CMAQ EMISSIONS CALCULATOR TOOLKIT

The purpose of the Congestion Mitigation and Air Quality Improvement Program Emissions Calculator Toolkit (CMAQ Toolkit) is to provide users a standardized approach to estimating emission reductions from the implementation of a CMAQ-funded project. The CMAQ Toolkit uses emission rates for highway vehicles based on a series of project-scale and national-scale runs of the Motor Vehicle Emission Simulator (MOVES) as well as other data sources. For each tool in the toolkit, the inputs and methodology are described in user guides along with some example cases. Emission estimates from the CMAQ Toolkit are not intended to meet specific requirements for State Implementation Plans (SIPs) or transportation conformity analyses. Information regarding the development of default emission rates and guidance on incorporating user-supplied emission rates can be found in the accompanying documentation of the emissions data.

Intersection Improvements Module

Modifying an existing intersection can improve both roadway performance and reduce emissions from vehicles moving through it. The Intersection Improvements Module of the Traffic Flow Improvements Tool estimates both performance metrics and emissions benefits for a single intersection for a project that:

- Installs a new traffic signal where a previous two-way stop or four-way stop existed before,
- Adds or modifies a signal's turn phase (i.e., dedicated left-turn or right-turn signal), and/or
- Increases capacity by adding a left-turn lane at an intersection with a left-turn phase.

This tool is intended to analyze a standard four-way intersection. Effects on emissions are calculated by estimating the reduction in idling emissions from proposed effects on delay at the intersection, and comparing to the existing/no-build delay. Emissions effects are calculated for peak- and off-peak hours on a typical weekday. [1]

This document is organized into three sections – User Guide, Tool Methodology, and Examples – to aid the user in understanding and interpreting results from the calculator. The User Guide directs the user on how to properly input values into the tool, and provides definitions of both user inputs and tool outputs. The Tool Methodology section outlines the steps taken by the tool to calculate emission reductions, as well as any assumptions incorporated into the tool. This section also describes the equations used within the tool to calculate emission benefits. The Examples section provides instructive examples of how to use the tool for project analysis.

[1] The most current version of the tool is dated July 2019. To verify the version, check the date on the Introduction page of the tool. Release notes are included in the Change Log tab, which can be viewed by right-clicking on any tab in the tool, selecting "Unhide", and revealing the tab.

Contents

USER GUIDE

This section describes each user input and tool output, as well as the emissions reductions report, error messages, and other assumptions present in the tool.

User Inputs

The Intersection Improvements Module contains a series of questions to guide the user in properly inputting information for emission reductions calculations in a step-by-step process. The inputs for this tool should be specific to the vehicles and road types involved in the project.

Table 1. User Inputs for Existing Conditions

User Input	Units	Description
Evaluation year	-----	Use the drop-down menu to choose a year between 2019 and 2030.
Area type	-----	Use the drop-down menu to indicate a rural or urban intersection. All road types refer to MOVES unrestricted roads (RoadType 3 or 5).
Business district	-----	If this intersection is located in a central business district, please use the drop-down menu to choose 'Yes'; otherwise, choose 'No'.
Total peak hours per day (AM+PM)	hours	Input the total number of peak hours the intersection experiences on a typical weekday. The default value is four hours.
Existing Intersection is	-----	If the existing intersection is controlled by a traffic signal, please use the drop-down menu to choose 'Signalized'; otherwise, choose 'Un-signalized'.
Average Annual Daily Traffic Volume (AADT), Roadway 1 (both directions)	vehicles/day	Input the annual average daily traffic for both approach directions and across all lanes.
Peak-hour volume (both directions)	vehicles/hour	Input the weekday peak average hourly volume of traffic for both approach directions and across all lanes.
Number of lanes (one direction)	-----	Input the number of existing through lanes for one approach direction.
Truck percentage	-----	Input the percent of traffic that is heavy-duty truck vehicles. The default value is 6%, based on MOVES default activity rates.
Existing delay per vehicle	seconds	Input the existing/no-build delay for one direction of Roadway 1 at the intersection. If field data is available, please choose the greater delay value of the two directions. If field data is not available, you can approximate an appropriate delay value from the table given the intersection's existing level of service. This table comes from the Highway Capacity Manual 2010, Exhibit 21-1
Existing left-turn phase	-----	If there is an existing protected left-turn signal for Roadway 1, please use the drop-down menu to choose 'Yes'; otherwise, choose 'No'. If the existing intersection is un-signalized, choose 'No'.

