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 default-scale[1] 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.

Managed Lanes Tool

Managed lane (ML) facilities[2], such as high-occupancy vehicle (HOV) and high-occupancy toll (HOT) lanes, on freeways have been shown to produce emission benefits through smoothing driving behavior, improving traffic flow, and increasing average travel speeds. There is no single ML definition, but typically they are separated from general purpose (GP) lane traffic and apply different management strategies such as pricing, vehicle eligibility, and/or controlled access. The appendix describes the different types of ML facilities in detail.

This tool relies on National Collaborative Highway Research Program (NCHRP 03-96) research on managed lanes (MLs) that was added to the Highway Capacity Manual (HCM) in 2012.[3] The tool is organized into two distinct modules: New Managed Lane Facilities and Managed Lane Conversions.

The New Managed Lane Facilities ('New Facilities') module considers the construction of a new ML facility on a freeway where such a facility did not previously exist. The New Facilities module quantifies the potential emission reductions from alleviated freeway congestion after the ML facility is implemented. The Lane Conversions module is designed to evaluate a ML conversion that changes facility operations and/or pricing. Any ML conversion project that will reduce emissions through changes in traffic flow and/or speed, such as converting a HOV lane to a HOT lane, can be assessed in the Lane Conversions module. Note that not all lane conversions are eligible under the CMAQ program. Users should consult the CMAQ program guidance for more information.

This document is organized into three sections – User Guide, Tool Methodology, and Examples – to aid the user in understanding and interpreting results from the emissions calculator tool. The User Guide provides direction on how to properly input values into the tool, and provides definitions of both user

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[1] 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.

[2] "Managed Lanes: A Primer," Federal Highway Administration, Office of Operations, Accessed: 17 Jan 2020, https://ops.fhwa.dot.gov/publications/managelanes_primer/index.htm.

[3] National Academies of Sciences, Engineering, and Medicine (NASEM), 2012, *Analysis of Managed Lanes on Freeway Facilities*. Washington, DC: The National Academies Press (https://doi.org/10.17226/22677).

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 illustrates how to use the tool for project analysis.

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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. As discussed above, the tool is organized into two modules (New Facilities and Lane Conversions) based on whether a new facility is being built or an existing facility is being modified.

User Inputs

Interfaces for the two Managed Lane Tool modules contain 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 proposed ML project. The user-defined inputs for both modules are described in Table 1.

Table 1. User Inputs for New Facilities and Lane Conversions

Item	User Input	Units	Description
(1)	Project evaluation year	-----	Use the drop-down menu to choose a year between 2019 and 2040.
(2)	Type of separation for managed lane facility	-----	Select between continuous access, buffer zones, or physical barriers to separate the managed lanes (MLs) and general purpose (GP) lanes. See appendix for definitions of these separation types.
(3a)	Number of existing general purpose lanes	-----	Choose between one and six GP lanes in one direction of highway before and after project completion. Users can enter up to ten GP lanes manually without error.
(3b)	Number of managed lanes	-----	Choose either one or two ML in same (one) direction as the GP highway lanes before and after project completion. HCM methodology includes speed-flow curves for up to two MLs. Therefore, facilities with more than two MLs cannot be modeled in this tool.
(4a)	Typical traffic flow	Vehicles per hour per lane (vphpl)	Enter a peak one-way traffic flow in vehicles per hour per lane (vphpl) for the GP lanes before and after project completion. Similarly for the Lane Conversions module, input peak flow before and after project is completed for the new managed lane(s). Whereas for the New Facilities module, since ML(s) are being constructed, there is only a ML traffic flow input after project completion.
(4b)	Free flow speed	Miles per hour (mph)	Select an unimpeded, free flow speed in miles per hour (mph) for the GP lanes and MLs. Free flow speeds often but do not always correspond to the posted speed limit. Acceptable speed entries range from 55 to 75 mph in 5-mph increments. Note that the New Facilities module does not have a speed input prior to the project being built.

Item	User Input	Units	Description
(5)	Percentage of heavy-duty vehicles	-----	Enter the percent of total traffic consisting of heavy-duty vehicles (i.e., buses, single-unit trucks, and combination trucks) on the GP lanes only. This tool assumes HDVs are not permitted on ML facilities.
(6a)	Peak vs. non-peak hour analysis	----	Indicate whether the ML facility will be operated during peak or non-peak hours. If both, a peak and non-peak hour analysis must be conducted separately.
(6a)	Number of peak or non-peak hours	hours	Input the number of peak or non-peak hours in operation per day (indicated above) in the analysis.
(7)	Length of facility	miles	Enter the length of the ML facility in miles.
(8)	Facility road type	----	Indicate whether the new ML facility will be constructed on an urban or rural roadway.

Traffic flow and free flow speed data may be either modeled or measured. If available, measurements from traffic counters, video footage, or other roadside sensors provide the most accurate traffic flow estimates, especially on existing lanes. When measurements are not readily available, traffic volumes can be estimated using travel demand models or microscopic traffic simulations. Free flow speeds can also be obtained either through traffic sensors or the posted speed limit if necessary.

This tool only considers emissions that occur during regular operating hours for the ML facility. If operated during non-peak hours, users will need to conduct a non-peak hour analysis separately and compute the net emission reductions, as described further in the Examples section. Some ML facilities are operated 24 hours each day and Examples 3 and 4 illustrate the peak and non-peak analysis for a 24-hour ML facility. Additionally, the tool has been designed to only handle one direction of traffic at a time. If traffic flow and free-flow speed data is available in both directions, then the user must calculate the network performance and emission reductions for one direction first and then run a separate calculation for the opposite direction. Some of the inputs such as traffic flow and operating hours may change based on the freeway direction.

The Lane Conversions module has nearly identical user inputs to the New Facilities module, as noted in Table 1 above. The only notable change is in Item 4, where the Lane Conversions module assumes that a ML facility for conversion exists and asks the user to input the ML traffic flow and free flow speed before and after the conversion. As for the New Facilities module, the Lane Conversions module require the traffic flow and free flow speed on the GP lanes before and after the conversion. The Lane Conversions module only considers operational and behavioral changes.

Tool Outputs

Outputs of this tool include network performance and emissions reductions, as described in detail below. Emission results will not automatically update. If any changes are made to the input parameters, the ‘Calculate Output” button must be clicked again to calculate updated emission reductions. If you would like to return to default settings and clear inputs, click on the ‘Reset to Default Values’ button at the top right of the interface.

Network Performance

The tool calculates the average speeds and estimated travel times for the new or converted ML(s) and the GP lanes before and after ML(s) are built. The average speed is derived using the speed-flow curves defined in the HCM methodology for managed lanes.[4] There are distinct curves for each type of lane separation (continuous access, buffer, or barrier) including whether the facility has one or two managed lanes, which enables numerical approximations for how much the actual average speeds are decreased from the ideal, free flow speeds based on the traffic flow. The HCM methodology for basic freeway facilities[5] is used to determine average speeds on the GP lanes. For reference, these HCM calculations of average speed are replicated in the appendix.

The tool also calculates the average time in minutes to travel the length of the facility on either the ML(s) or GP lanes before and after project completion. Travel time is calculated by dividing the facility length by the derived average speed and converting from hours to minutes, as expressed in Eq. 1 below:

$$Travel\ Time\ (mins) = \frac{Facility\ Length\ (mi)}{Average\ Speed\ (mph)} \cdot \left(\frac{60\ mins}{1\ hr}\right) \quad \textbf{(1)}$$

This output gives users the ability to quantify any time savings due to the new or converted managed lane facility, including for the GP lanes before and after the ML(s) are built.

Emission Reductions

Emission reductions are calculated for five pollutants – carbon monoxide (CO), particulate matter with diameters < 2.5 µm ($PM_{2.5}$), particulate matter with diameters < 10 µm (PM_{10}), nitrogen oxides (NOx), and volatile organic compounds (VOC) – in kilograms per day for CMAQ reporting. Reductions in carbon dioxide (CO_2), carbon dioxide equivalents (CO_2e), and total energy consumption (million BTU) per day are also provided for the New Facilities and Lane Conversions modules.

In this tool, emission reductions represent the incremental changes from adding a new or converted managed lane facility. Daily reductions specifically constitute the difference between the emissions associated with the GP lanes before the project is completed and the combined emissions associated with the new or converted ML(s) and GP lanes after the project is completed. Emissions reduction equations are described in detail in the Tool Methodology section below.

Error Messages

Table 2 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, press 'Calculate Output' to recalculate the results.

[4] NASEM (2012), https://doi.org/10.17226/22677.
[5] NASEM, 2010, *Highway Capacity Manual Chapter 11: Basic Freeway Facilities.* Washington, DC: Transportation Research Board (http://hcm.trb.org/vol2/chapter-11).

Table 2. Error Messages – New Managed Lane Facilities Module

Error Message	Reason for Error	Solution
Please select a valid project evaluation year for analysis.	Invalid Input: Project Evaluation Year	Choose an evaluation year from the pull-down list
Please select a particular type of managed lane facility.	Invalid Input: Managed Lane Facility	Choose a type of managed lane facility from the pull-down list
Please select a valid number of managed and general purposes lanes.	Invalid Input: Number of Lanes	Choose the number of MLs and GP lanes before and after project completion
Please enter traffic flows for before and after project completion.	Invalid Input: Traffic Flows	Input the traffic flows on the MLs and GP lanes before and after project completion
Please enter free flow speeds for before and after project completion.	Invalid Input: Free Flow Speeds	Choose the free flow speeds on the MLs and GP lanes before and after project completion
Please enter a percentage of heavy-duty vehicle traffic.	Invalid Input: Heavy-Duty Vehicle Traffic	Input a percentage of heavy-duty vehicle traffic
Please select a peak or non-peak hour analysis.	Invalid Input: Peak Hour Analysis	Choose whether peak hour or non-peak hour analysis
Please enter the number of peak/non-peak hours.	Invalid Input: Number of Peak/Non-peak Hours	Input the number of peak/non-peak hours for analysis
Please enter the facility length.	Invalid Input: Facility Length	Input the length of the managed lane facility
Please select whether the facility will be urban or rural.	Invalid Input: Rural/Urban Distinction	Choose an urban or rural roadway for analysis
Please reassess traffic flow values; The entered combination of traffic flow values and number of lanes produces a negative value for average speed and/or average travel time.	Invalid Traffic Flow Values	Entered values are not realistic. Please review data.
ERROR: The percentage of heavy-duty vehicles must be between 0 and 100%.	Invalid input for percentage of heavy-duty traffic.	Enter a percentage of heavy-duty traffic between zero and 100.
ERROR: An invalid peak hour designation has been entered.	Designation must be for peak or non-peak hour.	Choose either a peak or non-peak hour analysis.
ERROR: Analysis cannot use more than 24 hours per day.	Invalid input for hours of daily operation.	Enter a valid number of hours for operation.
ERROR: The value entered is not a valid urban or rural distinction.	The ML facility must be on an urban or rural freeway.	Choose either an urban or rural facility for analysis.

