can provide traffic volume data and vehicle activity data to estimate emission inventories.

The MOVES onroad vehicle emission model developed by the U.S. Environmental Protection Agency (EPA) is used in regulatory and other applications to estimate highway vehicle emissions for pollutants such as $CO_2$, CO, $NO_x$, hydrocarbons, and others. MOVES is based on second-by-second measurements of vehicle emissions that are stratified into Operating Mode ("OpMode") bins.[3] These bins are based on an estimate of engine load and ranges of speed. MOVES can be applied by the user at different geographic scales. Using the project level feature of MOVES, a user can enter driving schedules for each roadway link of interest. A driving schedule includes second-by-second speed. Similarly, some TSMs provide estimates of speed trajectories on a second-by-second basis.

MOVES has been used in combination with several TSMs, such as PARAMICS, Dynamic Urban Systems for Transportation (DynusT), and VISSIM.[4,5,6] The applications include case studies to evaluate the effect of alternative transportation fuels and Connected Vehicle (CV) technology. TSMs are also commonly used to evaluate the traffic implications of specific projects, such as modifications to intersections, lane additions, work zone lane closures, and others.

However, MOVES is computationally intensive if applied to estimate emissions for individual vehicles and roadway links based on TSM simulation output. Dynamic linkage of traffic and emissions models is challenging and can lead to significantly longer run times. Furthermore, MOVES performs calculations to adjust for temperature, humidity, air conditioning load, fuel properties, and other factors. Since TDMs or TSMs are typically applied to case studies that represent a narrow period of time on a particular type of day, such as peak morning or afternoon travel on a weekday, vehicle fleet mix, fuel properties, and ambient temperature are approximately constant for the simulation time period. Because many of the factors to which MOVES is sensitive are approximately constant during the time period of a typical TSM simulation, there is no need to run MOVES in its entirety for every link in a network. The main goal of emissions estimation in this context is to provide an appropriate estimate of the relative change in emissions as a result of controllable factors. Therefore, a simplified version of MOVES is needed that can be more efficiently coupled to or incorporated within a TSM. Because MOVES estimates emission factors based on weighted combinations of OpMode bins, a similar approach can be used as part of a simplified model.

This paper demonstrates a simplified version of MOVES, referred to here as "MOVES Lite," that is capable of estimating the same values for emission factors as MOVES but that is intended to enable rapid quantification of driving schedule average emission rates. The applicability of MOVES Lite to many driving schedules is illustrated via a case study based on over 200 empirical driving cycles.

# METHODS

A simplified version of MOVES is developed to estimate cycle average emission rates and is intended for later incorporation into a TSM. The accuracy of MOVES Lite is evaluated by comparing its results with those of MOVES for selected vehicle types and ages that represent the vast majority of the onroad fleet. A case study demonstrates the capability to quantify variability in cycle average emission rates based on empirical driving cycles. The case study is based on a stand-alone version of MOVES Lite implemented in MATLAB.

## Simplified Model

The cycle average emission rate for a pollutant for any link or vehicle speed trajectory for a fleet of vehicles is given by

$$CE_{p,c} = \sum_v \left\{ \left[ \sum_a \left( EF_{p,b,a,v} \times CCF_{p,c,a,v} \times f_{a,v} \right) \right] \times f_v \right\} \qquad \text{(Equation 1)}$$

Where,

$CE_{p,c,}$ = cycle average emission factor for any arbitrary driving cycle c, for pollutant p, for a fleet of vehicles with mixed types and ages, gram/mi

$ER_{p,b,a,v}$ = base emission rate for base cycle b, age a, vehicle type v, and pollutant p, gram/mi

$CCF_{p,c,a,v}$ = cycle correction factor for driving cycle c, age a, vehicle type v, and pollutant p

$f_{a,v}$ = age fraction for age a and vehicle type v

$f_v$ = vehicle type fraction for vehicle type v

c = cycle c

b = base cycle

p = pollutant

The Base Emission Rate (BER) ($EF_{p,b,a,v}$) can be estimated for any arbitrary driving cycle chosen as a base cycle. The Federal Test Procedure (FTP) is the basis for U.S. emissions certifications testing, and is selected here. The numerical value of the base emission rate is obtained for a given pollutant, vehicle type and age by running MOVES using the project level feature, and entering the second-by-second driving cycle for the base cycle.

