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.

Traffic Signal Synchronization Module

The signal synchronization project emission reductions calculator estimates the emissions benefits from coordinating traffic signal timing along a corridor.[1]

This tool is not intended for the addition of new signals, only for the synchronization of existing unsynchronized signals. Although this project does not examine the effect of signal coordination throughout a system or area, system-wide or area-wide emission reductions can be reasonably determined by combining the reductions estimated for corridors individually. Emission reductions are calculated for peak- and off-peak hours on a typical weekday.

Emission reductions are estimated by calculating the change in running emissions from an improved travel time along the corridor. The improved travel time is calculated by estimating the change in delay at each signal along the corridor, or travel time savings, and multiplying by a factor to account for the effect of traffic volume on travel time and speed.[2] Running emissions for the average speed associated with the existing and the improved travel time are compared to estimate emissions benefits.

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.

[2] Roadway performance calculations rely on the Highway Capacity Manual, Transportation Research Board National Academy of Sciences, Washington DC, 2010.

Contents

USER GUIDE 3
User Inputs 3
Tool Outputs 4
Error Messages 5
TOOL METHODOLOGY 6
Delay Reduction Calculation Methodology 6
Off-Peak Existing Average Speed Calculation Methodology 8
EXAMPLE 9
Urban Signal Synchronization 9

USER GUIDE

This section lists the units and description for each user input and tool output, as well as a description of emission reductions reporting and error messages.

User Inputs

The Traffic Signal Synchronization 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

User Input	Units	Description
Evaluation year	-----	Use the drop-down menu to choose a year between 2018 and 2040.
Road type	-----	Use the drop-down menu to choose the appropriate road type for the coordinated signalized corridor. Available road types are: rural and urban, indicating rural and urban unrestricted road types.
Corridor Length	miles	Input the length of the project corridor along which the lights will be synchronized. The default value is 1 mile.
Number of signalized intersections	-----	Input the number of traffic signals along the project corridor. The default value is 2 signals. Traffic signal synchronization projects can only be implemented in corridors with at least 2 intersections.
Number of lanes, one direction	-----	Input the average number of through lanes along the length of the project corridor for one approach direction. The default value is 1 lane.
Posted speed limit	mph	Input the average speed limit posted along the length of the project corridor. This is used as the mid-segment (between signals) free-flow speed. The tool's upper limit is 75 mph.
Average cycle length	seconds	Input the average cycle length of the traffic signals included in the signal synchronization project. The default value is 90 seconds, per the Highway Capacity Manual.
Truck Percentage		Input the percent of traffic along the corridor that is heavy-duty truck vehicles. The default value is 6%, based on default MOVES activity rates.
Annual Average Daily Traffic (AADT), both directions	vehicles/day	Input the AADT volume of traffic across all lanes of travel, in both approach directions along the length of the corridor.
Peak-hour volume, both directions	vehicles/hour	Input the average volume of traffic across all lanes, in both approach directions along the length of the corridor during typical weekday peak travel hours.
Existing corridor travel time	minutes	Input the average time in minutes that it takes for a vehicle to travel the length of the corridor.

User Input	Units	Description
Total peak hours per day (AM+PM)	hours	Input the total number of peak hours the project corridor experiences on a typical weekday. The default value is 4 hours.[3]

Tool Outputs

Once the input parameters are entered, click the 'Calculate Output' button to generate 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., the project increases emissions for a particular pollutant).

Table 2. Proposed Conditions

Output	Units	Description
Peak-hour volume (both directions)	vehicles/hour	The average hourly volume of traffic for both approach directions and across all lanes, as input by the user.
Off-peak hourly volume (both directions)	vehicles/hour	The calculated off-peak hourly volume found by subtracting total peak traffic from the annual average daily traffic in approach both directions and across all lanes.
Peak-hour existing average speed	miles per hour	The existing corridor average traveling speed as calculated from existing corridor travel time and length of the project corridor.
Off-peak existing average speed	miles per hour	Using the methodology explained below, the calculated corridor average traveling speed calculated from free-flow speed and a calculated delay at each signal along the corridor, based on off-peak volume and road capacity.
Peak-hour travel time savings	minutes	Using the methodology explained below, the calculated travel time savings (reduction in delay from coordinated signals) during peak-hour conditions.