TOOL METHODOLOGY

The following section describes how emission reductions are explicitly calculated in the Managed Lane tool. Emission rates were developed from project-level MOVES runs and driving behavior effects on

speed were estimated using traffic flow and free flow speeds. Equations for emission reductions for new facilities and conversions are provided below.

Emission Rate Data Sources

To estimate emission reductions due to speed changes, MOVES3[6] project-level runs were completed for each whole integer speed from zero to 75 miles per hour. Where possible, default-scale[7] data was used to populate project-level inputs. See the Emissions Data Documentation for additional details related to these MOVES runs. Composite emission rates for light-duty vehicles and heavy-duty vehicles were generated separately. The tool assumes that only light-duty vehicles are permitted to drive on the ML facility. Off network idle (ONI) emissions were not included in this analysis since the MOVES road type 1 (off-network) was excluded due to the nature of the managed lanes project type.

New Facilities

For new ML facilities, the net emissions are composed of three elements:

- emissions resulting from traffic on the GP lanes before project completion,
- emissions resulting from traffic on the GP lanes after completion, and
- emissions resulting from traffic on the new ML(s).

Emission equations (Eq. 2-9) for each of these elements and the final emissions reduction estimate can be found below. Emission rates are a function of road type and average speed. The average speed $\bar{v}$ is derived using the updated HCM speed-flow curves and corresponding equations for MLs. The speed-flow curves are provided in the appendix for reference. The New Facilities module assumes the number of GP lanes will not be changed during development of the ML facility.

$$E_{GP\ before} = E_{GP\ before_{HDV}} + E_{GP\ before_{LDV}} \quad \textbf{(2)}$$

$$E_{GP\ before_{LDV}} = e_{LDV_{rt,\bar{v}}} \cdot L \cdot \left[Q_{GP\ before_{total}} \cdot (1 - f_{HDV})\right] \cdot n_{GP} \cdot t_{peak}\ , \quad \textbf{(3)}$$

$$E_{GP\ before_{HDV}} = e_{HDV_{rt,\bar{v}}} \cdot L \cdot \left(Q_{GP\ before_{total}} \cdot f_{HDV}\right) \cdot n_{GP} \cdot t_{peak}\ , \quad \textbf{(4)}$$

$$E_{GP\ after} = E_{GP\ after_{LDV}} + E_{GP\ after_{HDV}}\ , \quad \textbf{(5)}$$

$$E_{GP\ after_{LDV}} = e_{LDV_{rt,\bar{v}}} \cdot L \cdot \left[Q_{GP\ after_{total}} \cdot (1 - f_{HDV})\right] \cdot n_{GP} \cdot t_{peak}\ , \quad \textbf{(6)}$$

[6] US Environmental Protection Agency, Office of Transportation and Air Quality, Motor Vehicle Emission Simulator (MOVES), https://www.epa.gov/moves/latest-version-motor-vehicle-emission-simulator-moves.

$$E_{GP\ after\ _{HDV}} = e_{HDV_{rt,\bar{v}}} \cdot L \cdot \left(Q_{GP\ after\ _{total}} \cdot f_{HDV}\right) \cdot n_{GP} \cdot t_{peak}\ , \quad \textbf{(7)}$$

$$E_{new\ ML} = e_{LDV_{rt,\bar{v}}} \cdot L \cdot Q_{new\ ML_{LDV}} \cdot n_{new\ ML} \cdot t_{peak}\ , \quad \textbf{(8)}$$

$$Emissions\ reduced = E_{GP\ before} - \left(E_{new\ ML} + E_{GP_{after}}\right). \quad \textbf{(9)}$$

The emissions reduction for a specified pollutant is equal to the emissions of GP lanes before project completion minus the sum of the emissions of the GP lanes after completion and the emissions of the new ML facility, described in Eq. 9 above, such that,

$e_{LDV_{rt,\bar{v}}}$= aggregated emission rate for light-duty vehicles (LDV) from project-level MOVES runs based on the road type rt and average speed $\bar{v}$ for a specified pollutant,
$e_{HDV_{rt,\bar{v}}}$= aggregated emission rate for heavy-duty vehicles (HDV) from project-level MOVES runs based on the road type rt and average speed $\bar{v}$ for a specified pollutant,
L = length of the ML facility (miles),
Q = traffic flow of vehicles (vphpl) on the given roadway, specified as either the total traffic volume of vehicles or the traffic volume of light-duty vehicles only,
f_{HDV} = fraction of traffic from heavy-duty vehicles (entered as a percentage out of 100%),
n = number of lanes, either general purpose or managed, depending on the roadway, and
t_{peak} = time duration, either peak or non-peak hours, that the facility is in operation.

Note that peak and non-peak hour analysis must be calculated separately. If known, users can specify the percentage of heavy-duty vehicles (HDVs) operating on the given roadway. The remaining non-HDVs are expected to be passenger vehicles. If unknown, the tool will default to 100% passenger vehicles.

The HCM methodology also includes a frictional adjustment on ML(s) according to the traffic density (vehicles per mile). In this context, traffic density D is defined as the traffic flow Q divided by the free flow speed FFS, as shown in Eq. 10 below,

$$D = \frac{Q}{FFS}. \quad \textbf{(10)}$$

If the density is greater than or equal to 35 passenger vehicles per mile (pvpm), then a frictional adjustment term is applied to the traffic speed-flow curves for continuous access and buffer ML facilities. If the density is less than 35 pvpm, then the frictional adjustment term is not applied. For more information, please see appendix.

Lane Conversions

Emission reductions from ML conversions are also based on changes to traffic flow and/or free flow speed. Thus, the Lane Conversions module has very similar methodology to the New Facilities module.

The only changes to the equations above are related to accounting for the ML operations before and after the conversion. This means the net emissions calculation will include the emission contributions from the managed and GP lanes both before and after the conversion, as shown below in Eq. 11-13. These calculations assume that the number of managed and GP lanes will not be changed during the conversion of the facility.

$$E_{ML\ before} = e_{LDV_{rt,\bar{v}}} \cdot L \cdot Q_{ML\ before\ _{LDV}} \cdot n_{ML} \cdot t_{peak}\ , \quad \textbf{(11)}$$

$$E_{ML\ after} = e_{LDV_{rt,\bar{v}}} \cdot L \cdot Q_{ML\ after\ _{LDV}} \cdot n_{ML} \cdot t_{peak}\ , \quad \textbf{(12)}$$

$$Emissions\ reduced = \left(E_{ML_{before}} + E_{GP_{before}}\right) - \left(E_{ML_{after}} + E_{GP_{after}}\right). \quad \textbf{(13)}$$

EXAMPLES

Example 1: New HOV Lane

A transportation agency is working to build a new continuous access high-occupancy vehicle (HOV) lane to open in 2020 (see appendix for a more detailed description of a continuous access facility). The existing three-lane highway has a peak traffic flow of 2,500 vehicles per hour per lane (vphpl) and a free flow speed of 60 miles per hour (mph). A new ML is expected to divert 1,500 vphpl with a 70-mph speed limit from the GP lanes and there is a proposal to increase the GP lane speed limit to 65 mph.[8]

The stated inputs for this proposed project are summarized in the screenshot of the New Facilities module below:

Module: New Facilities
Project evaluation year: 2020
Type of ML facility: Continuous Access

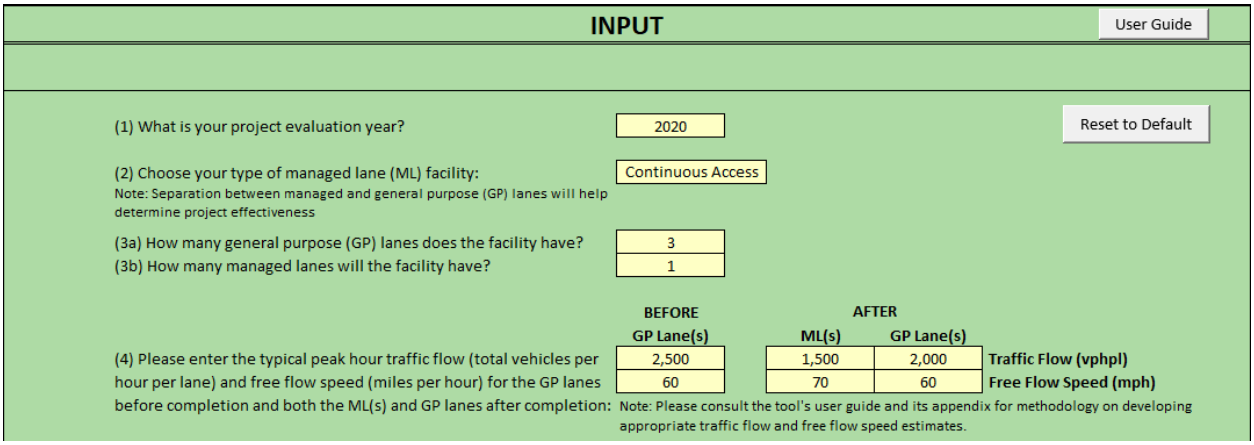
Number of GP lanes: 3
Number of ML(s): 1

Peak traffic flow of GP lanes before project: 2,500 vphpl
Free flow speed of GP lanes before project: 60 mph

Peak traffic flow of new ML after project: 1,500 vphpl
Free flow speed of new ML after project: 70 mph

[8] Traffic inputs have been pulled from a recent managed lane study, where volumes peaked roughly at 2,500 vphpl, X. Liu et al., 2011, "Analysis of Operational Interactions Between Freeway Managed Lanes and Parallel, General Purpose Lanes," *Transportation Research Record*, No. 2262, p. 62-73 (https://journals.sagepub.com/doi/pdf/10.3141/2262-07).