The Cycle correction factor (CCF) is the ratio of the emission rate for any cycle to that of the base cycle:

$$CCF_{p,c,a,v} = \left( \frac{\left(\sum_m f_m^c \times ER_{p,a,v,m}\right)}{\left(\sum_m f_m^b \times ER_{p,a,v,m}\right)} \right) \left( \frac{V^b}{V^c} \right) \qquad \text{(Equation 2)}$$

Where,

| | |
|---|---|
| $ER_{p,a,v,m}$ | = default emission rate for pollutant p, age a, vehicle type v, in operating mode bin m, gram/hour |
| $f_m^{\ c}$ | = fraction of time in OpMode bin m in cycle c |
| $f_m^{\ b}$ | = fraction of time in OpMode bin m for base cycle b |
| $V^c$ | = cycle average speed for cycle c, mph |
| $V^b$ | = cycle average speed for base cycle b, mph |

The key data sources for Equation (2) include: (a) default operating model bin emission rates taken directly from databases that are used by MOVES; (b) fraction of time in each operating mode bin for the base driving cycle based on analysis of the second-by-second speed and acceleration of the base cycle; (c) fraction of time in each operating mode bin for the driving cycle of interest based on analysis of its second-by-second speed and acceleration; and (d) average speeds of the base cycle and the cycle of interest. The base cycle is selected once and used consistently for all other calculations. The cycle of interest varies on a case-by-case basis and can be obtained from field measurements or simulation output of a TSM.

There are five types of vehicles in the simplified model including passenger car (PC), passenger truck (PT), light commercial truck (LCT), single unit short haul truck (SST), and combination long haul truck (LHT). These five types of vehicle comprise more than 95% of the vehicles in the fleet.

## Verification of the Simplified Model

In recent work, the ability of the simplified model to produce the same emission rates as MOVES was verified based on comparisons to MOVES predictions for selected driving cycles for each of five vehicle types, including PC, PT, LCT, SST, and LHT. For each vehicle type, MOVES has default driving cycles that cover a wide range of average speed from 2.5mph to 76mph. For PC, PT, and LCT, there are 18 default driving cycles used in MOVES. For SST and LHT, there are 11 default driving cycles.[7] For each vehicle type, comparisons of emission factors from MOVES Lite versus MOVES were made for vehicles of 0, 5, 10, and 15 years of age based on calendar year 2011. The evaluation focused on emission rates for $CO_2$, $NO_x$, CO, and hydrocarbons (HC).[8]

## Case Study of Evaluation of Variability of Emission Rates of Empirical Driving Cycles

The simplified model is implemented as a standalone model in MATLAB. The input to model includes the driving cycles, fleet distribution by vehicle type, and age distribution for each vehicle type. The model is applied to a case study to demonstrate the capability to rapidly estimate emissions for a large number of real-world driving cycles. From previous work, approximately 200 empirical driving cycles are available based on field measurements of approximately 30 vehicles that represent freeway and non-freeway vehicle operation.[9] For each vehicle, there are six empirical driving cycles. Of these, four are based on non-freeway road types, labeled as cycles A, C_NF, 1_NF, and 3. Two are comprised of freeways, labeled as cycles C_F and 1_F. MOVES Lite is applied to estimate cycle average emission factors for each of vehicles for each of these cycles, for a total of approximately 200 driving cycles. The MOVES Lite case studies are based on a fleet of new (0 year age) passenger cars. Cycle average emission factors are estimated for $CO_2$, $NO_x$, CO, and HC.