[3] https://nacto.org/publication/urban-street-design-guide/design-controls/design-hour/

Output	Units	Description
Off-peak travel time savings	minutes	Using the methodology explained below, the calculated travel time savings (reduction in delay from coordinated signals) during off-peak hours, based on off-peak hourly volume.
Peak-hour improved average speed	miles per hour	The calculated new travel speed along the corridor length from travel time savings during peak-hour conditions
Off-peak improved average speed	miles per hour	The calculated new travel speed along the corridor length from travel time savings during off-peak hour conditions

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 3. Error Messages

Error Message	Reason for Error	Solution
Truck percentage cannot be greater than 100%	Traffic volume is composed of more than 100% trucks	Reduce truck volume
Roadway is over capacity.	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.
Conditions indicate corridor is operating above the posted speed limit.	The travel time and corridor length conditions input by the user indicate that the average speed on the roadway exceeds the posted speed limit	Adjust the travel time or roadway length.
Corridor already operating at speed limit. No improvement made	Traffic is moving along corridor at free-flow speed	No adjustment necessary if these are operating conditions; if this is not correct, please adjust travel time along corridor.
AADT cannot be less than total volume of all peak hours	Peak-hour volume times the number of peak hours is greater than the reported total daily traffic	Adjust peak-hour volume, number of peak hours, or AADT.
Under input conditions, there is no improvement in speed along corridor	Traffic already operating at maximum speed for volume and capacity for length of corridor	No adjustment necessary if these are operating conditions; if this is not correct, please adjust inputs.

TOOL METHODOLOGY

Delay Reduction Calculation Methodology

The methodology for calculating emission reductions as a result of signal synchronization relies on the calculation of time savings for travel along the project corridor by reducing delay at each intersection. The Highway Capacity Manual (2010) provides the following equation for calculating uniform delay, d_1, at a signalized intersection[4]:

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

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[5]:

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

where

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

c = capacity

N = number of lanes (one direction), and

s = saturation flow rate/lane (vehicles/lane/hour).

Saturation flow rate is calculated using an adjustment of a base saturation flow rate. The base saturation flow rate uses a default value of 1900 passenger vehicles per lane per hour in urban areas, and 1750 passenger vehicles per lane per hour for rural areas[6]. This base rate is adjusted to account for heavy duty vehicle percent distributions on the roadway to obtain the saturation flow rate in vehicles per lane per hour in the specific scenario. The other default used in the tool is the green-time-to-cycle-time ratio, set at 0.5 for this tool.

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

[5] Equations 18-17 and 18-19, Chapter 18: Signalized Intersections, Highway Capacity Manual, Transportation Research Board National Academy of Sciences, Washington DC, 2010.

[6] Exhibit 18-28 in Chapter 18: Signalized Intersection, Highway Capacity Manual, Transportation Research Board National Academy of Sciences, Washington DC, 2010.

Aside from the saturation flow rate and green-time-to-cycle-time ratio, the other variables in the delay calculation are user inputs. This delay is multiplied by a progression factor (PF) in order to account for coordinated and uncoordinated signals. Uncoordinated signals throughout a corridor correspond to an Arrival Type 3 and a progression factor, PF, of 1.00, while traffic subject to coordinated signals is characterized as an Arrival Type 4 with a PF of 0.67.[7] The delay then, for newly coordinated signals, d_2, is given as:

$$d_2 = 0.67 d_1 \quad (1)$$

In other words, delay is reduced along a corridor by a factor of 0.67. The delay reduction for the project corridor is calculated by multiplying the delay reduction for one signal by the number of signals along the corridor.

This total delay reduction is subtracted from the existing travel time and a new travel speed along the corridor is calculated. The existing travel time is provided by the user for peak-hours and the new travel speed is calculated using the methodology described below. To account for volume of traffic and the effect of traffic volume on travel speed along a corridor, a volume factor, f_v, is applied to the travel time savings calculation, given as[8]:

$$f_v = \frac{2}{1 + \left(1 - \frac{v}{52.8 N S_{PL}}\right)^{0.21}} \quad (2)$$

Where:

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

N = number of lanes (one direction), and

S_{PL} = posted speed limit (which is our estimate of the free flow speed).

For higher traffic volumes, travel time savings are reduced. When the traffic volume is critically over capacity, travel time savings are negligible. In this tool, when critical overcapacity occurs, denoted when the term:

$$\left(1 - \frac{v}{52.8 N S}\right)$$

is less than zero, the travel time savings is reported as zero and an error message is displayed.

The final adjusted travel time savings is calculated as:

$$\frac{d_1 - d_2}{f_v} \quad (5)$$

[7] Progression factor, PF, is calculated by the equation: PF = (1- [1.33g/C])/(1- g/C). Exhibit 31-46, Chapter 31: Signalized Intersections: Supplemental, Highway Capacity Manual, Transportation Research Board National Academy of Sciences, Washington DC, 2014.

[8] Equation 17-5, Chapter 17: Urban Street Segments, Highway Capacity Manual, Transportation Research Board National Academy of Sciences, Washington DC, 2010.

