Emissions Calculator Technical Documentation and User Guide

Technical Report

prepared for

Atlanta Regional Commission

prepared by

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1.0 Introduction

As part of an Atlanta Regional Commission (ARC) General Support Services Contract, Cambridge Systematics, Inc. developed an emissions calculator to support the selection of projects for Congestion Mitigation and Air Quality (CMAQ) funding, and to assist in annual CMAQ reporting requirements after authorization of project funding. The calculator was developed to support other potential applications as well to include:

- Calculating emissions for off-model projects in a conformity determination; and
- Estimating delay reduction, vehicle miles traveled (VMT) reduction, and emissions for smaller-scale, off-model projects for project evaluation and prioritization process.

The calculator estimates emissions reductions associated with the eight-hour ozone standard (ozone precursors NO_x and VOC), annual $PM_{2.5}$ standard ($PM_{2.5}$ and NO_x), and greenhouse gases (CO2, CH_4, and N_2O combined into GHG equivalent units). Emissions benefits can be calculated for any year between 2010 and 2020. The Calculator contains a separate tab for 16 separate transportation strategies, which are grouped into five emphasis areas:

- Roadway ITS/Operations/Incident Management;
- Transit Start-up Operations and Expansion;
- Managed Lanes;
- Travel Demand Management; and
- Clean Fuel and Technology.

Chapters 2 to 6 of this document provide guidance on using each of the strategies arranged by the five emphasis areas. Chapter 7 provides information on additional tabs in the calculator including MOVES emission rate preparation, other variables, and sources/comments by model parameter.

2.0 Roadway ITS/Operations/Incident Management

2.1 Advanced Traffic Management Systems (ATMS)

Project Types

This approach evaluates the emission benefits of adding an advanced traffic management system (ATMS) along a corridor. Projects under this category can include signal equipment upgrade/retiming, installation of CCTV or other sensors, installation of a signal communications network, signal monitoring and real-time adjustment, among similar projects. The proposed project should have the effect of reducing the average delay at intersections through better signal timing, conveying traffic information to the public resulting in better route choice, etc. Installing sensors/communications equipment that only provides data that is not acted upon will not improve average delay or reduce emissions.

Projects that install adaptive signal systems are also included in this strategy, but use different delay reduction assumptions due to the higher level of delay reduction that can be achieved through this advanced technology.

Methodology Limitations

ATMS are a fairly new technology with new innovations being frequently applied. Up-to-date research and case studies should be consulted to ensure delay reduction assumptions are accurate and appropriate for the ATMS improvement.

This calculator predicts the overall emission benefits based on the average reduction in delay; therefore, the project under analysis must have an effect on delay.

User-Defined Inputs

The methodology requires the set of project-specific, user-defined inputs presented in Table 2.1. Table 2.2 provides intersection control delay associated with varying levels of service to help the user in selecting a general delay value if more detailed information is not available.

Table 2.1 ATMS Project User-Defined Inputs

User-Defined Input	Default Values	Input Guidance
Average Peak Hour Intersection Delay before ATMS (s/veh)	80	• Enter the peak hour intersection delay averaged over all intersections in the entire corridor. • Table 2.2 below can be used to help select general values when detailed values are not available from other sources. • 80 seconds/vehicle is the control delay at a LOS F signalized intersection and can be used as the default value if the intersection is known to be highly congested. Higher values may be entered if supported by a recent study.
Peak Hour Volume Along Corridor		• Enter the total peak hour volume along the corridor under analysis. • Obtain from traffic counts or travel demand model.
Truck percent		• Enter the average percentage of trucks in the corridor. • Obtain from traffic counts or travel demand model.
Does the Project Include an Adaptive Signal System?		• If the project is an adaptive signal system, enter 'Y," otherwise enter 'N'.
Number of Intersections along Corridor		• Enter the total number of intersections along the corridor under analysis.