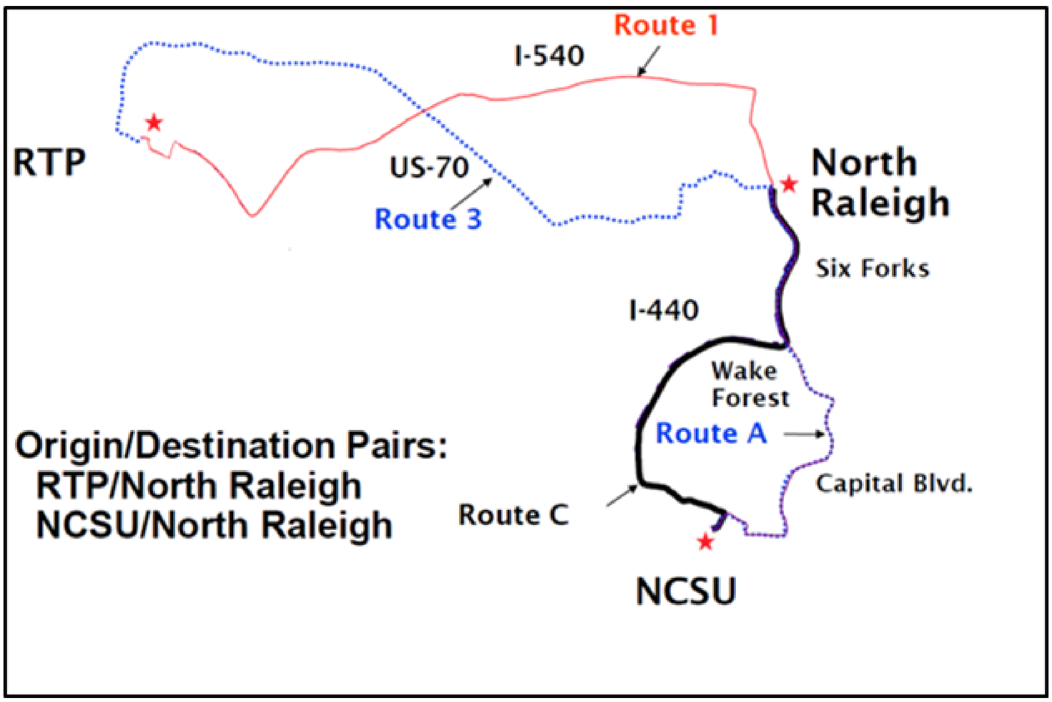


**Figure 1. Routes Used in Measurements of Empirical Driving Cycles**

# RESULTS AND DISCUSSION

The simplified model was verified in comparison to MOVES. For PCs, PTs, and LCTs, the cycle average emission factors were typically within 0.3% of the MOVES estimates for $CO_2$, and within 10 percent among NOx, CO, and HC depending on the cycle. All the errors are within -3.3% to 2.5% among all pollutants, ages, and cycles. For SHT and LHT, the differences between MOVES results and simplified model are between -2.24% to 2.31%. Taking into account six vehicle types, four ages, four pollutants, and approximately a dozen or more driving cycles depending on the vehicle type, more than 92% of the prediction errors of the simplified model are less than 1% compared to the MOVES prediction. Over a range of five types of vehicle, four vehicle age groups, all MOVES default driving cycles, and four pollutants, the errors in the cycle average estimates from MOVES Lite compared to MOVES are within ±0.5%. Thus, the model predicts the same cycle average emission rates as obtained from MOVES within numerical round off error in nearly all cases. There are a few exceptions based on lack of clarity regarding how MOVES actually quantifies cycle average emission rates for some regulatory classes within a vehicle fleet category, particularly for SST and LHT. The lack of clarify is based on incomplete documentation of the MOVES model itself.