User Input	Units	Description
Existing right-turn phase	-----	If you have an existing protected right-turn signal for Roadway 1, please use the drop-down menu to choose 'Yes'; otherwise, choose 'No'. If the existing intersection is un-signalized, choose 'No'

Table 2. Proposed Conditions

User Input	Units	Description
Cycle length	seconds	Input the proposed/new cycle length of the intersection. The default value is 90 seconds.
Number of Left-Turn Lanes to Add, Roadway 1, (one direction)	-----	Input the number of dedicated left-turn lanes for one approach direction that the project will build for Roadway 1.
Number of Left-Turn Lanes to Add, Roadway 2, (one direction)	-----	Input the number of dedicated left-turn lanes for one approach direction that the project will build for Roadway 2.
Left-turn phase, Roadway 1, (proposed)	-----	If the proposed project will have a protected left-turn signal for Roadway 1, please use the drop-down menu to choose 'Yes'; otherwise, choose 'No'.
Left-turn phase, Roadway 2, (proposed)	-----	If the proposed project will have a protected left-turn signal for Roadway 2, please use the drop-down menu to choose 'Yes'; otherwise, choose 'No'.
Right-turn phase, Roadway 1, (proposed)	-----	If your proposed project will have a protected right-turn signal for Roadway 1, please use the drop-down menu to choose 'Yes'; otherwise, choose 'No'.
Right-turn phase, Roadway 2, (proposed)	-----	If your proposed project will have a protected right-turn signal for Roadway 2, please use the drop-down menu to choose 'Yes'; otherwise, choose 'No'.
Ratio of green time per cycle time, Roadway 1	-----	Input the ratio of the time the signal is green to total cycle time for Roadway 1. Note: The green to cycle ratio for Roadways 1 and 2 should sum to 1.
Ratio of green time per cycle time, Roadway 2	-----	Input the ratio of the time the signal is green to total cycle time for Roadway 2. Note: The green to cycle ratio 1 for Roadways 1 and 2 should sum to 1.

Tool Outputs

Once the input parameters are entered, click the 'Calculate Output' button to generate your results. Emission results will not automatically update: if any changes are made to the input parameters, this button must be clicked again to calculate updated emission reductions. If you would like to return to default settings and clear input values, click on the 'Reset to Default Values' button.

Emission reductions are calculated for five pollutants – carbon monoxide (CO), particulate matter < 2.5 µm ($PM_{2.5}$), particulate matter < 10 µm (PM_{10}), nitrogen oxides (NOx), and volatile organic compounds (VOC) – in kilograms per day. Reductions in carbon dioxide equivalents (CO_2e) and total energy consumption (million BTU) are also provided. These parameters are outputs from MOVES related to greenhouse gas reporting.

Note that a '0' value for an emission reduction indicates no change in emissions associated with the project. A negative emissions reduction indicates a disbenefit (i.e., implementation of the project results in an increase in emissions for the particular pollutant).

Table 3. Proposed Conditions

Output	Units	Description
Peak-hour existing capacity (both directions)	vehicles/hour	The calculated capacity for the existing intersection conditions
Off-peak existing capacity (both directions)	vehicles/hour	The calculated capacity for the existing intersection conditions. This tool assumes the same capacity for peak-hour and off-peak conditions
Peak-hour proposed capacity (both directions)	vehicles/hour	The calculated capacity for proposed intersection conditions, including phase changes and added left-turn capacity.
Off-peak proposed capacity (both directions)	vehicles/hour	The calculated capacity for proposed intersection conditions, including phase changes and added left-turn capacity. This tool assumes the same capacity for peak-hour and off-peak conditions
Peak hour volume (both directions)	vehicles/hour	The weekday peak hours average hourly volume of traffic for both directions and across all lanes, as input by the user
Off-peak volume (both directions)	vehicles/hour	The calculated off-peak hourly volume found by subtracting total peak traffic from the annual average daily traffic in both directions and across all lanes
Peak-hour delay reduction per vehicle	seconds/vehicle	The calculated delay reduction from the existing delay input by the user
Off-peak delay reduction per vehicle	seconds/vehicle	The calculated delay reduction from the existing calculated delay
Roadway intersection delay reduction per day	hours	Delay reduction per vehicle multiplied by the volume of traffic for all hours
Total intersection delay reduction per day	hours	Summed delay reduction for Roadways 1 and 2 for all traffic volume during all hours

Error Messages

Table 4 below lists error messages the user may encounter in this tool, the reason for the error message, and the solution. Once you correct any errors, please press ‘Calculate Output’ to recalculate the results.