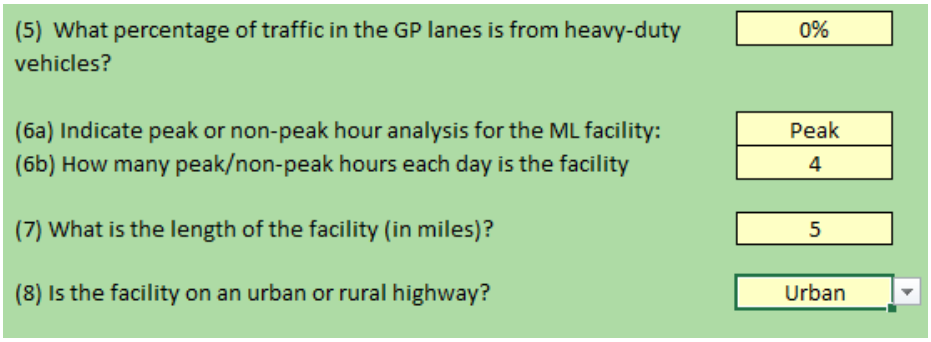
Peak traffic flow of GP lanes after project: 2,000 vphpl
Free flow speed of GP lanes after project: 60 mph



INPUT | User Guide | Reset to Default

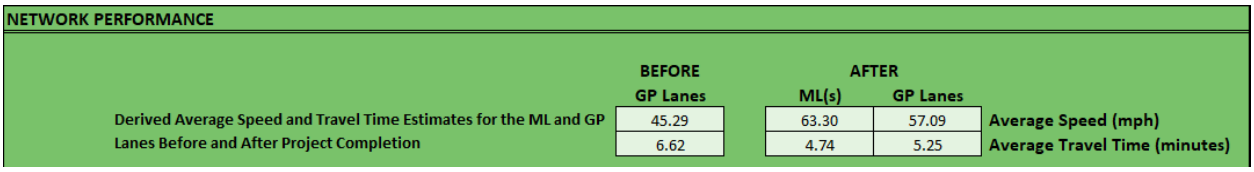
		BEFORE	AFTER		
		GP Lane(s)	ML(s)	GP Lane(s)	
(1) What is your project evaluation year?		2020			
(2) Choose your type of managed lane (ML) facility: Note: Separation between managed and general purpose (GP) lanes will help determine project effectiveness		Continuous Access			
(3a) How many general purpose (GP) lanes does the facility have?		3			
(3b) How many managed lanes will the facility have?		1			
(4) Please enter the typical peak hour traffic flow (total vehicles per hour per lane) and free flow speed (miles per hour) for the GP lanes before completion and both the ML(s) and GP lanes after completion: Note: Please consult the tool's user guide and its appendix for methodology on developing appropriate traffic flow and free flow speed estimates.	Traffic Flow (vphpl)	2,500	1,500	2,000	Traffic Flow (vphpl)
	Free Flow Speed (mph)	60	70	60	Free Flow Speed (mph)

The agency did not differentiate between light-duty and heavy-duty vehicles in their traffic counts; however, they found the busiest commuting hours are from 8 to 10am and 4 to 6pm and subsequently are proposing to open the new five-mile, urban HOV lane facility for four hours each day. Those example input parameters have been specified in the image below.



(5) What percentage of traffic in the GP lanes is from heavy-duty vehicles?	0%
(6a) Indicate peak or non-peak hour analysis for the ML facility:	Peak
(6b) How many peak/non-peak hours each day is the facility	4
(7) What is the length of the facility (in miles)?	5
(8) Is the facility on an urban or rural highway?	Urban

Using this Managed Lanes tool, the agency found that the selected highway under current traffic conditions has an average speed of roughly 45 mph during peak hours and an estimated average travel time of 6.6 minutes. Upon running this CMAQ tool, the agency has calculated that the new facility will improve average speeds and travel times on both the GP lanes and the new HOV lane. The network performance output can be found in the screenshot below.



NETWORK PERFORMANCE

		BEFORE	AFTER		
		GP Lanes	ML(s)	GP Lanes	
Derived Average Speed and Travel Time Estimates for the ML and GP Lanes Before and After Project Completion	Average Speed (mph)	45.29	63.30	57.09	Average Speed (mph)
	Average Travel Time (minutes)	6.62	4.74	5.25	Average Travel Time (minutes)

Average speed on GP lanes before project: 45.29 mph
Estimated travel time on GP lanes before project: 6.62 mins

Average speed on new ML after project: 63.30 mph
Estimated travel time on new ML after project: 4.74 mins

Average speed on GP lanes after project: 57.09 mph
Estimated travel time on GP lanes after project: 5.25 mins

These network performance improvements translate to emission reductions of all the criteria pollutants considered in the CMAQ program. Specific reductions for this example project have been captured in the following image of the tool's output.

EMISSION REDUCTIONS

Pollutant	Total (kg/day unless otherwise noted)
Carbon Monoxide (CO)	27.5119
Particulate Matter <2.5 µm ($PM_{2.5}$)	0.2934
Particulate Matter <10 µm (PM_{10})	1.8919
Nitrogen Oxide (NOx)	0.0274
Volatile Organic Compounds (VOC)	2.2304
Carbon Dioxide (CO_2)	2,759.4135
Carbon Dioxide Equivalent (CO_2e)	2,790.5289
Total Energy Consumption (MMBTU/day)	36.3552

CO: 27.5119 kg/day
PM2.5: 0.2934 kg/day
PM10: 1.8919 kg/day
NOx: 0.0274 kg/day
VOCs: 2.2304 kg/day

CO_2: 2,759.4135 kg/day
CO_2e: 2,790.5289 kg/day
Energy: 36.3552 MMBTU/day

Example 2: Adding HOT Lanes

Another transportation agency in a heavily congested urban area has decided to add two HOT lanes to their existing highway infrastructure for improved traffic flow and reduced emissions. Traffic counts on the current four-lane expressway are roughly 2,750 vphpl during peak periods resulting in noticeable slowdowns from the posted 55 mph speed limit.[9] They anticipate that the buffer-separated HOT lanes will lead to some induced demand on the expressway as some commuters switch from taking rail or bus to driving. The agency projects that peak period traffic flow on the MLs will be 1,500 vphpl with a free flow speed of 65 mph and that peak flow on the GP lanes will be 2,250 vphpl after completion of the HOT lanes. Example inputs are shown below:

[9] Based on measured peak hour delays and speeds from a recent HOT lane facility study of Interstate 95 near Fredericksburg by the Virginia Department of Transportation, http://www.virginiadot.org/projects/resources/Fredericksburg/Traffic_Technical_Report.pdf.

Module: New Facilities
Project evaluation year: 2020
Type of ML facility: Buffer

Number of GP lanes: 4
Number of ML(s): 2

Peak traffic flow of GP lanes before project: 2,750 vphpl
Free flow speed of GP lanes before project: 55 mph

Peak traffic flow of new ML after project: 1,500 vphpl
Free flow speed of new ML after project: 65 mph

Peak traffic flow of GP lanes after project: 2,250 vphpl
Free flow speed of GP lanes after project: 55 mph

INPUT | User Guide | Reset to Default

(1) What is your project evaluation year?	2020				
(2) Choose your type of managed lane (ML) facility: Note: Separation between managed and general purpose (GP) lanes will help determine project effectiveness	Buffer				
(3a) How many general purpose (GP) lanes does the facility have?	4				
(3b) How many managed lanes will the facility have?	2				
	BEFORE	AFTER			
	GP Lane(s)	ML(s)	GP Lane(s)		
(4) Please enter the typical peak hour traffic flow (total vehicles per hour per lane) and free flow speed (miles per hour) for the GP lanes before completion and both the ML(s) and GP lanes after completion:	2,750	1,500	2,250	Traffic Flow (vphpl)	
	55	65	55	Free Flow Speed (mph)	
Note: Please consult the tool's user guide and its appendix for methodology on developing appropriate traffic flow and free flow speed estimates.					

Truck and other heavy-duty traffic is estimated to constitute about 5% of the volume on the expressway. Given the current levels of congestion, the agency is proposing to operate the HOT lanes during peak business hours from 7am to 7pm, a 12-hour window each weekday, on a ten-mile stretch of expressway leading into (and out of) the city. Those inputs are summarized in the screenshot below.

(5) What percentage of traffic in the GP lanes is from heavy-duty vehicles?	5%
(6a) Indicate peak or non-peak hour analysis for the ML facility:	Peak
(6b) How many peak/non-peak hours each day is the facility	12
(7) What is the length of the facility (in miles)?	10
(8) Is the facility on an urban or rural highway?	Urban

Under these conditions, the estimated commute time will nearly be cut in half on the new HOT lanes and more than six minutes on the GP lanes after project completion. Average speeds also increase substantially after the HOT lanes are added due to reduced congestion. The example output for network performance can be found in the image below.

OUTPUT Calculate

NETWORK PERFORMANCE

	BEFORE	AFTER		
	GP Lanes	ML(s)	GP Lanes	
Derived Average Speed and Travel Time Estimates for the ML and GP Lanes Before and After Project Completion	32.72	65.00	50.00	Average Speed (mph)
	18.34	9.23	12.00	Average Travel Time (minutes)

Average speed on GP lanes before project: 32.72 mph
Estimated travel time on GP lanes before project: 18.34 mins

Average speed on new ML after project: 65.00 mph
Estimated travel time on new ML after project: 9.23 mins

Average speed on GP lanes after project: 50.00 mph
Estimated travel time on GP lanes after project: 12.00 mins

As described in the previous example, smoother driving through higher average speeds enables emission reductions and decreased travel times. This particular example provides sizeable pollutant reductions, as captured in the screenshot of the tool's output below.

