CMAQ Emissions Calculator Toolkit

Documentation of Emissions Data for the Travel Advisories Tool

This document supplements the User Guide for the Travel Advisories Tool in the Congestion Mitigation and Air Quality Improvement Program Emissions Calculator Toolkit (CMAQ Toolkit). It discusses the primary data sources and how the emission datasets for this tool were derived. Emission estimates from the CMAQ Toolkit are not intended to meet specific requirements for State Implementation Plans (SIPs) or transportation conformity analyses.

The document highlights the emissions data obtained from the US Environmental Protection Agency's (EPA) Motor Vehicle Emissions Simulator (MOVES).[1] The MOVES Methodology section describes the specific inputs and outputs, pre-processing, and post-processing that were used to generate the default-scale emission rates used within the tool.

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[1] US Environmental Protection Agency, Office of Transportation and Air Quality, https://www.epa.gov/moves

TRAVEL ADVISORIES

Travel advisories can take many shapes ranging from signage, to radio messages, to in-app alerts, and serve the purpose of alerting drivers of upcoming roadway conditions. The travel advisories considered in this tool are variable message signs (VMS) and variable speed limits (VSL). VMS often provide warnings about temporary road events such as congestion, construction, or inclement weather, while VSL adjust the permitted speed to make travel conditions safer in response to roadway conditions.

Travel advisories prepare the driver for upcoming roadway conditions and subsequently cause the driver to adjust their behavior. When drivers are alerted of upcoming roadway conditions, driving patterns become smoother with fewer instances of hard braking or acceleration.[2] To represent this adjusted driving pattern, a smoothing spline was applied to standard driving cycles built into EPA's MOVES model. Relatively little research has been performed in this area to differentiate between the impacts of various travel advisories or to quantify the smoothing impact. However, Liu et al. (2017) investigated the impact of connected and autonomous vehicles (CAVs) within a mixed fleet using a smoothing spline.[3] This tool incorporates a similar approach, including using the same smoothing value as the default, but allows users to adjust for lower levels of smoothing.

MOVES METHODOLOGY

MOVES3 project-level runs were used to determine running emission rates at different speeds, vehicle classes (Light-Duty or LD, and Heavy-Duty or HD), and smoothing factors for this tool. The Travel Advisories Tool runs included speeds of 30 to 70 miles per hour (mph) at approximately 10-mph intervals. Project-scale links were created to correspond to the drive cycle and smoothing factor. As such, each MOVES linkID was formed by using the driveScheduleID for unaltered drive cycles and concatenating the driveScheduleID with 0, 1, or 2 to represent the level of smoothing (i.e., the lambda value, or λ), with 0 representing λ = 0, 1 representing λ = 0.115, and 2 representing λ = 0.22999 (the value used in Liu et al. (2017)).

Default-Scale MOVES Parameters

Both default-scale[4] and project-scale runs were conducted in MOVES. Outputs from default-scale runs were used as inputs for project-scale runs. These default-scale runs were necessary to be able to differentiate emission rates by the different drive cycles used in this tool. Table 1 details the inputs to the default-scale runs, while details on the project-scale runs are included in the Project-Scale MOVES Parameters Section.

Table 1: Default-Scale Run Specifications

Categories	**Variable**	**Input**
Description	-----	<blank>
Scale	Model	Onroad
	Domain/Scale	Default Scale
	Calculation Type	Inventory

[2] Lee, C., Abdel-Aty, M., 2008. Testing Effects of Warning Messages and Variable Speed Limits on Driver Behavior Using Driving Simulator: Transportation Research Record. https://doi.org/10.3141/2069-08

[3] Liu, J., Kockelman, K., Nichols, A., 2017. Anticipating the Emissions Impacts of Smoother Driving by Connected and Autonomous Vehicles, Using the MOVES Model. Presented at the Transportation Research Board 96th Annual Meeting.

[4] MOVES3 uses the term "default-scale" to refer to what was previously called "national-scale". To maintain consistency, this document will use "default-scale" throughout.