Table 4. Error Messages

Error Message	Reason for Error	Solution
Please enter an appropriate project evaluation year between 2019-2030 before proceeding.	Invalid or missing project evaluation year.	Select an appropriate value from the drop-down menu.
You have not entered a valid area type. Please revise before proceeding.	--	Select an appropriate value from the drop-down menu.
You have not correctly entered whether the project occurs in a business district.	--	Select an appropriate value from the drop-down menu.
The project's total peak hours per day is invalid.	Value is either negative or exceeds 24 hours.	Ensure that this value is both positive and does not exceed 24 hours before proceeding.
You have not selected whether the existing intersection is signalized.	--	Select an appropriate value from the drop-down menu.
Adding a turn lane requires a turn phase in the proposed intersection.	--	Adjust values before proceeding.
Proposed improvements should not remove signal phases from existing intersections.	--	Adjust values before proceeding.
Truck percentage cannot be greater than 100%	Traffic volume is composed of more than 100% trucks	Reduce truck volume
Volume-to-capacity ratio is greater than one.	--	Adjust number of lanes, posted speed-limit or traffic volume to remedy volume-to-capacity ratio. The tool assumes no emission reductions for volume-to-capacity ratio greater than one.
The total green light signal phase time cannot be greater than 100%	The sum of the green-time-to-cycle-time ratios is greater than one, meaning the light is green for both directions at the same time – which would result in accidents.	Fix green-time-to-cycle-time ratio for either roadway.

TOOL METHODOLOGY

Delay Reduction Equations

The methodology for calculating emission reductions is derived from the calculation of delay reduction at the intersection as a result of intersection improvements. The Highway Capacity Manual (2010) provides the following equation for calculating uniform delay, d_1, at a signalized intersection[2]:

$$d_1 = \frac{0.5C(1-\frac{g}{C})^2}{1-\left[\min(1,X)\frac{g}{C}\right]} \qquad (1)$$

Where:

C = cycle length (seconds),

g/C = green light duration to total cycle duration ratio;

min(1, X) is function to limit the volume to capacity ratio to a maximum of 1.0 by choosing the smallest value of 1 or X; and

X, defined as the highest volume to capacity ratio of any turning movement or lane group at intersection, is expressed in the following equation[3]:

$$X = \frac{v}{c} = \frac{v}{Ns\frac{g}{C}} \qquad (2)$$

where:

v = volume (vehicles/hour) (one direction),

c = capacity,

N = number of throughput lanes + 0.5*number of added left-turn lanes, (one direction), and

s = saturation flow rate/lane (passenger cars/lane/hour).

Saturation, given in the equation below, starts with a base saturation rate of 1,800 passenger vehicles per hour and applies appropriate factors that account for heavy-duty trucks, area type, and protected left- and right-turns[4]:

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[2] Equation 18-20 in Chapter 18: Signalized Intersection, Highway Capacity Manual, Transportation Research Board National Academy of Sciences, Washington DC, 2010.

[3] Equation, Chapter 18: Signalized Intersections, Highway Capacity Manual, Transportation Research Board National Academy of Sciences, Washington DC, 2010.

[4] Equation, Chapter 18: Signalized Intersections, Highway Capacity Manual, Transportation Research Board National Academy of Sciences, Washington DC, 2010

$$s = s_0 f_{HV} f_a f_{RT} f_{LT} \tag{3}$$

where:

s_0 = base saturation rate/lane (passenger cars/lane/hour),

f_{HV} = adjustment factor for heavy-duty trucks = $\frac{100}{100 + P_{HV}(E_T - 1)}$,

where P_{HV} = percent trucks and E_T = car equivalency = 2.0,

f_a = adjustment factor for area type = 0.90 for a central business district and 1.00 otherwise,

f_{RT} = adjustment factor for protected right-turns = $\frac{1}{E_R}$,

where E_R = the equivalent number of through cars for a protected right-turning vehicle = 1.18, and

f_{LT} = adjustment factor for protected left-turns = $\frac{1}{E_L}$,

where E_L = the equivalent number of through cars for a protected left-turning vehicle = 1.05.

The left-turn and right-turn factors are only applied when the user indicates that such signal phasing will exist in the improved intersection. Likewise, the area type adjustment factor is only applied for areas that are in central business districts.

For peak hour calculations, the volume is given by the user. For off-peak calculations, the volume is calculated by subtracting the total peak-hour volume in a typical weekday from the annual average daily traffic volume given by the user.