EMISSION REDUCTIONS

Pollutant	Total (kg/day unless otherwise noted)
Carbon Monoxide (CO)	424.3576
Particulate Matter <2.5 µm ($PM_{2.5}$)	15.3545
Particulate Matter <10 µm (PM_{10})	51.7078
Nitrogen Oxide (NOx)	118.6804
Volatile Organic Compounds (VOC)	45.7428

Carbon Dioxide (CO_2)	23,108.5246
Carbon Dioxide Equivalent (CO_2e)	23,752.8715
Total Energy Consumption (MMBTU/day)	295.7861

CO: 424.3576 kg/day
PM2.5: 15.3545 kg/day
PM10: 51.7078 kg/day
NOx: 118.6804 kg/day
VOCs: 45.7428 kg/day

CO_2: 23,108.5246 kg/day
CO_2e: 23,752.8715 kg/day
Energy: 295.7861 MMBTU/day

Example 3: HOV-to-HOT Lane Conversion

A transportation agency has an underutilized HOV lane that they plan to convert a HOT lane, as well as converting one GP lane in order to create greater demand and access. Using vehicle count detectors, they measured different peak morning and evening traffic flow volumes. During a typical weekday morning commute, the current GP lanes have peak traffic counts of about 2,750 vphpl and a free flow speed of 65 mph while the current barrier-separated HOV lane has peak counts of about 1,000 vphpl

and a free flow speed of 70 mph. After the HOV-to-HOT lane conversion, they expect double the peak traffic flow on the two new MLs and will be able to divert some traffic off the GP lanes—although the peak traffic flow between the MLs and GP lanes is anticipated to increase slightly after the HOT lane conversion. Results from this peak hour analysis in Example 3 are combined with a non-peak hour analysis in Example 4 to calculate a project like this in 24-hour operation. For reference, the morning commute inputs from this third example are provided below:

Module: Lane Conversions
Project evaluation year: 2020
Type of ML facility: Barrier

Number of GP lanes before project: 4
Number of ML(s) before project: 1

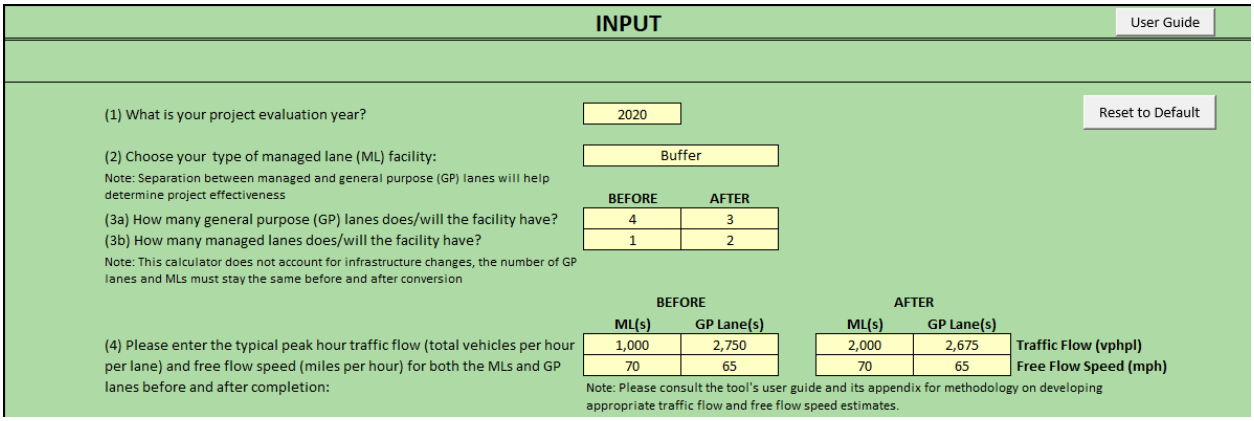
Number of GP lanes after project: 3
Number of ML(s) after project: 2

Peak traffic flow of ML before project: 1,000 vphpl
Free flow speed of ML before project: 70 mph

Peak traffic flow of GP lanes before project: 2,750 vphpl
Free flow speed of GP lanes before project: 65 mph

Peak traffic flow of ML after project: 2,000 vphpl
Free flow speed of ML after project: 70 mph

Peak traffic flow of GP lanes after project: 2,675 vphpl
Free flow speed of GP lanes after project: 65 mph



The agency has measured that heavy-duty vehicles comprise about five percent of the total traffic during peak hours on the 20-mile urban facility. The converted ML facility is planned to be operated for four peak morning hours. The emissions during the four peak evening hours, for a total of eight hours per day, are calculated below. These additional inputs are noted in the image below.

(5) What percentage of traffic in the GP lanes is from heavy-duty vehicles?	5%
(6a) Indicate peak or non-peak hour analysis for the ML facility:	Peak
(6b) How many peak/non-peak hours each day is the facility operated?	4
(7) What is the length of the facility (in miles)?	20
(8) Is the facility on an urban or rural highway?	Urban

Based on these example inputs, the agency calculated that the GP lanes would see small benefits—two-minute drop in travel time and about a three-mph increase in average speed, while the ML(s) would also see modest improvements in travel time and average speed. The specific network performance results of this example have been captured in the screenshot below.

OUTPUT Calculate

NETWORK PERFORMANCE

	BEFORE		AFTER		
	ML(s)	GP Lane(s)	ML(s)	GP Lane(s)	
Derived Average Speed and Travel Time Estimates for the ML and GP Lanes Before and After Project Completion	64.62	39.16	70.00	41.95	Average Speed (mph)
	18.57	30.65	17.14	28.61	Average Travel Time (minutes)

Average speed on ML before project: 64.62 mph
Estimated travel time on ML before project: 18.57 mins

Average speed on GP lanes before project: 39.16 mph
Estimated travel time on GP lanes before project: 30.65 mins

Average speed on new MLs after project: 70.00 mph
Estimated travel time on new MLs after project: 17.14 mins

Average speed on GP lanes after project: 41.95 mph
Estimated travel time on GP lanes after project: 28.61 mins

Despite the small increase in travel time and decrease in average speed on the converted HOT lanes, the project still provides emission reductions for most pollutants when accounting for the GP lanes and MLs. A negative value for Carbon Monoxide (CO) indicates an increase in this pollutant. The estimated reductions for this project are shown below.

EMISSION REDUCTIONS

Pollutant	Total (kg/day unless otherwise noted)
Carbon Monoxide (CO)	-27.4124
Particulate Matter <2.5 µm ($PM_{2.5}$)	4.8629
Particulate Matter <10 µm (PM_{10})	14.9452
Nitrogen Oxide (NOx)	68.5574
Volatile Organic Compounds (VOC)	15.0656
Carbon Dioxide (CO_2)	15,661.3996
Carbon Dioxide Equivalent (CO_2e)	15,859.0588
Total Energy Consumption (MMBTU/day)	201.6197

CO: -27.4124 kg/day
PM2.5: 4.8629 kg/day
PM10: 14.9452 kg/day
NOx: 68.5574 kg/day
VOCs: 15.0656 kg/day

CO_2: 15,661.3996 kg/day
CO_2e: 15,859.0588 kg/day
Energy: 201.6197 MMBTU/day

For the evening commute, the free-flow speeds are the same as the morning, but the GP peak traffic flow are unchanged before and after the project but the traffic flow on the converted HOT lanes doubles, as noted in the inputs below:

Module: Lane Conversions
Project evaluation year: 2020
Type of ML facility: Barrier

Number of GP lanes before project: 4
Number of ML(s) before project: 1

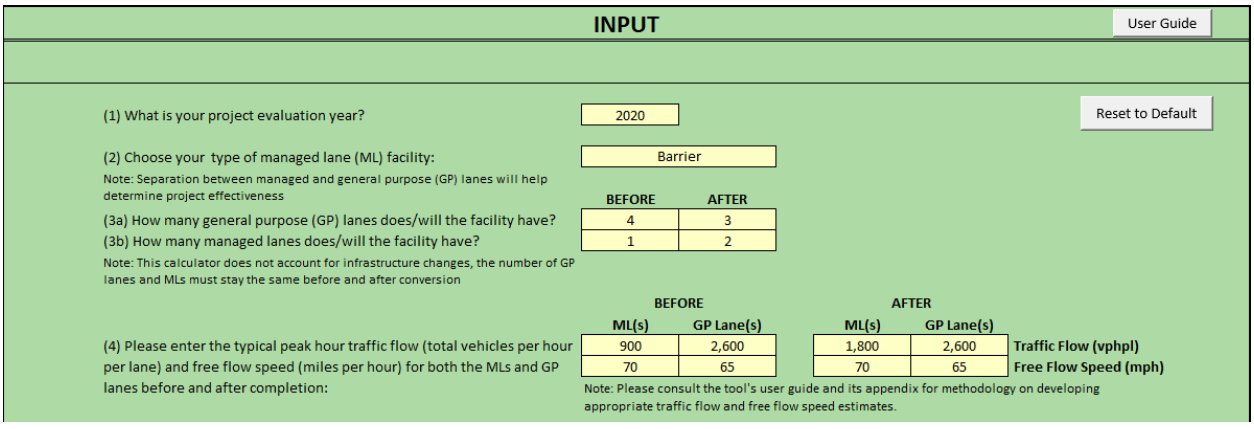
Number of GP lanes after project: 3
Number of ML(s) after project: 2

Peak traffic flow of ML before project: 900 vphpl
Free flow speed of ML before project: 70 mph

Peak traffic flow of GP lanes before project: 2,600 vphpl
Free flow speed of GP lanes before project: 65 mph

Peak traffic flow of ML after project: 1,800 vphpl
Free flow speed of ML after project: 70 mph

Peak traffic flow of GP lanes after project: 2,600 vphpl
Free flow speed of GP lanes after project: 65 mph



The rest of the inputs are unchanged from the morning peak for the four-hour evening peak commute, as shown in the screenshot below.

(5) What percentage of traffic in the GP lanes is from heavy-duty vehicles?	6%
(6a) Indicate peak or non-peak hour analysis for the ML facility:	Peak
(6b) How many peak/non-peak hours each day is the facility operated?	4
(7) What is the length of the facility (in miles)?	20
(8) Is the facility on an urban or rural highway?	Urban

As expected, the network performance results are similar for the evening peak hours as the morning peak hours. Those results have been captured below.

OUTPUT Calculate Output

NETWORK PERFORMANCE

	BEFORE		AFTER		
	ML(s)	GP Lane(s)	ML(s)	GP Lane(s)	
Derived Average Speed and Travel Time Estimates for the ML and GP Lanes Before and After Project Completion	65.74	44.58	70.00	44.58	Average Speed (mph)
	18.25	26.92	17.14	26.92	Average Travel Time (minutes)

EMISSION REDUCTIONS

Average speed on ML before project: 65.74 mph
Estimated travel time on ML before project: 18.25 mins

Average speed on GP lanes before project: 44.58 mph
Estimated travel time on GP lanes before project: 26.92 mins

Average speed on ML after project: 70.00 mph
Estimated travel time on ML after project: 17.14 mins

Average speed on GP lanes after project: 44.58 mph
Estimated travel time on GP lanes after project: 26.92 mins

Given the closeness of average speed and travel time changes, the evening peak also carries similar emission trends as the morning peak, as shown below.

EMISSION REDUCTIONS

Pollutant	Total (kg/day unless otherwise noted)
Carbon Monoxide (CO)	-133.9331
Particulate Matter <2.5 µm ($PM_{2.5}$)	3.5519
Particulate Matter <10 µm (PM_{10})	7.9955
Nitrogen Oxide (NOx)	64.0018
Volatile Organic Compounds (VOC)	7.1722

Carbon Dioxide (CO_2)	9,538.6395
Carbon Dioxide Equivalent (CO_2e)	9,625.6882
Total Energy Consumption (MMBTU/day)	120.9754

CO: -133.9331 kg/day
PM2.5: 3.5519 kg/day
PM10: 7.9955 kg/day
NOx: 64.0018 kg/day
VOCs: 7.1722 kg/day

CO_2: 9,538.6395 kg/day
CO_2e: 9,625.6882 kg/day
Energy: 120.9754 MMBTU/day

To find the total peak hour benefits for converting the HOV lane to a HOT lane, we can simply add the morning (AM) and evening (PM) peak hour benefits, as provided in the table below.

