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.

Roundabouts Module

The roundabout project emission reductions calculator estimates the emissions benefit for installing a roundabout in place of a traditional signalized or un-signalized intersection. This tool is intended for a single or double lane roundabout with three or four approaches.[1]

Emission reductions are estimated by calculating the reduction in idling emissions as a result of installing the roundabout. This is accomplished by calculating the post-build delay at the roundabout and subtracting it from the existing/no-build delay at the intersection. Emission reductions are calculated for peak and off-peak hours during a typical weekday.

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 June 2022. 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.

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USER GUIDE

This section lists the units and description for each user input and tool output. A description of emission reductions reporting and error messages as well as other assumptions inherent in the tool is provided.

User Inputs

Note: When entering values for the approaches, please do so in a clockwise direction to allow for proper roundabout calculation of emission reductions.

The user-defined inputs for this type of project are shown below:

Table 1. User Inputs for Existing Conditions

User Input	Units	Description
Evaluation year	-----	Use the drop-down menu to choose a year between 2018 and 2030.
Area type	-----	Use the drop-down menu to choose either Rural or Urban to indicate a rural or urban unrestricted intersection.
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 4 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 (AADT) volume, each approach	vehicles/day	Input the AADT volume of traffic across all lanes of travel for each approach.
Peak-hour volume, each approach	vehicles/hour	Input the average hourly volume of traffic across all lanes during weekday peak hours of travel for each approach.
Truck percentage, each approach	-----	Input the percent of heavy-duty traffic for each approach. The default value is 6%, per MOVES activity rates.
Existing delay per vehicle, each approach	seconds	Input the existing/no-build build delay for each approach of the existing intersection. Please use field data when available. If field data is not available, you can approximate an appropriate delay value from the table given the intersection's existing level of service.[2]
Number of lanes, each approach	-----	Use the drop-down menu to choose either '1' or '2' lanes to indicate the number of lanes for each

[2] Exhibit 21-1, Highway Capacity Manual, Transportation Research Board National Academy of Sciences, Washington DC, 2010.

User Input	Units	Description
		approach of the intersection. The default value is 1 lane.
Percent left turns, each approach	-----	Input the percent of traffic in each approach that takes a left turn at the existing intersection.
Percent right turns, each approach	-----	Input the percent of traffic in each approach that takes a right turn at the existing intersection.

Table 2: Proposed Conditions

User Input	Units	Description
Number of circulating roundabout lanes (proposed)	-----	Use the drop-menu to choose either '1' or '2' to indicate the number of circulating lanes that the proposed roundabout will have. The default value is 1 lane.

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 atmospheric carbon dioxide, 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 Modifications

Output	Units	Description
Peak-hour proposed capacity, each approach	vehicles/hour	Calculated capacity for each approach's entry for a peak hour into the roundabout, calculated from the conflicting flow rate within the roundabout circulating lane(s).
Off-peak proposed capacity, each approach	vehicles/hour	Calculated capacity for each approach's entry during off-peak hours into the roundabout, calculated from the conflicting flow rate within the roundabout circulating lane(s).

Output	Units	Description
Peak-hour volume, each approach	vehicles/hour	The average peak-hour hourly volume of traffic for each approach, adjusted to account for heavy-duty vehicles.
Off-peak volume, each approach	vehicles/hour	The average off-peak hourly volume of traffic for each approach, calculated from AADT and adjusted to account for heavy-duty vehicles.
Peak-hour delay reduction per vehicle, each approach	seconds/vehicle	Using the methodology explained below, the calculated delay reduction from the existing delay input by the user for each approach for peak hours.
Off-peak delay reduction per vehicle, each approach	seconds/vehicle	Using the methodology explained below, the calculated delay reduction from the existing delay input by the user for each approach for off-peak hours.
Approach delay reduction per day, each approach	hours	Delay reduction per vehicle multiplied by the volume of traffic for peak- and off-peak hours for each approach in a typical weekday.
Total roundabout delay reduction per day	hours	Summed delay reduction for all approaches during peak- and off-peak hours in a typical weekday.