Categories	Variable	Input
Time Spans	Time Aggregation Level	Year
	Years	[2018, 2020, 2025, 2030, 2035, 2040]
	Months	All Selected
	Days	All Selected
	Hours	All Selected
Geographic Bounds	-----	No selections required
Onroad Vehicles	Selections	All Fuel/Type Combinations Selected
Road Type	Road Type	All Road Types
Pollutants and Processes	Total Gaseous Hydrocarbons	Running Exhaust, Crankcase Running Exhaust
	Non-methane Hydrocarbons	Running Exhaust, Crankcase Running Exhaust
	Volatile Organic Compounds	Running Exhaust, Crankcase Running Exhaust
	Carbon Monoxide (CO)	Running Exhaust, Crankcase Running Exhaust
	Oxides of Nitrogen (NOx)	Running Exhaust, Start Exhaust, Crankcase Running Exhaust, Crankcase Start Exhaust
	Primary Exhaust PM2.5 – Total	Running Exhaust, Crankcase Running Exhaust
	Primary Exhaust PM2.5 – Species	Running Exhaust, Crankcase Running Exhaust
	Primary PM2.5 – Brakewear Particulate	Brakewear
	Primary PM2.5 – Tirewear Particulate	Tirewear
	Primary Exhaust PM10 – Total	Running Exhaust, Crankcase Running Exhaust
	Primary Exhaust PM10 – Species	Running Exhaust, Crankcase Running Exhaust
	Primary PM10 – Brakewear Particulate	Brakewear
	Primary PM10 – Tirewear Particulate	Tirewear
	Total Energy Consumption (TEC)	Running Exhaust
	Atmospheric CO2	Running Exhaust, Crankcase Running Exhaust
	CO2 Equivalent	Running Exhaust, Crankcase Running Exhaust
General Output	Units	Mass: kilograms, Energy: million BTU, Distance: miles
	Activity	Source Hours Operating
Output Emissions Detail	Output Aggregation	Year, Nation
	For All Vehicle/Equipment Categories	Model Year

Categories	Variable	Input
	On Road	Road Type
	Nonroad	<Not selectable>
Create Input Database	Database	Enter desired file name
Advanced Features	Preaggregation Options	Time Aggregation: Year, Region Aggregation: Nation

DRIVE CYCLE SMOOTHING METHODOLOGY: Smoothing Spline

The standard drive cycles used in this tool and their average speeds are listed in Table 2. These drive cycles were taken from the MOVES database and run through a standard cubic spline function in R to produce smoothed drive cycles (Equation 1).

Table 2: Drive Cycles and Associated Speeds

Vehicle Class	Drive Schedule ID	Average Speed (mph)
LD	153	30.5
	1020	46.1
	1019	58.8
	1018	64.4
	1009	73.8
HD	351	34.3
	352	47.1
	353	54.2
	354	59.4
	355	71.7

$$\sum_{i=1}^{n}(y_i - f(x))^2 + \lambda \int f''(x)^2 dx \qquad \textbf{(1)}$$

The λ variable (with a range from 0 to 1) represents the level of smoothing and as lambda increases from 0 to 1 the drive cycle (a line representing a vehicle's instantaneous speed over time) becomes less variable (i.e., smoother). The following values were used for this tool: λ = 0, 0.115, 0.22999 and no smoothing. The newly smoothed drive cycles created in R were then used as inputs for project-scale MOVES runs.

Project-Scale MOVES Parameters

Table 3a details the inputs to the project-scale runs while Table 3b details the national defaults used as inputs for the Project Data Manager. When using MOVES for project-scale runs, the user can enter data into the Project Data Manager to adjust default values generated by the model.

Table 3a: Project-Scale Run Specifications

Category	Variable	Input
Description	-----	<blank>
Scale	Model	Onroad
	Domain/Scale	Project
	Calculation Type	Inventory
Time Spans	Years[5]	2018, 2020, 2025, 2030, 2035, 2040
	Months	January
	Days	Weekdays
	Hours	00:00 – 00:59
Geographic Bounds	Selections:	Middlesex County, MA (25017)
Onroad Vehicles	Sections	Combination Long-Haul Truck – Diesel Fuel; Passenger Car – Diesel Fuel, Electricity, Ethanol (E-85), Gasoline
Road Type	Road Types	Rural Restricted Access
Pollutants and Processes (selected)	Total Gaseous Hydrocarbons	Running Exhaust, Crankcase Running Exhaust
	Non-methane Hydrocarbons	Running Exhaust, Crankcase Running Exhaust
	Volatile Organic Compounds	Running Exhaust
	Methane (CH4)	Running Exhaust, Crankcase Running Exhaust
	Carbon Monoxide (CO)	Running Exhaust, Crankcase Running Exhaust
	Oxides of Nitrogen (NOx)	Running Exhaust, Crankcase Running Exhaust
	Nitrous Oxide (N2O)	Running Exhaust, Crankcase Running Exhaust
	Primary Exhaust PM2.5 – Total	Running Exhaust, Crankcase Running Exhaust
	Primary PM2.5 – Species	Running Exhaust, Crankcase Running Exhaust
	Primary PM2.5 – Brakewear Particulate	Brakewear
	Primary PM2.5 – Tirewear Particulate	Tirewear
	Primary Exhaust PM10 – Total	Running Exhaust, Crankcase Running Exhaust

[5] To avoid an excessively large output database, each evaluation year was run individually, and results were placed in separate output databases.