	Morning Peak Hour Reduction (kg/day)	Evening Peak Hour Reduction (kg/day)	Peak Hour Reduction (kg/day)
CO	-27.4124	-133.9331	-161.346
PM2.5	4.8629	3.5519	8.4148
PM10	14.9452	7.9955	22.9407
NOx	68.5574	64.0018	132.5592
VOCs	15.0656	7.1722	22.2378
CO_2	15,661.3996	9,538.6395	25200.04
CO_2e	15,859.0588	9,625.6882	25484.75
Energy	201.6197	120.9754	322.5951

Note that the large CO emissions increase during the morning and evening peak commute, while all the other pollutants do have peak reductions. Abou-Senna et al. (2013) found a similar result when comparing MOVES project-scale emissions using: 1) average speeds, and 2) link-level trajectory data, such that CO increased for the average speed case, whereas NOx, PM, and CO_2 decreased. The trajectory data case showed only emission reductions.[10]

Example 4: Non-peak Hour ML Operations

Building upon Example 3 above, the transportation agency is also considering the impact of the HOT lane conversions during non-peak hour commuting times. In order to determine the net impact between peak and non-peak hours, the agency decided to calculate the potential benefits for operating the ML facility during non-peak hours. They estimate that changes in free flow speeds will be negligible, but average non-peak ML traffic flow would be 500 vphpl before the HOV-to-HOT lane conversion and 600 vphpl after conversion while average non-peak GP traffic flow would be 1,500 vphpl before conversion and 2,000 vphpl after. Example inputs are below.

Module: Lane Conversions
Project evaluation year: 2020
Type of ML facility: Barrier

Number of GP lanes before project: 4
Number of ML(s) before project: 1

Number of GP lanes after project: 3
Number of ML(s) after project: 2

[10] H. Abou-Senna et al. (2013), "Using a traffic simulation model (VISSIM) with an emissions model (MOVES) to predict emissions from vehicles on a limited-access highway," *Journal of the Air & Waste Management Association*, 63:7, 819-831, https://www.tandfonline.com/doi/pdf/10.1080/10962247.2013.795918.

Peak traffic flow of ML before project: 500 vphpl
Free flow speed of ML before project: 70 mph

Peak traffic flow of GP lanes before project: 1,500 vphpl
Free flow speed of GP lanes before project: 65 mph

Peak traffic flow of ML after project: 600 vphpl
Free flow speed of ML after project: 70 mph

Peak traffic flow of GP lanes after project: 2,000 vphpl
Free flow speed of GP lanes after project: 65 mph

INPUT User Guide

Reset to Default

(1) What is your project evaluation year?	2020	
(2) Choose your type of managed lane (ML) facility:	Barrier	
Note: Separation between managed and general purpose (GP) lanes will help determine project effectiveness	BEFORE	AFTER
(3a) How many general purpose (GP) lanes does/will the facility have?	4	3
(3b) How many managed lanes does/will the facility have?	1	2

Note: This calculator does not account for infrastructure changes, the number of GP lanes and MLs must stay the same before and after conversion

(4) Please enter the typical peak hour traffic flow (total vehicles per hour per lane) and free flow speed (miles per hour) for both the MLs and GP lanes before and after completion:	BEFORE ML(s)	BEFORE GP Lane(s)	AFTER ML(s)	AFTER GP Lane(s)	
	500	1,500	600	2,000	Traffic Flow (vphpl)
	70	65	70	65	Free Flow Speed (mph)

Note: Please consult the tool's user guide and its appendix for methodology on developing appropriate traffic flow and free flow speed estimates.

While the HOT lanes are proposed to be operation during the 16 non-peak hours, it is likely to have a negative impact on the overall benefits of the project. The 8% of truck traffic, 20-mile facility length, and urban freeway setting are unchanged from Example 3, as shown in the screenshot below.

(5) What percentage of traffic in the GP lanes is from heavy-duty vehicles?	8%
(6a) Indicate peak or non-peak hour analysis for the ML facility:	Non-Peak
(6b) How many peak/non-peak hours each day is the facility operated?	16
(7) What is the length of the facility (in miles)?	20
(8) Is the facility on an urban or rural highway?	Urban

The inputs above result in a slight increase in non-peak GP travel times and non-peak GP speed reductions due to the GP-to-HOT lane conversion. Given that the ML facility is less likely to be utilized in non-peak hours, it is only estimated that a non-peak increase of 100 vphpl will occur after the HOT lane conversions. The image below summarizes the network performance output for non-peak hours for this HOT facility.

OUTPUT Calculate

NETWORK PERFORMANCE

	BEFORE ML(s)	BEFORE GP Lane(s)	AFTER ML(s)	AFTER GP Lane(s)	
Derived Average Speed and Travel Time Estimates for the ML and GP Lanes Before and After Project Completion	68.00	64.86	70.00	59.90	Average Speed (mph)
	17.65	18.50	17.14	20.03	Average Travel Time (minutes)

Average speed on ML before project: 68.00 mph
Estimated travel time on ML before project: 17.65 mins

Average speed on GP lanes before project: 64.86 mph
Estimated travel time on GP lanes before project: 18.50 mins

Average speed on ML after project: 70.00 mph
Estimated travel time on ML after project: 17.14 mins

Average speed on GP lanes after project: 59.90 mph
Estimated travel time on GP lanes after project: 20.03 mins

This particular example of non-peak inputs leads to disbenefits for all pollutants. The non-peak emissions results are shown in the screenshot below.

EMISSION REDUCTIONS

Pollutant	Total (kg/day unless otherwise noted)
Carbon Monoxide (CO)	-537.7120
Particulate Matter <2.5 µm ($PM_{2.5}$)	-0.4743
Particulate Matter <10 µm (PM_{10})	-6.6490
Nitrogen Oxide (NOx)	-5.4359
Volatile Organic Compounds (VOC)	-24.4339
Carbon Dioxide (CO_2)	-54,120.8294
Carbon Dioxide Equivalent (CO_2e)	-54,392.6935
Total Energy Consumption (MMBTU/day)	-716.2777

CO: -537.7120 kg/day
PM2.5: -0.4743 kg/day
PM10: -6.6490 kg/day
NOx: -5.4359 kg/day
VOCs: -24.4339 kg/day

CO_2: -54,120.8294 kg/day
CO_2e: -54,392.6935 kg/day
Energy: -716.2777 MMBTU/day

As a final step, the daily net emission impacts are computed for each pollutant by adding the peak hour reductions from Example 3 and the non-peak hour reductions in this example below. For this project, some peak hour criteria pollutant benefits do outweigh non-peak hour disbenefits and would be eligible for CMAQ funding, as shown in the table below.

	Peak Hour Reduction (kg/day)	Non-peak Hour Reduction (kg/day)	Daily Reduction (kg/day)
CO	-161.346	-537.7120	-699.058
PM2.5	8.4148	-0.4743	7.9405
PM10	22.9407	-6.6490	16.2917
NOx	132.5592	-5.4359	127.1233
VOCs	22.2378	-24.4339	-2.1961

CO_2	25,200.04	-54,120.8294	-28,920.8
CO_2e	25,484.75	-54,392.6935	-28,907.9
Energy	322.5951	-716.2777	-393.683

Appendix – Types of Managed Lane Facilities

The following sections include a number of figures reproduced from the Highway Capacity Manual appendix on managed lanes (MLs)[11] from 2012. It show examples of three types of ML facilities—continuous access, buffer, and barrier—considered in this tool along with methodology for calculating average speed based on the free flow speed and traffic flow. Each type of ML facility is described in greater detail below.

Continuous Access Lanes

A continuous access ML allows vehicles to enter or exit at any point. The GP and ML facilities run in parallel and movement between the two facilities is unrestricted. Figure 1 from the HCM appendix shows an example continuous access ML facility.

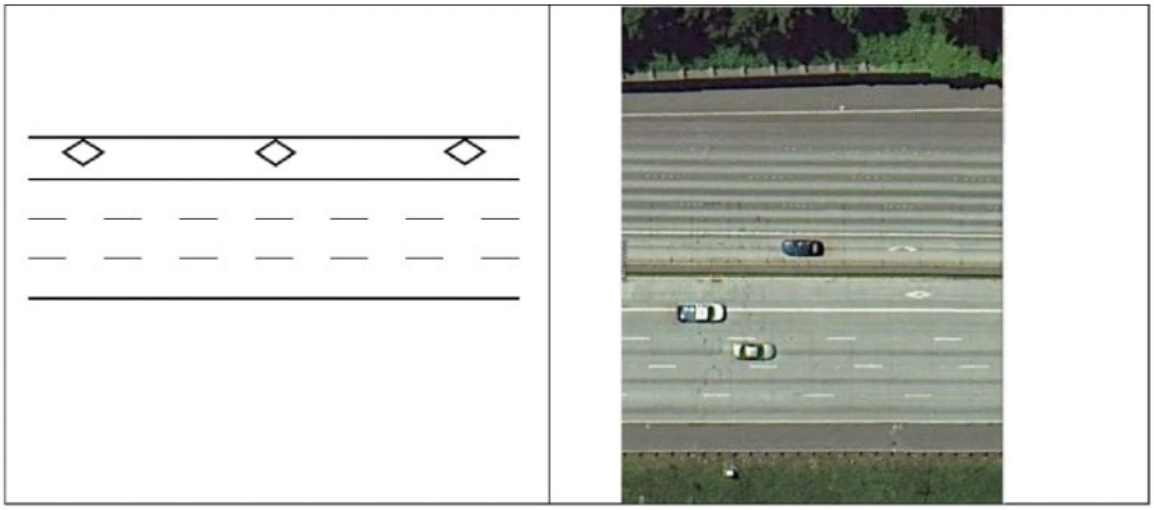


Figure 1. (left) Reproduction of diagram of a continuous access ML facility, and (right) Google Earth image of a ML example facility on I-5 near Seattle, Washington (Exhibit 4, NASEM, 2012)[11]

The accompanying speed-flow curves and equations for a continuous access facility have also been copied from the HCM appendix, as shown in Figure 2 and Table 3. Note that this type of facility accounts for a frictional adjustment.

[11] NASEM (2012), NCHRP Web-Only Document 191, Appendix B, https://doi.org/10.17226/22677.