Delay reduction is calculated by taking the difference of the calculated intersection delay from existing delay for a single vehicle approaching the intersection on that roadway. For peak hours, the existing delay is input by the user. For off-peak hours, the existing delay, d_1, is calculated from hourly volume and existing road capacity using equation (1) for an existing signalized intersection or using the following equation for an existing un-signalized intersection[5]:

$$d_1 = \frac{3600}{c} + 900T\left[\frac{v}{c} - 1 + \sqrt{\left(\frac{v}{c} - 1\right)^2 + \frac{\left(\frac{3600}{c}\right)x}{450T}}\right] + 5 \tag{4}$$

[5] Equation 19-64, Chapter 19: Two-Way Stop-Controlled Intersections, Highway Capacity Manual, Transportation Research Board National Academy of Sciences, Washington DC, 2010. (Note: This equation follows the same form as for a four-way stop controlled intersection)

where:

x = volume-to-capacity ratio of lane = v/c,

c = capacity of the approach (vehicles/hour), which was defined previously[6], and

T = time period (hours) (T = 0.25 hours for a 15-minute analysis).

Volume for off-peak hours, in vehicles/hour, is calculated using the following equation:

$$v_{off-peak} = \frac{AADT - h_{peak}\, v_{peak}}{24 - h_{peak}} \quad (5)$$

where:

AADT = annual average daily traffic (vehicles/day),

h_{peak} = the number of peak hours in a day (hours),

v_{peak} = peak-hour hourly volume (vehicles/hour).

The intersection approach to delay reduction for a given roadway is then multiplied across the total volume for that roadway to account for delay reductions for all traffic on the roadway during a weekday.

Idling emission rates (kg/hr) for the analysis year and area type are multiplied by the delay reduction for that roadway and then summed with the product from the other roadway to obtain total emission reductions for a given pollutant for the entire intersection for both peak-hours and off-peak hours. The peak-hour emission reductions and off-peak hour emission reductions are summed to yield total daily emission reductions for a weekday, reported in kilograms/day.

[6] This project assumes no change in capacity except for left-turn lane added capacity. Therefore, for the existing intersection, the capacity for signalized intersections is used for un-signalized intersections in the off-peak delay calculations

EXAMPLES

The examples below describe how to use the Intersection Improvements Module.

Example 1: Signalization

A rural municipal government has determined that an intersection currently controlled by stop signs could benefit from signalization. They conduct an analysis in order to simulate the anticipated benefits.

Using this information, the user would enter the following inputs into the tool to analyze the scenario, as shown below:

INPUT

EXISTING CONDITIONS

Reset to Default Values

Evaluation Year	2028	
Area Type	Rural	
Business District	No	
Total peak hours per day(AM+PM)	4	
Existing Intersection is	Un-signalized	

	Roadway 1	Roadway 2	
Average Annual Daily Traffic volume (AADT) (both directions)	14,750	12,500	veh/day
Peak-hour Volume (both directions)	1,625	1,400	veh/hr
Number of Lanes (one direction)	1	1	
Truck Percentage	6%	6%	
Existing Delay per Vehicle	35	40	sec/veh
Existing Left-turn Phase	No	No	
Existing Right-turn Phase	No	No	

PROPOSED CONDITIONS

Cycle Length	90	seconds

	Roadway 1	Roadway 2
Number of Left-Turn Lanes to Add (one direction)	1	1
Left-turn Phase	Yes	Yes
Right-turn Phase	No	No
Ratio of Green Time per Cycle Time	0.5	0.5

Project evaluation year: 2028
Area type: Rural
Business district: No
Total peak hours: 4
Existing intersection: Un-signalized

Existing Conditions
AADT: 14,750/12,500
Peak hour volume: 1,625/1,400
Number of lanes: 1 for both
Truck percentage: 6% for both
Existing delay per vehicle: 35/40
Existing left turn phase: No for both
Existing right turn phase: No for both

Proposed Conditions
Cycle length: 90 seconds
Number of left turn lanes to add: 1 each
Left turn phase: Yes for both
Right turn phase: No for both
Green time ratio: 0.5 for each

Pressing the "Calculate Output" button produces the following results:

PERFORMANCE

Roadway	PEAK-HOUR 1	PEAK-HOUR 2	OFF-PEAK 1	OFF-PEAK 2	
Existing Capacity (both directions)	1,698	1,698	1,698	1,698	veh/hr
Proposed Capacity (both directions)	2,426	2,426	2,426	2,426	veh/hr
Volume (both directions)	1,625	1,400	413	345	veh/hr
Delay Reduction per vehicle	18.1	24.2	-4.5	-4.5	sec/veh

Roadway	1	2	
Roadway Intersection Delay Reduction per day	22.3	29.1	hours
Total Intersection Delay Reduction per day	51.4		hours