The standalone version of MOVES Lite implement in MATLAB runs much faster than MOVES. For example, the processing time for the case study for one vehicle type with 18 driving cycles is approximately 10 minutes for MOVES using a 2.93 GHz processor with 8 GB memory, while the processing time is 0.2 seconds using the simplified model in MATLAB for the same number of driving cycles in MATLAB. Thurs, the simplified model is 3,000 times faster than MOVES. For the current version of the simplified model implemented in MATLAB, three input files are needed, including driving cycles, vehicle type distribution, and vehicle age distribution. In contrast, MOVES uses at least six input data files.

To demonstrate the capability of MOVES Lite, the new model was applied to estimate cycle average $CO_2$ and $NO_x$ emissions rates for over 30 vehicles operated on each of six routes, as shown in Figures 2 and 3, respectively. Each figure depicts the cumulative distribution of emission factors for each route, based on field measurements of real world driving cycles for each of over 30 vehicles operated on the selected route. The predictions are based on new passenger cars in calendar year 2011.

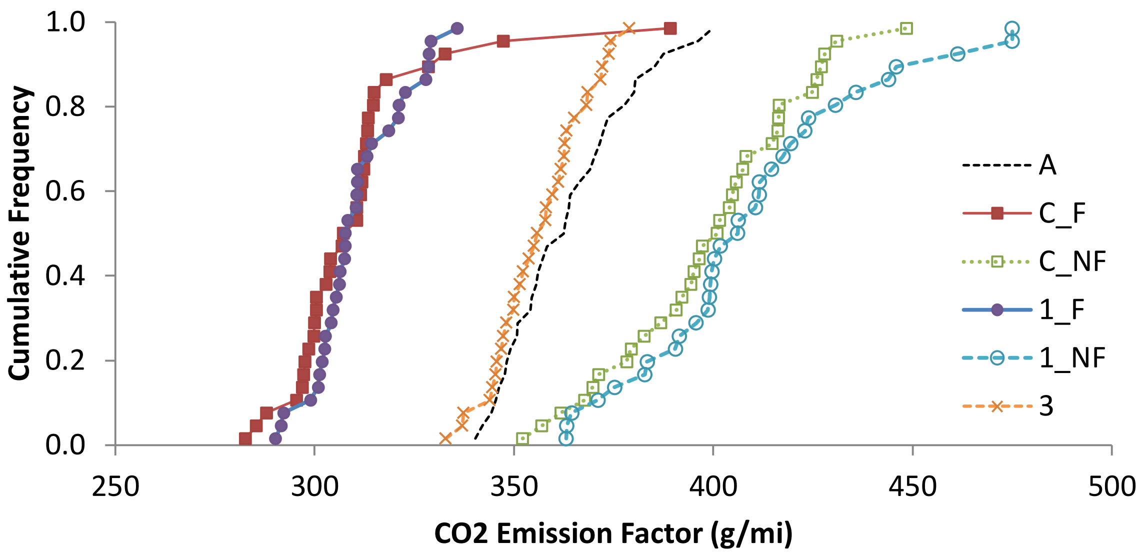


**Figure 2. Cumulative Distribution Functions of Inter-Cycle Variability in $CO_2$ Emission Factors by Routes Based On Empirical Driving Cycles**