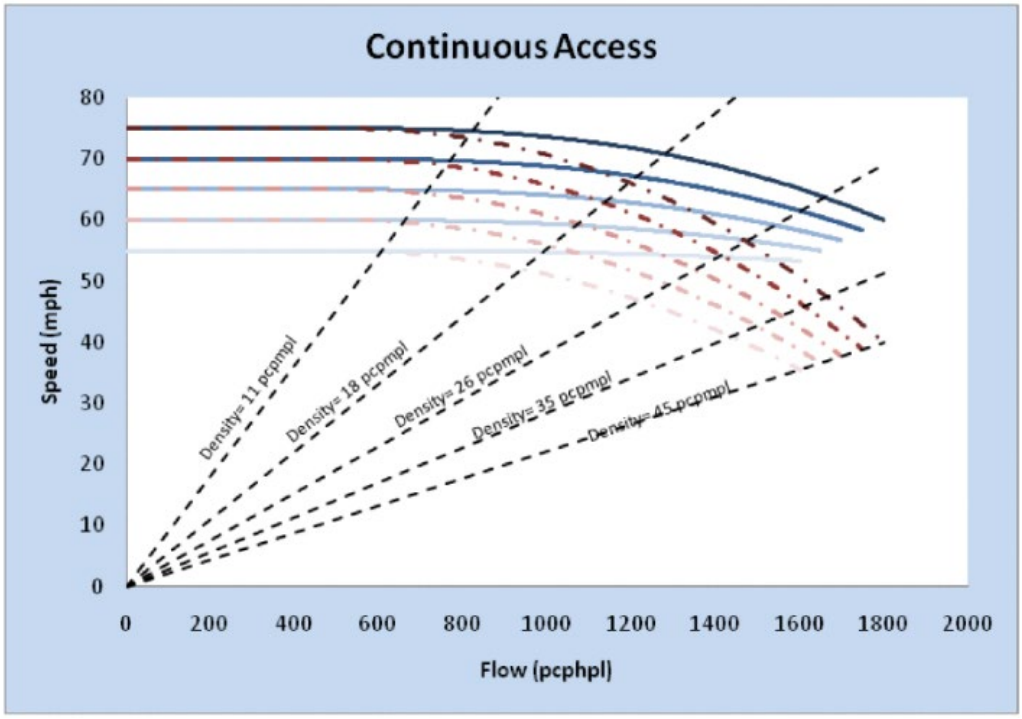


Figure 2. Reproduction of speed-flow curves for a continuous access ML facility based on free flow speeds, traffic flow, and density (Exhibit 11, NASEM, 2012) [11]

Table 3. Reproduction of numerical approximations of average speed on a continuous access ML facility according to free flow speed (FFS) and traffic flow (Exhibit 12, NASEM, 2012) 9

FFS (mph)	Flow Rate Range	
	0-500 pc/hr/ln	500 pc/hr/ln – Max. Flow*
75	75	$75 - \left(2.46 \times 10^{-7}\left(v_p - 500\right)^{2.5}\right) - (0/1)(1.8 \times 10^{-5}\left(v_p - 500\right)^2)$
70	70	$70 - \left(2.12 \times 10^{-7}\left(v_p - 500\right)^{2.5}\right) - (0/1)(1.24 \times 10^{-5}\left(v_p - 500\right)^2)$
65	65	$65 - \left(1.67 \times 10^{-7}\left(v_p - 500\right)^{2.5}\right) - (0/1)(1.31 \times 10^{-5}\left(v_p - 500\right)^2)$
60	60	$60 - \left(1.12 \times 10^{-7}\left(v_p - 500\right)^{2.5}\right) - (0/1)(1.39 \times 10^{-5}\left(v_p - 500\right)^2)$
55	55	$55 - \left(4.15 \times 10^{-8}\left(v_p - 500\right)^{2.5}\right) - (0/1)(1.47 \times 10^{-5}\left(v_p - 500\right)^2)$

*(0/1) represents values for non-friction (0) and friction (1) curves, respectively

Buffer-Separated Single Lane

A ML facility with buffer separation offers intermittent access to the GP lanes. The buffer usually deploys striping techniques, such as a solid white line or double yellow lines, or other at-grade separation. The occasional buffer opening areas are designated by dashed lines. Figure 3 from the HCM appendix shows an example buffer-separated single ML facility.

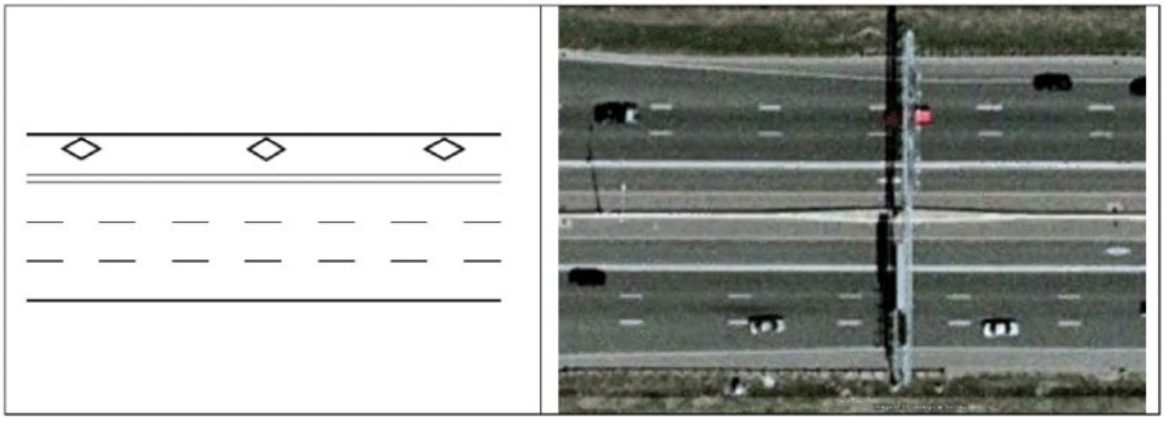


Figure 3. (left) Reproduction of diagram of a single lane buffer-separated facility, and (right) Google Earth image of a ML example facility on I-394 near Minneapolis, Minnesota (Exhibit 5, NASEM, 2012)[11]

The accompanying speed-flow curves and equations for a buffer-separated single lane facility are reproduced from the HCM appendix in Figure 4 and Table 4 below. Note that this type of facility accounts for a frictional adjustment.

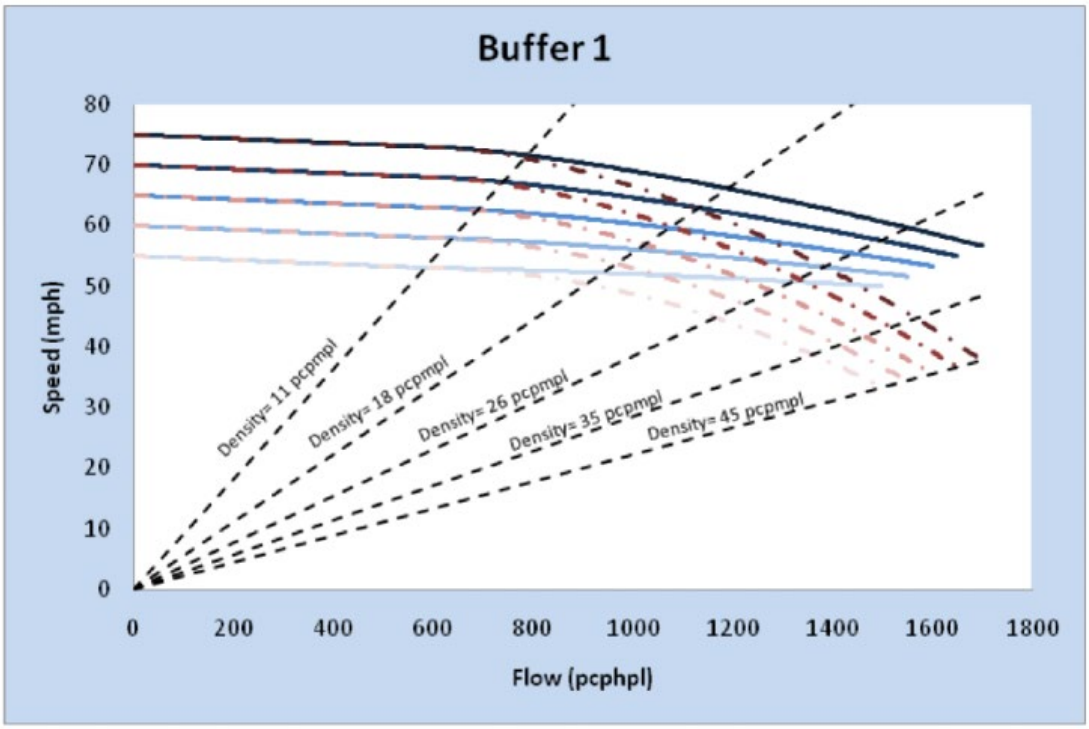


Figure 4. Reproduction of speed-flow curves for a single lane buffer-separated ML facility based on free flow speeds, traffic flow, and density (Exhibit 13, NASEM, 2012)[11]

Table 4. Reproduction of numerical approximations of average speed on a single lane buffer-separated ML facility according to free flow speed (FFS) and traffic flow (Exhibit 14, NASEM, 2012) 9

FFS (mph)	Flow Rate Range	
	0 - 600 pc/hr/ln	600 pc/hr/ln – Max. Flow*
75	$75 - 0.00333(v_p)$	$73 - \left(0.00090\left(v_p - 600\right)^{1.4}\right) - (0/1)(1.38 \times 10^{-5}\left(v_p - 600\right)^2)$
70	$70 - 0.00333(v_p)$	$68 - \left(0.00077\left(v_p - 600\right)^{1.4}\right) - (0/1)(1.46 \times 10^{-5}\left(v_p - 600\right)^2)$
65	$65 - 0.00333(v_p)$	$63 - \left(0.00061\left(v_p - 600\right)^{1.4}\right) - (0/1)(1.56 \times 10^{-5}\left(v_p - 600\right)^2)$
60	$60 - 0.00333(v_p)$	$58 - \left(0.00043\left(v_p - 600\right)^{1.4}\right) - (0/1)(1.66 \times 10^{-5}\left(v_p - 600\right)^2)$
55	$55 - 0.00333(v_p)$	$53 - \left(0.00022\left(v_p - 600\right)^{1.4}\right) - (0/1)(1.65 \times 10^{-5}\left(v_p - 600\right)^2)$

*(0/1) represents values for non-friction (0) and friction (1) curves, respectively

Buffer-Separated Multiple Lanes

As with buffer-separated single lane facility, a multiple lane facility has intermittent access. The MLs will be distinguished by striping or other at-grade separation, typically with dashed lines for ingress and egress points. As shown below, Figure 5 from the HCM appendix illustrates an example buffer-separated multiple ML facility.