Category	Variable	Input
	Primary PM10 – Brakewear Particulate	Brakewear
	Primary PM10 – Tirewear Particulate	Tirewear
	Sulfur Dioxide (SO2)	Running Exhaust, Crankcase Running Exhaust
	Total Energy Consumption	Running Exhaust, Crankcase Running Exhaust
	Atmospheric CO2	Running Exhaust, Crankcase Running Exhaust
	CO2 Equivalent	Running Exhaust, Crankcase Running Exhaust
General Output	Units	Mass: kilograms, Energy: million BTU, Distance: miles
	Activity	Distance Traveled, Source Hours Operating
Output Emissions Detail	For All Vehicle/Equipment Categories	Model Year, Fuel Type, Emission Process
	Onroad	Road Type, Source Use Type
	Nonroad	<Not selectable>
Create Input Database	Database	Enter desired file name
Advanced Features	Preaggregation Options	<Not selectable>

Considering that the MOVES project-scale runs utilized a series of inputs from the default-scale runs outlined above and from the MOVES default database, the data entered into each Project Data Manager tab has been recorded in Table 3b.

Table 3b. Project Data Manager – Inputs by Tab

Data	Source
Age Distribution	Adopted MOVES3 age distributions for all evaluation years from 2018 through 2040 (taken from sourcetypeagedistribution table in movesdb20210726 database)
AVFT	Used default tables for each run
Fuel Formulation	Used default tables for each run
Fuel Supply	Used default tables for each run
Fuel Usage Fraction	Used default tables for each run
Generic	---
Hotelling	---
I/M Programs	Selected “No I/M Program”
Links	Customized input with the following data: • linkID: driveScheduleID concatenated with smoothing factor • countyID: 25017 • zoneID: 250170 • roadTypeID: 2 • linkLength: 10

Data	Source
	• linkVolume: 1000 • linkAvgSpeed: Average speed per drive cycle as shown in Table 2 • linkDescription: --- • linkAvgGrade: 0
Link Source Type	Customized input with the following data: • linkID: driveScheduleID concatenated with smoothing factor • sourceTypeID: 21 for LD runs, 62 for HD runs • sourceTypeHourFraction: 1
Link Drive Schedule	Customized input with the following data: • linkID: driveScheduleID concatenated with smoothing factor • Second ID: developed from standard drive cycle with smoothing spline applied • Speed: developed from standard drive cycle with smoothing spline applied • Grade: 0
Meteorological Data	Used default tables for each run
Off-Network	---
Operating Mode Distribution	---
Retrofit Data	---
Tools	---

Post-MOVES Run Data Processing

Results from the project-scale MOVES runs described above were utilized to obtain different categories of data for use in the Travel Advisories tool. The following section describes how MOVES activity and emissions inventory data were used to develop the tool's emissions rates.

Light- and heavy-duty vehicle emission rates were calculated separately using otherwise identical procedures: light-duty rate aggregate output for passenger vehicles (sourceTypeID 21); heavy-duty rate output for combination trucks (sourceTypeID 62). Brake- and tire-wear were aggregated into the particulate matter (PM) results for both sets of rates.

1. **Activity rates –** To obtain project-scale activity rates, the distance travelled (activityType1) was extracted from the results for all vehicles.
2. **Hourly emissions –** Emission rates were generated on a per-mile basis. This involved joining emission inventories from the movesoutput table and activity from the movesactivityoutput. To determine emission rates, emissions (aggregated across all processes) were divided by distance travelled.

Emission rates were based on project evaluation year, speed, pollutant, and road type. This process was repeated for each evaluation year (2018, 2020, 2025, 2030, 2035, 2040) and the tables were appended.

MULTIVARIABLE LINEAR REGRESSIONS

Emission benefit rates were calculated by subtracting the emission rates of the smoothed drive cycles from the rates of the standard drive cycles. The rates were then used to construct 14 multivariable linear regression (MLR) equations (2 vehicle classes x 7 pollutants). Each equation was based on 90 data points and estimates the emission benefit rate by pollutant based on evaluation year, smoothing coefficient (i.e., lambda value), and average speed. The MLRs for emission benefit rates, e_s, by vehicle class and pollutant, all take the same general form as Equation 2 for consistency and comparability:

$$e_{s_{veh,pol}} = \beta_{\lambda_{veh,pol}} \cdot \lambda + \beta_{s_{veh,pol}} \cdot s + \beta_{y_{veh,pol}} \cdot y + \beta_{0_{veh,pol}} \quad \textbf{(2)}$$

where,

$\beta_{\lambda_{veh,pol}}$ = regression coefficient for smoothing coefficient by vehicle class and pollutant,
$\beta_{s_{veh,pol}}$ = regression coefficient for average speed by vehicle class and pollutant,
$\beta_{y_{veh,pol}}$ = regression coefficient for evaluation year by vehicle class and pollutant,
$\beta_{0_{veh,pol}}$ = regression y-intercept by vehicle class and pollutant,