EMISSION REDUCTIONS

Pollutant	Peak Hours Kilograms/day	Off-Peak Hours Kilograms/day	Daily Total Kilograms/day
Carbon Monoxide (CO)	0.120	0.000	0.120
Particulate Matter <2.5 µm ($PM_{2.5}$)	0.009	0.000	0.009
Particulate Matter <10 µm (PM_{10})	0.009	0.000	0.009
Nitrogen Oxide (NOx)	0.101	0.000	0.101
Volatile Organic Compounds (VOC)	0.018	0.000	0.018
Carbon Dioxide Equivalent (CO2e)	197.043	-0.053	196.990
Total Energy Consumption (MMBTU)	2.586	-0.001	2.585

The total daily emission reductions in kg/day and TEC reductions in millions of British Thermal Units (MMBTU) are:

Carbon Monoxide (CO): 0.120
Particulate Matter (PM2.5): 0.009
Particulate Matter (PM10): 0.009
Nitrogen Oxide (NOx): 0.101
Volatile Organic Compounds (VOC): 0.018

Carbon Dioxide Equivalent (CO_2e): 196.990
Total Energy Consumption (TEC): 2.585

Example 2: Signal Improvements

A municipal government has determined that an existing signalized intersection should be optimized. They propose adding left and right turn phases where none existed before.

Using this information, the user would enter the following inputs into the tool to analyze the scenario, as shown below:

INPUT

EXISTING CONDITIONS

Reset to Default Values

Evaluation Year	2028
Area Type	Urban
Business District	No
Total peak hours per day(AM+PM)	4
Existing Intersection is	Signalized

	Roadway 1	Roadway 2	
Average Annual Daily Traffic volume (AADT) (both directions)	22,000	20,500	veh/day
Peak-hour Volume (both directions)	1,405	1,385	veh/hr
Number of Lanes (one direction)	2	2	
Truck Percentage	6%	6%	
Existing Delay per Vehicle	40	40	sec/veh
Existing Left-turn Phase	No	No	
Existing Right-turn Phase	No	No	

PROPOSED CONDITIONS

Cycle Length	90	seconds

	Roadway 1	Roadway 2
Number of Left-Turn Lanes to Add (one direction)	1	1
Left-turn Phase	Yes	Yes
Right-turn Phase	Yes	Yes
Ratio of Green Time per Cycle Time	0.5	0.5

Project evaluation year: 2028
Area type: Urban
Business district: No
Total peak hours: 4
Existing intersection: Signalized

Existing Conditions
AADT: 22,000/20,500
Peak hour volume: 1,405/1,385
Number of lanes: 2 for both
Truck percentage: 6% for both
Existing delay per vehicle: 40 for both
Existing left turn phase: No for both
Existing right turn phase: No for both

Proposed Conditions
Cycle length: 90 seconds
Number of left turn lanes to add: 1 each
Left turn phase: Yes for both
Right turn phase: Yes for both
Green time ratio: 0.5 for each

Pressing the "Calculate Output" button produces the following results:

PERFORMANCE

	PEAK-HOUR		OFF-PEAK		
Roadway	**1**	**2**	**1**	**2**	
Existing Capacity (both directions)	3,396	3,396	3,396	3,396	veh/hr
Proposed Capacity (both directions)	4,043	4,043	4,043	4,043	veh/hr
Volume (both directions)	1,405	1,385	819	748	veh/hr
Delay Reduction per vehicle	26.4	26.4	0.3	0.2	sec/veh

Roadway	**1**	**2**	
Roadway Intersection Delay Reduction per day	42.4	41.7	hours
Total Intersection Delay Reduction per day	84.1		hours

EMISSION REDUCTIONS

Pollutant	Peak Hours Kilograms/day	Off-Peak Hours Kilograms/day	Daily Total Kilograms/day
Carbon Monoxide (CO)	0.134	0.000	0.134
Particulate Matter <2.5 µm ($PM_{2.5}$)	0.010	0.000	0.010
Particulate Matter <10 µm (PM_{10})	0.010	0.000	0.010
Nitrogen Oxide (NOx)	0.111	0.000	0.111
Volatile Organic Compounds (VOC)	0.020	0.000	0.020
Carbon Dioxide Equivalent (CO2e)	226.419	0.006	226.425
Total Energy Consumption (MMBTU)	2.972	0.000	2.972

The total daily emission reductions in kg/day and TEC reductions in millions of British Thermal Units (MMBTU) are:

Carbon Monoxide (CO): 0.134
Particulate Matter (PM2.5): 0.010
Particulate Matter (PM10): 0.010
Nitrogen Oxide (NOx): 0.111
Volatile Organic Compounds (VOC): 0.020

Carbon Dioxide Equivalent (CO_2e): 226.425
Total Energy Consumption (TEC): 2.972