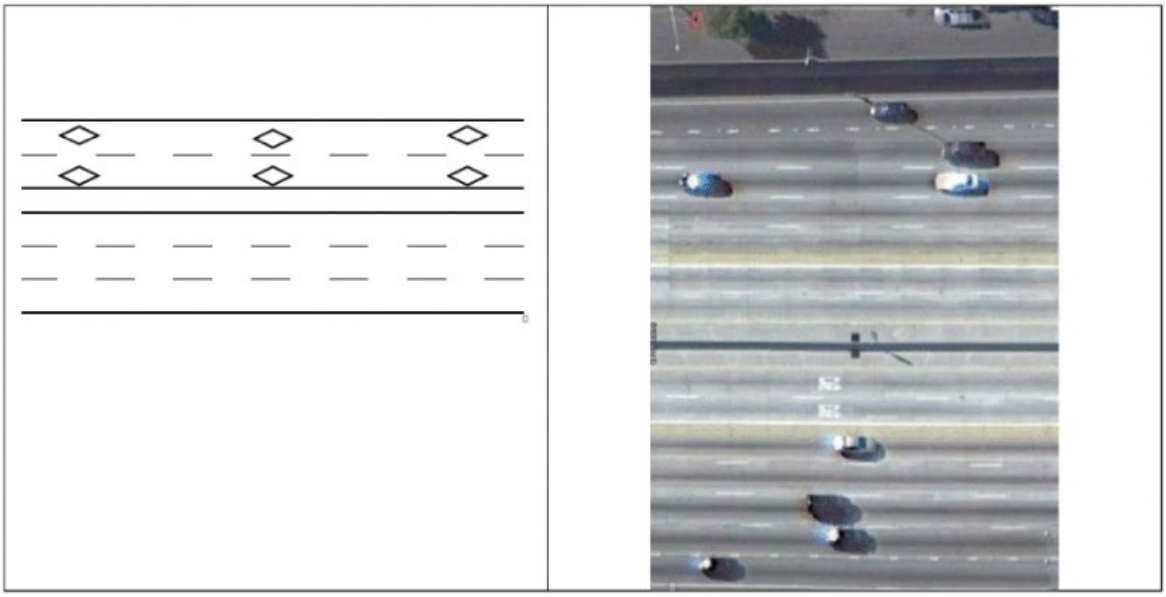


Figure 5. (left) Reproduction of diagram of a multiple lane buffer-separated ML facility, and (right) Google Earth image of a ML example facility on I-110 near Los Angeles, California (Exhibit 6, NASEM, 2012) [11]

For reference, the accompanying speed-flow curves and equations for a buffer-separated multiple lanes facility are reproduced from the HCM appendix in Figure 6 and Table 5 below. Note that this type of facility does not consider a frictional adjustment.

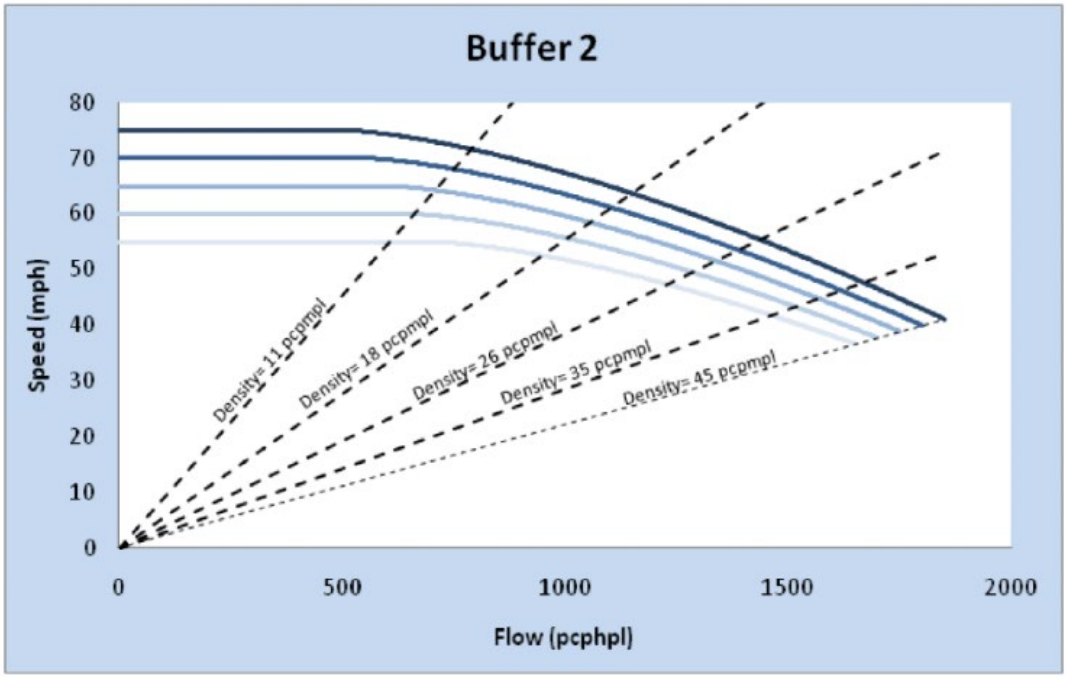


Figure 6. Reproduction of speed-flow curves for a multiple lane buffer-separated ML facility based on free flow speeds, traffic flow, and density (Exhibit 15, NASEM, 2012) [11]

Table 5. Reproduction of numerical approximations of average speed on a multiple lane buffer-separated ML facility according to free flow speed (FFS) and traffic flow (Exhibit 16, NASEM, 2012) [9]

FFS (mph)	Flow Rate Range	
	0 - Breakpoint pc/hr/ln	Breakpoint – Max. Flow pc/hr/ln
75	75	$75 - 0.000683(v_p - 500)^{1.5}$
70	70	$70 - 0.000679(v_p - 550)^{1.5}$
65	65	$75 - 0.000670(v_p - 600)^{1.5}$
60	60	$75 - 0.000653(v_p - 650)^{1.5}$
55	55	$75 - 0.000626(v_p - 700)^{1.5}$

Barrier-Separated Single Lane

As indicated above, a ML facility with barrier separation will have discontinuous access. Barriers such as concrete wall, flexible pylons, landscaping, or any other physical separation schemes prevent vehicles from entering or exiting the ML except at designated locations. An example of a barrier-separated single ML facility is shown below in Figure 7 from the HCM appendix.

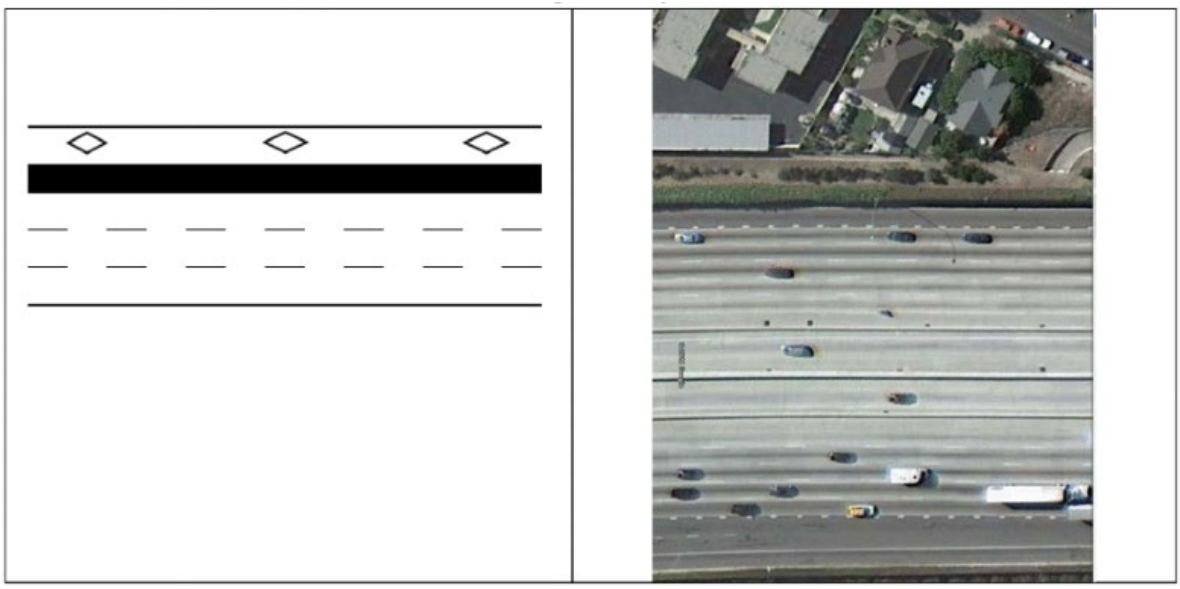


Figure 7. (left) Reproduction of diagram of a single lane barrier-separated ML facility, and (right) Google Earth image of a ML example facility on I-5 in Orange County, CA (Exhibit 7, NASEM, 2012) [11]

The associated speed-flow curves and equations for a barrier-separated single lane facility are copied from the HCM appendix in Figure 8 and Table 6 below. Note that this type of facility does not consider a frictional adjustment.