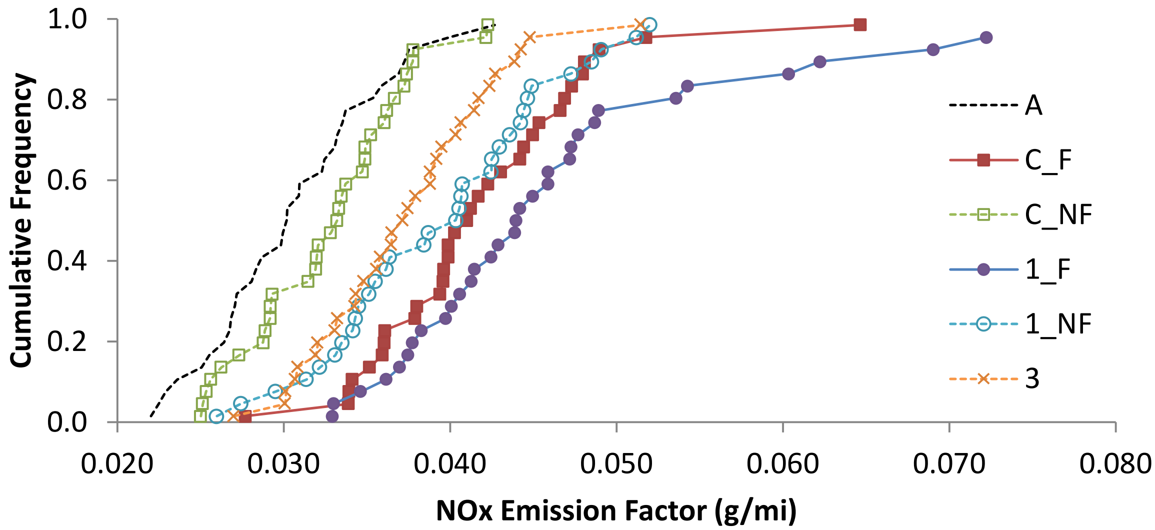


**Figure 3. Cumulative Distribution Functions of Inter-Cycle Variability in NOx Emission Factors by Routes Based On Empirical Driving Cycles**

For the cycle average $CO_2$ emission rates, the overall variability in predicted emission rate among the six routes and the 30 vehicles is from approximately 280 g $CO_2$/mile to over 470 g $CO_2$/mile. Since typically over 99 percent of the carbon in gasoline is converted to $CO_2$, these emission rates are also related to vehicle fuel efficiency. Higher values of $CO_2$ emission rate imply higher fuel consumption per mile. In the figures, solid lines are for freeway cycles and dashed lines are for arterial cycles.

The routes with the lowest cycle average $CO_2$ emission rates include "C_F" and "1_F." Both are comprised entirely of limited access freeways, and specifically include portions of I-40, I-440, and I-540 in the Raleigh, NC area. The cycle average emission rates for these routes range from approximately 280 g $CO_2$/mile to 330 g $CO_2$/mile. For example, the average speed on route "C_F" is 58 mph. The highest cycle average emission rate on route "C_F" is 389 g $CO_2$//mi is because of traffic congestion that lead to a substantially reduced average speed of only 25.5 mph. Routes "A" and "3" have average emission rates higher than those of the freeway cycles but lower than those of Routes "1_NF" and "C_NF." Routes "A" and "3" include vehicle operation mostly on signalized arterial roads with speed limits of 45 to 55 mph. Routes "1_NF" and "C_NF" are also comprised of arterials but with more variability in driving speed. The average speed on route "C_NF" is 23 mph. Although there is substantial variability in the run-to-run cycle average emission rates within a route, there are also noticeable differences when comparing frequency distributions for different routes. For example, routes 1_F, 3, and 1_NF have very little overlap with each other, and progressively higher cycle average emission rates.

For $NO_x$, there is more relative variability in run-to-run emission rates for a given route than for $CO_2$. For example, for Route "1_F," The $NO_x$ emission factors vary from 33 to 72 mg/mile, or a factor of more than two from the smallest to highest value, versus a factor of only 1.14 for $CO_2$ emission factors. $NO_x$ emission rates are typically more sensitive to variation in engine load than $CO_2$ emission rates. There is more overlap between the frequency distribution of emission rates when comparing routes for $NO_x$ than for $CO_2$. However, the trend in typical emission rates among the routes is different for $NO_x$ than for $CO_2$. For example, although the freeway cycles tend to have the lowest $CO_2$ emission rates compared to the arterial cycles, the opposite is the case for $NO_x$. Furthermore, the route with lowest average $NO_x$ emission rate is route "A," which is comprised of signalized arterials. However, another route comprised of signalized arterials, Route "1_NF," has much higher $NO_x$ emission rates than route "A." Thus, the cycle average emission rates are sensitive to differences in the driving cycle even for similar types of roadways.