Error Messages

Table 3 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 2018-2040 before proceeding.	Invalid or missing project evaluation year.	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.
Truck percentage cannot be greater than 100%	Traffic volume is composed of more than 100% trucks	Reduce truck volume.
Roadway is over capacity.	--	Adjust correct traffic volume, truck percentage, number of lanes, or left- and right-turn percentages before proceeding.

TOOL METHODOLOGY

The methodology for calculating emission reductions is derived from the calculation of delay reduction at the intersection as a result of installing a roundabout. The Highway Capacity Manual (2010) provides the following equation for calculating the average control delay, d, at a roundabout[3]:

$$d = \frac{3600}{c} + 900T\left[x - 1 + \sqrt{(x-1)^2 + \frac{\left(\frac{3600}{c}\right)x}{450T}}\right] + 5 \times \min[x, 1] \quad (1)$$

where:

d = average control delay (seconds/vehicle),

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

c = capacity of the subject lane (vehicles/hour),

min( ) 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

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

The capacity, c, and volume-to-capacity, x, for a lane in a roundabout approach are heavily influenced by the circulating flow within the roundabout. As such, an important parameter in the calculation of capacity and volume-to-capacity is the conflicting flow, or the flow that passes directly in front of the subject lane. For this tool, the conflicting flow that affects the volume coming into the roundabout for the subject lane, $v_{c,pce,n}$, is defined using the following equation for a three- or four-approach roundabout:

$$v_{c,pce,n} = \begin{cases} (1 - P_{RT,n-1})v_{pce,n-1}, & N_a = 3 \\ (1 - P_{RT,n-1})v_{pce,n-1} + P_{LT,n-2}v_{pce,n-2}, & N_a = 4 \end{cases} \quad (2)$$

where:

N_a = number of approaches to the roundabout

[3] Equation 21-17 in Chapter 21: Roundabouts, Highway Capacity Manual, Transportation Research Board, National Academy of Sciences, Washington DC, 2010.

$P_{RT,n-1}$ = percent of right-turning passenger vehicles from the approach entering the roundabout directly upstream of the subject approach,
$v_{pce,n-1}$ = volume of vehicles entering the roundabout directly upstream the subject approach,

$P_{LT,n-2}$ = percent of left-turn passenger vehicles from the approach entering the roundabout two entries upstream the subject approach, and
$v_{pce,n-2}$ = volume of vehicles entering the roundabout two entries upstream the subject approach.

The volumes, $v_{i,pce}$, entering the roundabouts are input based on a passenger car entry volume and adjusted for heavy-trucks using the following equation[4]:

$$v_{i,pce} = \frac{v_i}{f_{HV}} \quad (2)$$

where:

v_i = volume of the approach and

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

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

The equations that are used to define capacity vary depending on roundabout geometry (number of circulating lanes and number of entry lanes).

Capacity of an approach into a roundabout, $c_{e,pce}$, with one circulating lane is given as[5]:

$$c_{e,pce} = 1{,}130Ne^{(-1.0\times10^{-3})v_{c,pce}} \quad (3)$$

Where:

N = number of lanes of the subject approach and

$v_{c,pce}$ = conflicting flow of the subject approach, defined previously.

Capacity for an approach into a roundabout with two circulating lanes, $c_{e,pce}$, is defined with the equation[6]:

[4] Equations 21-9 and 21-10 in Chapter 21: Roundabouts, Highway Capacity Manual, Transportation Research Board, National Academy of Sciences, Washington DC, 2010.
[5] Equations 21-1 and 21-2 in Chapter 21: Roundabouts, Highway Capacity Manual, Transportation Research Board, National Academy of Sciences, Washington DC, 2010.
[6] Equations 21-3, 21-2, and 21-3 in Chapter 21: Roundabouts, Highway Capacity Manual, Transportation Research Board, National Academy of Sciences, Washington DC, 2010.

$$c_{e,pce} = \begin{cases} 1{,}130e^{(-0.7\times10^{-3})v_{c,pce}}, & N_c = 1 \\ 1{,}130e^{(-0.7\times10^{-3})v_{c,pce}} + 1{,}130e^{(-0.75\times10^{-3})v_{c,pce}}, & N_c = 2 \end{cases} \quad (4)$$

where:

N_c = number of approach lanes and

$V_{c,pce}$ = conflicting flow of the subject approach, defined previously.