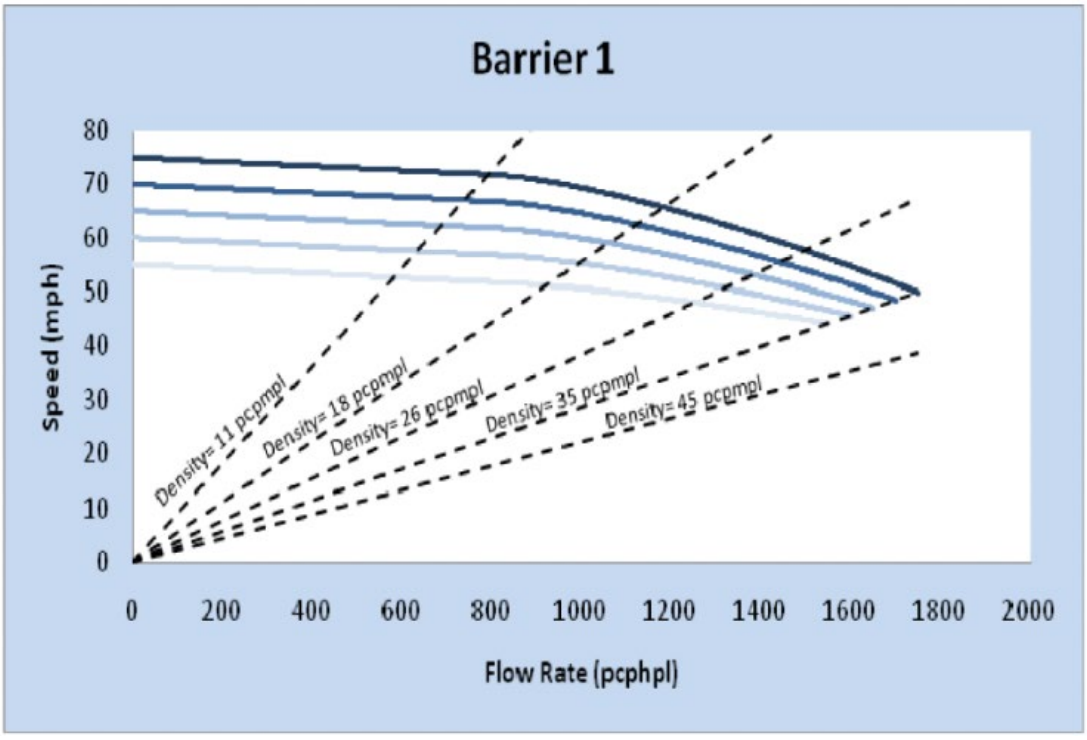


Figure 8. Reproduction of speed-flow curves for a single lane barrier-separated ML facility based on free flow speeds, traffic flow, and density (Exhibit 17, NASEM, 2012) [11]

Table 6. Reproduction of numerical approximations of average speed on a multiple lane barrier-separated ML facility according to free flow speed (FFS) and traffic flow (Exhibit 18, NASEM, 2012)

FFS (mph)	Flow Rate Range	
	0 - Breakpoint pc/hr/ln	Breakpoint – Max. Flow pc/hr/ln
75	$75 - (0.004v_p)$	$71.8 - 0.00148(v_p - 800)^{1.4}$
70	$70 - (0.004v_p)$	$66.8 - 0.00133(v_p - 800)^{1.4}$
65	$65 - (0.004v_p)$	$61.8 - 0.00116(v_p - 800)^{1.4}$
60	$60 - (0.004v_p)$	$56.8 - 0.00096(v_p - 800)^{1.4}$
55	$55 - (0.004v_p)$	$51.8 - 0.00071(v_p - 800)^{1.4}$

Barrier-Separated Multiple Lanes

A barrier-separated multiple lane facility utilizes a wall or other physical separation scheme mentioned above. As in the single ML facility with a barrier, this type of facility limits ingress and egress to specific points along the roadway. It operates effectively as an independent facility from the GP lanes. Figure 9 from the HCM appendix has a schematic of a barrier-separated multiple ML facility for reference.

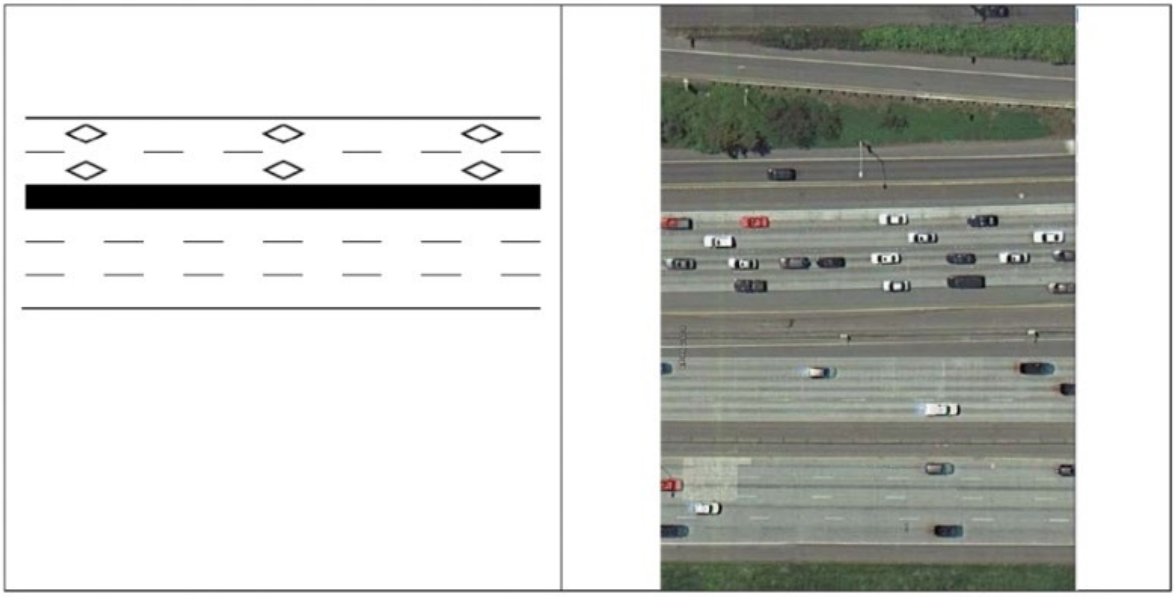


Figure 9. (left) Reproduction of diagram of a multiple lane barrier-separated ML facility, and (right) Google Earth image of a ML example facility on I-5 near Seattle, Washington (Exhibit 8, NASEM, 2012)

The associated speed-flow curves and equations for a barrier-separated multiple lane facility are reproduced from the HCM appendix in Figure 10 and Table 7 below for reference. Note that this type of facility does not consider a frictional adjustment.

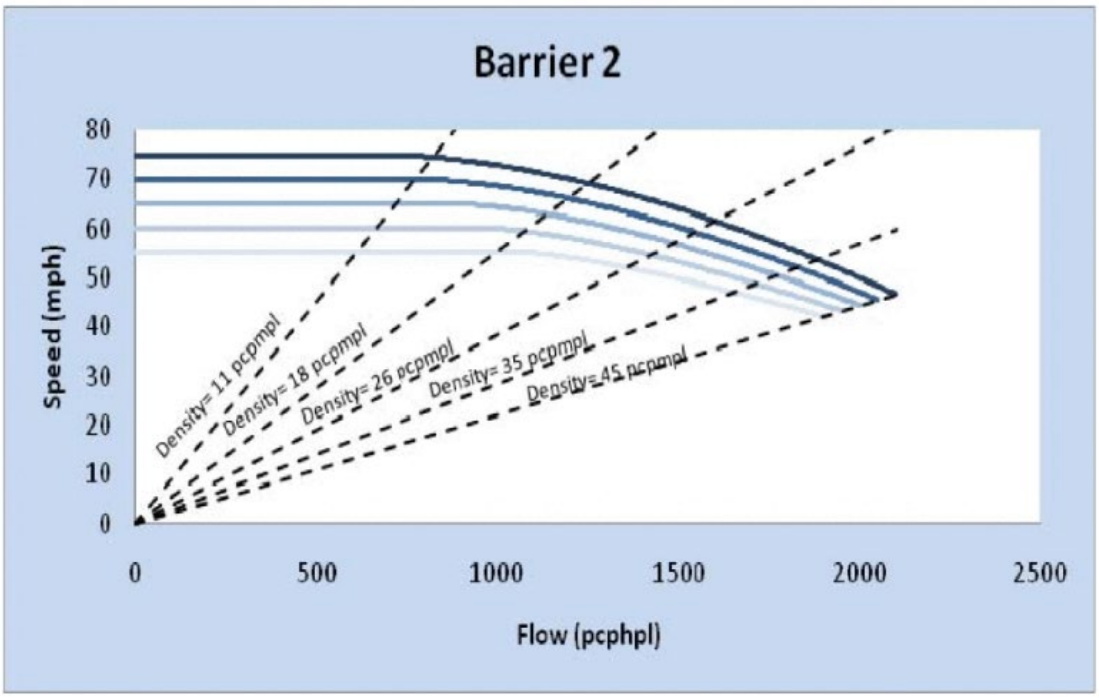


Figure 10. Reproduction of speed-flow curves for a multiple lane barrier-separated ML facility based on free flow speeds, traffic flow, and density (Exhibit 19, NASEM, 2012) [11]

Table 7. Reproduction of numerical approximations of average speed on a multiple lane barrier-separated ML facility according to free flow speed (FFS) and traffic flow (Exhibit 20, NASEM, 2012) [9]

FFS (mph)	Flow Rate Range	
	0 - Breakpoint pc/hr/ln	Breakpoint – Max. Flow pc/hr/ln
75	75	$75 - (0.000127(v_p - 700)^{1.7}$
70	70	$70 - (0.000271(v_p - 800)^{1.6}$
65	65	$65 - (0.000563(v_p - 900)^{1.5}$
60	60	$60 - (0.00113(v_p - 1000)^{1.4}$
55	55	$55 - (0.00215(v_p - 1100)^{1.3}$

General Purpose Lanes

The HCM speed-flow equations for GP lanes that are used in the tool have also been reproduced below. Table 8 is replicated from a 2014 Transportation Research Record paper[12] that expands the HCM speed-flow equations for free flow speeds for 80 and 85 mph in the event that vehicles are traveling faster on GP lanes of a particular studied freeway. A similar analysis has not been performed for MLs, which have a maximum free flow speed of 75 mph.

[12] Robertson et al., Texas A&M Transportation Institute, 2014, "Determining Level of Service on Freeways and Multilane Highways with Higher Speeds," *Transportation Research Record*, No. 2461, p. 85-93 (https://journals.sagepub.com/doi/pdf/10.3141/2461-11).

Table 8. Reproduction of numerical approximations of average speed on GP lanes according to free flow speed (FFS) up to 85 mph and traffic flow, which extends HCM methodology (Table 8, Robertson et al., 2014)[10]

	Flow Rate Range			
FFS (mph)	Break Point (pcphpl)	Less Than Break Point	Less Than Break Point and Greater Than Capacity	Source
85	**600**	**85**	$\mathbf{85 - 0.00000897\ (flow\ rate - 600)^2}$	**New**
80	**800**	**80**	$\mathbf{80 - 0.00001043\ (flow\ rate - 800)^2}$	**New**
75	1,000	75	$75 - 0.00001107\ (flow\ rate - 1{,}000)^2$	HCM
70	1,200	70	$70 - 0.00001160\ (flow\ rate - 1{,}200)^2$	HCM
65	1,400	65	$65 - 0.00001418\ (flow\ rate - 1{,}400)^2$	HCM
60	1,600	60	$60 - 0.00001816\ (flow\ rate - 1{,}600)^2$	HCM
55	1,800	55	$55 - 0.00002469\ (flow\ rate - 1{,}800)^2$	HCM