$e_{s_{veh,pol}}$ = Emission benefit rate for smoothed drive cycles by vehicle class and pollutant ($\frac{kg}{mi} \times veh$),
λ = user-supplied input for smoothing coefficient value,
s = user-supplied average speed (mph),
y = project evaluation year.

All predictive variables were included in each MLR equation for consistency between scenarios, as detailed in Table 4.

Table 1. Smoothed MLR coefficients and associated correlation coefficients

Scenario	Pollutant	Adj. R^2	y-intercept	Lambda Coef.	Speed Coef.	Year Coef.
HD	CO	0.648	3.40E-03	1.51E-04	-5.07E-06	-1.48E-06
HD	NOx	0.183	1.95E-02	4.32E-04	-7.55E-06	-9.22E-06
HD	VOC	0.599	7.59E-04	1.14E-05	1.88E-07	-3.73E-07
HD	PM2.5	0.629	3.51E-03	1.81E-05	-2.27E-07	-1.72E-06
HD	PM10	0.555	3.91E-03	3.38E-05	-2.45E-07	-1.91E-06
HD	CO2e	0.218	1.57E+00	1.03E-01	-2.56E-03	-6.59E-04
HD	Energy	0.218	2.03E-02	1.33E-03	-3.30E-05	-8.50E-06
LD	CO	0.708	2.41E-02	5.64E-04	-4.89E-06	-1.16E-05
LD	NOx	0.596	1.49E-03	1.98E-05	-2.47E-07	-7.25E-07
LD	VOC	0.610	2.54E-04	3.95E-06	-4.14E-08	-1.24E-07
LD	PM2.5	0.333	1.89E-05	1.23E-06	6.26E-10	-9.34E-09
LD	PM10	0.291	1.83E-05	7.63E-06	3.15E-08	-1.02E-08
LD	CO2e	0.736	2.59E-01	1.78E-02	-2.57E-04	-1.19E-04
LD	Energy	0.592	2.71E-03	1.89E-04	-3.83E-06	-1.20E-06

To evaluate the MLR results, the Pearson correlation coefficient (r, ideal value of 1), normalized mean square error (NMSE, ideal value of 0), and fractional bias (FB, ideal value of 0) were calculated for each model as compared to the MOVES output data (Table 5).

Table 5. MLR coefficients and associated correlation coefficients

Scenario	Pollutant	r	NMSE	FB
HD	CO	0.846	0.105	0.021
HD	PM10	0.764	0.276	0.020
HD	PM2.5	0.806	0.323	0.005
HD	VOC	0.774	0.056	-0.015
HD	NOx	0.507	0.283	-0.001
HD	CO2e	0.564	0.298	0.007
HD	Energy	0.565	0.297	0.005
LD	CO	0.886	0.075	-0.074
LD	PM10	0.396	4.741	-0.182
LD	PM2.5	0.613	0.644	-0.093
LD	VOC	0.818	0.422	-0.045
LD	NOx	0.804	0.657	-0.031
LD	CO2e	0.887	0.112	-0.014
LD	Energy	0.881	0.112	-0.022

A second set of regression models was built to accommodate scenarios when user inputs for average speed and volume are different before and after travel advisories implementation. These models are based on MOVES3 standard drive cycles (with no smoothing). The equation for these models is similar to Equation 2, but with the addition of a speed-squared term and no smoothing variable. The MLRs for unsmoothed emission rates, e_d, by vehicle class and pollutant, take the general form of Equation 3:

$$e_{d_{veh,pol}} = \beta_{0_{veh,pol}} + \beta_{s_{veh,pol}} \cdot s + \beta_{y_{veh,pol}} \cdot y + \beta_{\alpha_{veh,pol}} \cdot \alpha \quad \textbf{(3)}$$

where,

$\beta_{s_{veh,pol}}$ = regression coefficient for average speed by vehicle class and pollutant,
$\beta_{y_{veh,pol}}$ = regression coefficient for evaluation year by vehicle class and pollutant,
$\beta_{0_{veh,pol}}$ = regression y-intercept by vehicle class and pollutant,

$\beta_{\alpha_{veh,pol}}$ = regression coefficient for average speed squared by vehicle class and pollutant,

$e_{d_{veh,pol}}$ = Emission benefit rate for default drive cycles by vehicle class and pollutant $\left(\frac{kg}{mi} \times veh\right)$,
s = user-supplied average speed (mph),
y = project evaluation year,
α = user-supplied average speed squared $(mph)^2$.