Once the appropriate capacity, c, is calculated, volume-to-capacity, x_i, can be calculated using the following[7]:

$$x_i = \frac{v_{i,pce} f_{HV}}{c_{i,pce} f_{HV}} \quad (5)$$

Where:

$v_{i,pce}$ = adjusted passenger car volume of the subject approach,

$c_{i,pce}$ = capacity of the subject approach, and

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

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

Once delay for the subject approach to the roundabout is calculated, a delay reduction can be found by subtracting from the existing/pre-build project delay input by the user. For off-peak hours, the existing delay, d_1, is calculated from hourly volume and existing road capacity using equation (7), below, for an existing un-signalized intersection[8] or using equation (8), for an existing signalized intersection:

$$d_1 = \frac{3600}{c} + 900T\left[\frac{v}{c} - 1 + \sqrt{\left(\frac{v}{c} - 1\right)^2 + \frac{\left(\frac{3600}{c}\right)x}{450T}}\right] + 5 \quad (7)$$

Where:

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

[7] Equations 21-13, 21-14, and 21-16 in Chapter 21: Roundabouts, Highway Capacity Manual, Transportation Research Board, National Academy of Sciences, Washington DC, 2010.

[8] 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)

c = capacity of the approach (vehicles/hour), which was defined previously[9], and

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

The Highway Capacity Manual (2010) provides the following equation for calculating uniform delay, d_1, at a signalized intersection[10]:

$$d_1 = \frac{0.5C(1-\frac{g}{C})^2}{1-\left[\min(1,X)\frac{g}{C}\right]} \quad (8)$$

Where:

C = cycle length (seconds),

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

X = volume/capacity, calculated previously.

For the signalized existing delay calculation, the cycle length and green to total light ratio used default values of 90 and 0.5, respectively.

Multiplying by the approach volume and the number of peak hours in a day yields the delay reduction for all peak-hour traffic for that approach in a typical weekday. Likewise, multiplying the off-peak approach volume by the off-peak hours gives the off-peak total delay for a typical weekday.

Appropriate idling emission rates (grams/hour) for the analysis year and area type, which were previously calculated in MOVES are weighted appropriately to reflect a user-specified light-duty/heavy-duty (truck) fleet mix. The weighted fleet mix emission rates for a given pollutant are multiplied by the delay reduction for the approach and then summed with the product from the other approaches to obtain total emission reductions for a given pollutant for the entire roundabout for both peak- and off-peak hours in a typical weekday, reported in kilograms/day.