Once a new travel speed is calculated, multiplying emissions rates by the vehicle miles traveled during peak-hours in both directions of travel yields peak-hour emission reductions. Following this same procedure for the new travel speed for conditions during off-peak hours results in off-peak hour emission reductions. The peak-hour and off-peak emission reductions are added to give total emission reductions for a weekday along the project corridor, reported in kilograms/day.

Off-Peak Existing Average Speed Calculation Methodology

Assuming that the mid-segment (roadway between signals) travel speed is the free-flow speed along the corridor, the corridor travel time, t_R, in seconds, is expressed in the following equation from the Highway Capacity Manual, 2010[9]:

$$t_R = N_s \frac{6.0 - l_1}{(0.0025L)5280} f_x + \frac{3600L}{S_{PL}} f_v + N_s d_1 \quad (6)$$

where:

l_1 = start-up lost time = 2.0 for signalized intersections,

L = corridor length (miles),

f_x = 1.00 for signalized through movement,

S_{PL} = posted speed limit (miles per hour),

f_v = traffic volume proximity factor, defined previously,

N_s = number of signals along project corridor,

d_1 = calculated delay (seconds), defined previously.

The existing travel speed along the corridor, S_1, is then given by the equation:

$$S_1 = \frac{3600L}{t_R} \quad (7)$$

where:

L = corridor length (miles).

[9] Equation 17-6, 17-7, Chapter 17: Urban Street Segments, Highway Capacity Manual, Transportation Research Board National Academy of Sciences, Washington DC, 2010.

EXAMPLE

Urban Signal Synchronization

A municipality is considering synchronizing a two-mile corridor with three signalized intersections, which could improve traffic flow by smoothing the drive cycle and raising the average speed through the corridor.

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

INPUT User Guide

Evaluation Year	2030	
Area Type	Urban	
Corridor Length	2	miles
Number of Signalized Intersections	3	
Number of Lanes (one direction)	2	
Posted Speed Limit	45	miles per hour (1 - 75 MPH)
Average Cycle Length	90	seconds
Truck Percentage	6%	
Annual Average Daily Traffic (AADT) (both directions)	50,000	veh/day
Peak-hour Volume (both directions)	4,500	veh/hr
Existing Corridor Travel Time	3	minutes
Total peak hours per day (AM+PM)	4	

Project evaluation year: 2030
Area type: Urban
Corridor length: 2 miles
Number of signalized intersections: 3
Number of lanes: 2
Posted speed limit: 45
Average cycle length: 90 seconds
Truck percentage: 6%
AADT: 50,000
Peak hour volume: 4,500
Existing corridor travel time: 3 minutes
Total peak hours per day: 4 hours

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

OUTPUT Calculate Output

PERFORMANCE

	PEAK-HOUR	OFF-PEAK	
Volume (both directions)	4,500	1600	veh/hr
Existing Average Speed	40	35	miles per hour
Travel Time Savings	21	14	minutes
Proposed Average Speed	45	37	miles per hour

EMISSION REDUCTIONS

Pollutant	Peak-hour Kilograms/day	Off-Peak Kilograms/day	Total Kilograms/day
Carbon Monoxide (CO)	4.738	4.686	9.425
Particulate Matter <2.5 µm ($PM_{2.5}$)	0.054	0.055	0.109
Particulate Matter <10 µm (PM_{10})	0.339	0.348	0.687
Nitrogen Oxide (NOx)	0.691	0.683	1.374
Volatile Organic Compounds (VOC)	0.160	0.158	0.318
Atmospheric Carbon Dioxide (CO2)	279.137	276.817	555.954
Carbon Dioxide Equivalent (CO2e)	282.910	280.528	563.438
Total Energy Consumption (MMBTU)	3.665	3.634	7.299

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

Carbon Monoxide (CO): 9.425
Particulate Matter (PM2.5): 0.109
Particulate Matter (PM10): 0.687
Nitrogen Oxide (NOx): 1.374
Volatile Organic Compounds (VOC): 0.318

Atmospheric CO_2: 555.954
Carbon Dioxide Equivalent (CO_2e): 563.438
Total Energy Consumption (TEC): 7.299

Note that some signal synchronization projects may show a disbenefit for certain pollutants, indicating that the project increases emissions for this pollutant. There are known trade-offs between PM and NOx, including for speed.[10]

[10] Mark, Jason, and Candace Morey. "Diesel Passenger Vehicles and the Environment." Union of Concerned Scientists, April 1999. https://www.ucsusa.org/sites/default/files/legacy/assets/documents/clean_vehicles/diesel-toc.pdf.; Feibig, Michael, Andreas Wiartalla, Bastian Holderbaum, and Sebastian Kiesow. "Particulate Emissions from Diesel Engines: Correlation between Engine Technology and Emissions." Journal of Occupational Medicine and Toxicology 9, no. 6 (March 7, 2014). https://doi.org/10.1186/1745-6673-9-6.