The runtime to estimate cycle average emission rates for $CO_2$, NOx, CO, and HC for 198 empirical driving cycles is 2.2 seconds using the simplified model. The runtime to estimate the emission rates for 198 cycles is approximate 90 minutes using MOVES. Therefore, the simplified model runs about 2,400 times faster than MOVES in this case study.

## SUMMARY

The simplified model can estimate accurate emission factors for a variety of driving cycles, vehicle types, ages, and pollutants. The runtime is significantly improved by 3,000 times comparing with MOVES. The simplified model can be used more quickly than MOVES to evaluate the variability of emission factors for real-world driving cycles. As part of ongoing work, MOVES Lite will be incorporated with a TSM and applied to case studies to estimate the relative change and emissions as a result of a modification of transportation infrastructure, operations, or both. The current version of MOVES Lite is developed with using link driving schedule as the key input. The OpMode distribution is inferred from the driving schedule. If there is a future need to adapt MOVES Lite to use OpMode distributions as a direct input, this can be easily accommodated.

MOVES Lite can be used as an alternative method of estimating onroad vehicle emission factors for MOVES, particularly in situations for which many iterative emission estimates are needed. For example, MOVES Lite can be used in sensitivity analysis for vehicle type distributions, vehicle age distributions, and variations in driving cycles, or it can be directly incorporated into a microscale traffic simulation model. The latter is being done as part of ongoing work.

## ACKNOWLEDGMENTS

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# REFERENCES


1. NRC (2000). "Modeling Mobile-Source Emissions." National Research Council (U.S.), National Academy Press. Washington, D.C., 2000.

2. Frey, H. C., K. Zhang, and N. M. Rouphail. Vehicle-Specific Emissions Modeling Based upon on-Road Measurements. *Environmental Science & Technology*, 44(9):3594-3600 (2010).

3. EPA. *MOVES2010a User Guide*. EPA-420-B-09-041, U.S. Environmental Protection Agency, Ann Arbor, MI, 2010.

4. Xie, Y., M, Chowdhury, P. Bhavsar, Y.Zhou, An Integrated Tool for Modeling the Inpact of Alternative Fueled Vehicles on Traffic Emissions: A Case Study of Greenville, South Carolina, 11-3880, Proceedings of the 90th Transportation Research Board Annual Meeting, Transportation Research Board, Washington, DC, 2011.

5. Lin, J., Y. Chiu, S. Bai, and S. Vallamsundar. Integration of MOVES and Dynamic Traffic Assignment Models for Fine Grained Transportation and Air Quality Analyses *Integrated and Sustainable Transportation System (FISTS), 2011 IEEE Forum*, pp.176-181, 2011.

6. Song, G., Yu, L., Zhang, Y. Applicability of Traffic Micro-simulation Models in Vehicle Emission Estimations: A Case Study of VISSIM, 12-0642, *Proceedings of the 91st Transportation Research Board Annual Meeting*, Transportation Research Board, Washington, DC, 2012.

7. EPA. DrivingScheduleSecond in MOVES Default Database, Version MOVESDB20100830, U.S. Environmental Protection Agency, Ann Arbor, MI, 2010.

8. Frey, H. C., B. Liu, Development and Evaluation of a Simplified Version of MOVES for Coupling with a Traffic Simulation Model, 13-1201, Proceedings of the 92nd Transportation Research Board Annual Meeting, Transportation Research Board, Washington, DC, 2013.

9. Liu, B., and H.C. Frey, "Development and Evaluation of a Simplified Version of MOVES for Coupling with a Traffic Simulation Model," 2012-A-279-AWMA, Proceedings, 105th Annual Meeting of the Air & Waste Management Association, Orlando, FL, June 19-22, 2012.




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