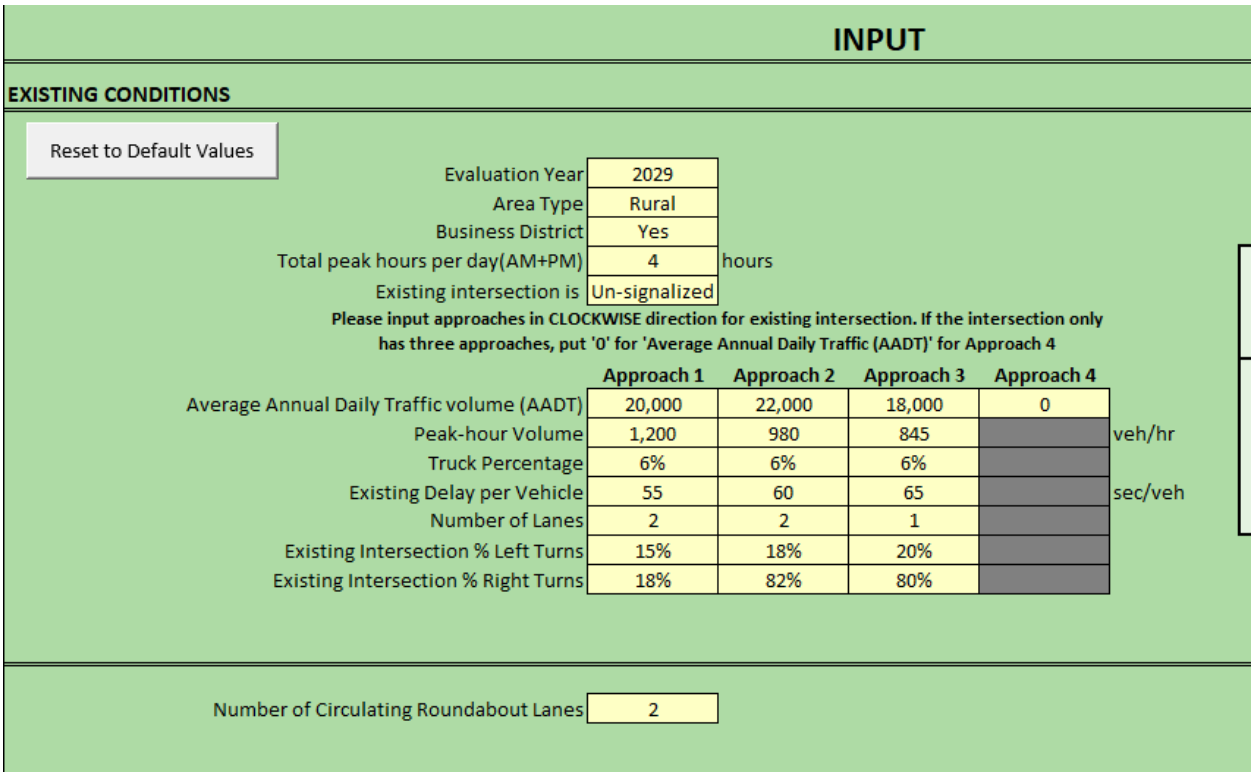
[9] This project assumes no change in capacity except for left-turn lane added capacity. Therefore, for the existing intersection, the capacity for signalized intersections is used for unsignalized intersections in the off-peak delay calculations

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

EXAMPLE

Rural Installation

A three-way intersection at one end of a rural municipality's main street is currently controlled by stop signs. This frequently causes backups into the street: cars and trucks idle, and pedestrians complain about the noise and fumes, especially when the weather is nice. The city's department of transportation is considering installing a three-legged roundabout in its place. Using this information, the user would enter the following into the tool to analyze the scenario:



INPUT

EXISTING CONDITIONS

Reset to Default Values

Evaluation Year	2029
Area Type	Rural
Business District	Yes
Total peak hours per day(AM+PM)	4 hours
Existing intersection is	Un-signalized

Please input approaches in CLOCKWISE direction for existing intersection. If the intersection only has three approaches, put '0' for 'Average Annual Daily Traffic (AADT)' for Approach 4