All predictive variables were included in each MLR equation for consistency between scenarios, as detailed in Table 6.

Table 6. Unsmoothed MLR coefficients and associated correlation coefficients

Scenario	Pollutant	Adj. R^2	y-intercept	Speed Coef.	Speed^2 Coef.	Year Coef.
HD	CO	0.938	1.27E-01	-1.45E-04	1.10E-06	-5.95E-05
HD	NOx	0.876	7.33E-01	-4.15E-04	3.53E-06	-3.53E-04
HD	VOC	0.891	2.97E-02	-6.60E-06	4.42E-08	-1.45E-05
HD	PM2.5	0.854	2.89E-02	-1.40E-05	1.05E-07	-1.39E-05
HD	PM10	0.907	3.18E-02	-3.78E-05	2.80E-07	-1.50E-05
HD	CO2e	0.923	4.42E+01	-5.15E-02	4.65E-04	-2.04E-02
HD	Energy	0.923	5.69E-01	-6.62E-04	5.97E-06	-2.62E-04
LD	CO	0.945	2.32E-01	-1.53E-04	1.44E-06	-1.11E-04
LD	NOx	0.840	3.15E-02	-1.81E-06	2.45E-08	-1.55E-05
LD	VOC	0.799	5.42E-03	-1.48E-06	1.18E-08	-2.64E-06
LD	PM2.5	0.978	2.09E-04	-4.42E-07	3.13E-09	-9.41E-08
LD	PM10	0.999	3.40E-04	-3.07E-06	2.05E-08	-1.06E-07
LD	CO2e	0.956	9.38E+00	-5.64E-03	4.88E-05	-4.43E-03
LD	Energy	0.956	1.23E-01	-7.39E-05	6.41E-07	-5.81E-05

These regression coefficients and correlation statistics, as well as the underlying traffic and emissions data, can be unhidden in Excel[6] and can be changed if a user wishes to supply their own emissions data for this tool. Users should already have project-specific, project-scale emission rate results prior to attempting to run MLR on their own.

TOOL METHODOLOGY

The following section describes how network performance changes and emissions reductions are calculated in the Travel Advisories tool.

Emission Reductions

Emissions data were obtained from hourly project-scale MOVES runs with standard drive cycles as well as the same drive cycles with a smoothing equation applied to them. Since MOVES was used to perform analyses for only six years (2018, 2020, 2025, 2030, 2035, 2040), a regression model was used to interpolate the data points for the years not evaluated. Regression models were constructed to estimate both emissions benefit rates per hour (kg/hr) and pre- and post-condition emission rates for non-smoothing based emissions changes, for each pollutant.

The first set of 14 regression equations (2 vehicle classes x 7 pollutants), each containing 90 data points were generated with data from the difference in emission rates between the smoothed MOVES drive cycles and the unsmoothed drive cycles. This data is used to calculate the emissions benefits gained from drive cycle smoothing

[6] Unhide underlying traffic and emissions data in Excel by right-clicking on any tab in the tool and selecting to Unhide the Emission_Rate_MLRs sheet.

experienced as a result of implementing travel advisories. A second set of regression models were constructed to calculate the emission benefit (or disbenefit) from a change in average traffic volume and speed.

For each pollutant, the change in emissions (kg/day) reported in the CMAQ tool is the difference between the emissions before (pre-) versus after (post-) implementation of a travel advisories project. The detailed tool methodology, including equations, can be found in the *User Guide Document*.

The Travel Advisories tool uses the results of the MLR to estimate emission benefits for given user input to the tool. Total emissions by scenario are calculated from the product of the emission rates for each input scenario (as determined by user inputs for evaluation year and average speed), the length of the roadway, the traffic volume, and the hours of operation. Emission rates are calculated separately for peak and non-peak traffic periods and incorporate both heavy-duty and light-duty vehicle classes.

Network performance values are calculated based on user inputs of average speed and traffic volume. If the user opts to not input 'after' values, the network performance will be reported as '0' for all metrics since smoothing only modifies the variability of the drive cycle, not the average speed.

For all traffic conditions, a negative value can be interpreted as a decrease in the traffic condition parameter resulting from the conversion project. Positive values are interpreted as an increase in the traffic condition parameter post-conversion.