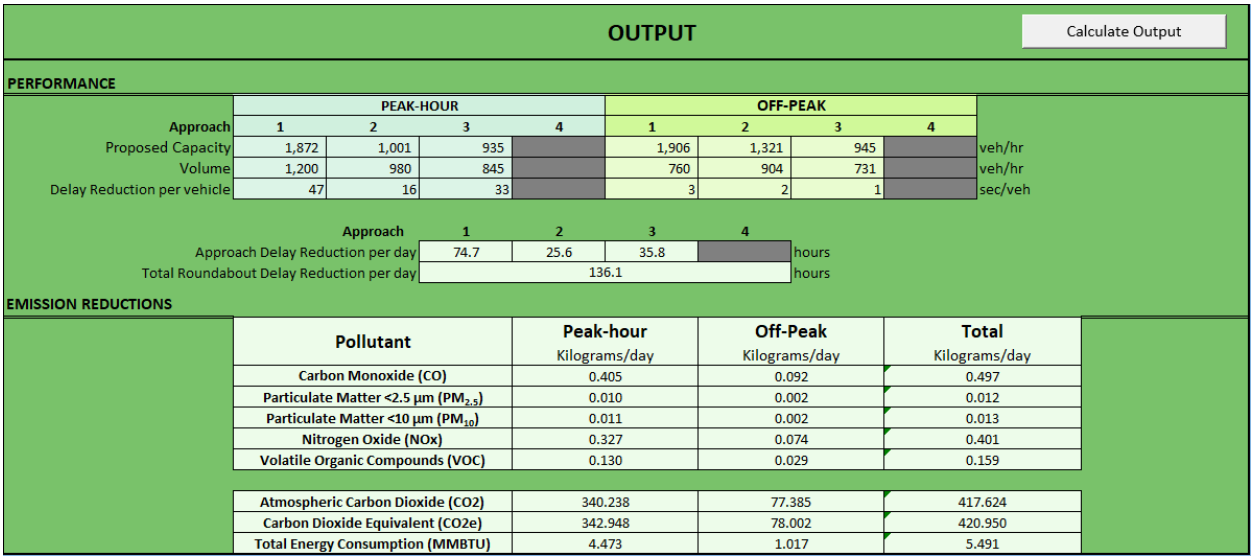
	Approach 1	Approach 2	Approach 3	Approach 4	
Average Annual Daily Traffic volume (AADT)	20,000	22,000	18,000	0	
Peak-hour Volume	1,200	980	845		veh/hr
Truck Percentage	6%	6%	6%		
Existing Delay per Vehicle	55	60	65		sec/veh
Number of Lanes	2	2	1		
Existing Intersection % Left Turns	15%	18%	20%		
Existing Intersection % Right Turns	18%	82%	80%		

Number of Circulating Roundabout Lanes: 2

Project evaluation year: 2029
Area type: Rural
Business district: Yes
Total peak hours: 4
Existing intersection: Un-signalized
Number of circulating lanes: 2

Parameter	Approach 1	Approach 2	Approach 3
Average Annual Daily Traffic volume (AADT)	20,000	22,000	18,000
Peak-hour Volume	1,200	980	845
Truck Percentage	6%	6%	6%
Existing Delay per Vehicle	55	60	65
Number of Lanes	2	2	1
Existing Intersection % Left Turns	15%	18%	20%
Existing Intersection % Right Turns	18%	82%	80%

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



OUTPUT — Calculate Output

PERFORMANCE

	PEAK-HOUR				OFF-PEAK				
Approach	1	2	3	4	1	2	3	4	
Proposed Capacity	1,872	1,001	935		1,906	1,321	945		veh/hr
Volume	1,200	980	845		760	904	731		veh/hr
Delay Reduction per vehicle	47	16	33		3	2	1		sec/veh

Approach	1	2	3	4	
Approach Delay Reduction per day	74.7	25.6	35.8		hours
Total Roundabout Delay Reduction per day	136.1				hours

EMISSION REDUCTIONS

Pollutant	Peak-hour Kilograms/day	Off-Peak Kilograms/day	Total Kilograms/day
Carbon Monoxide (CO)	0.405	0.092	0.497
Particulate Matter <2.5 µm ($PM_{2.5}$)	0.010	0.002	0.012
Particulate Matter <10 µm (PM_{10})	0.011	0.002	0.013
Nitrogen Oxide (NOx)	0.327	0.074	0.401
Volatile Organic Compounds (VOC)	0.130	0.029	0.159

Atmospheric Carbon Dioxide (CO2)	340.238	77.385	417.624
Carbon Dioxide Equivalent (CO2e)	342.948	78.002	420.950
Total Energy Consumption (MMBTU)	4.473	1.017	5.491

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

Carbon Monoxide (CO): 0.497
Particulate Matter (PM2.5): 0.012
Particulate Matter (PM10): 0.013
Nitrogen Oxide (NOx): 0.401
Volatile Organic Compounds (VOC): 0.159

Atmospheric CO_2: 417.624
Carbon Dioxide Equivalent (CO_2e): 420.950
Total Energy Consumption (TEC): 5.491