Table 2.2 Level of Service Criteria for Signalized Intersections (HCM 2000)

Level of Service (LOS)	Control Delay (Seconds per Vehicle)	General Description
A	≤ 10	Free-flow
B	> 10-20	Stable Flow (slight delays)
C	> 20-35	Stable Flow (acceptable delays)
D	> 35-55	Approaching unstable flow (tolerable delay, occasionally wait through more than one signal cycle before proceeding)
E	> 55-80	Unstable flow (intolerable delay)
F	> 80	Forced flow (jammed)

Methodology

The purpose of ATMS is to improve travel time, flow, and safety along a corridor. These technological improvements are installed at most, if not all, intersections along a corridor to provide real-time traffic data. This data can subsequently affect signal timings, driver route choice, and other factors that reduce delay along a corridor.

The calculation for predicting emission reductions for this improvement is based on the average decrease in intersection delay. From the Georgia of Department of Transportation, a recent Regional Traffic Operations Program (RTOP) study concluded that ATMS type projects reduced delay by an average of 12 percent[1]. This 12 percent reduction factor was multiplied by the user-defined current average intersection delay to predict the improved delay.

Projects that used adaptive signal control delays had an even greater delay reduction. From a U.S. Department of Transportation study, ATMS reduced delay between 19 to 44 percent[2]. The average, 31.5 percent was multiplied by the current average intersection delay to calculate the improved delay.

These delay reductions were used along with idle emission rates to estimate the emission reductions for ATMS projects.

2.2 Signal Synchronization

Project Types

This approach evaluates the emissions benefits associated with synchronizing traffic signals to allow vehicles to hit multiple green lights in a row when traveling at a reasonable speed along a corridor. Travel time savings at each intersection along the corridor are calculated and aggregated by applying a delay reduction factor.

Methodology Limitations

This method specifically evaluates signal synchronization along an arterial corridor, and cannot estimate systemwide or areawide improvements. However, areawide improvements can be estimated by testing individual corridors separately and summing their unique impacts. The length of the corridors and the signals being improved for synchronization should be reasonably spaced to achieve a meaningful reduction in travel savings. For example, travel time savings will be minimal for two signals spaced a mile apart compared to seven signals in a one-mile corridor.

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[1] Georgia Department of Transportation. (2014). *Regional Traffic Operations Program.* Accessed at: http://www.dot.ga.gov/travelingingeorgia/trafficcontrol/Pages/Operations.aspx.

[2] Sussman, J. et al. (2000). What Have We Learned About ITS? *Federal High Administration, U.S. Department of Transportation.* Accessed at: http://www.itsbenefits.its.dot.gov/its/benecost.nsf/0/B56A52DA1C256C8E8525725F00691912.

This method assumes that all travel time savings benefits will be realized during the morning and afternoon weekday peak periods. Alterations to the strategy would be required to consider travel time savings outside the morning and afternoon weekday peak periods. Also, the signal synchronization strategy is set up for a corridor with a pattern of high morning inbound traffic and high afternoon outbound traffic. Alternations to the strategy would be required to consider a corridor with comparable traffic in both directions.

User-Defined Inputs

The methodology requires the set of project-specific, user-defined inputs presented in Table 2.3. Two columns of inputs are required: one for the inbound direction during the morning peak and one for the outbound direction during the evening peak.

Table 2.3 Signal Synchronization Project User-Defined Inputs

User-Defined Input	Default Values	Input Guidance
Length of the signalized corridor (miles)		• Enter length of corridor targeted for signal synchronization
Existing number of signalized intersections		• Enter number of signalized intersections in the corridor
Existing number of lanes (one direction)		• Enter the average number of through lanes in each direction in the corridor • Intersection turn pockets are represented by ½ lane
Average hourly volume during peak period (one direction)		• Enter the average hourly volume over the multihour peak period and over all segments in the corridor
Truck Percentage (one direction)		• Enter the average truck percentage for each direction during the peak period over all segments in the corridor
Average corridor travel time (one direction) during peak period (minutes)		• Enter time it currently takes for a vehicle to travel the length of the corridor in each direction during the peak period
Existing average cycle length (seconds)		• Enter average cycle length of all the signalized intersections in the corridor

Methodology

This methodology uses California Department of Transportation's (Caltrans) Traffic Light Synchronization Program (TLSP)[3] evaluation algorithms to calculate delay at each intersection along a defined corridor. The TLSP offers an established method of calculating various benefits of corridor traffic signal synchronization in California, and is consistent with the evaluation and calculation of fuel savings from signal synchronization projects in the State of California. Travel time savings due to the synchronization are estimated by calculating average delay at each intersection in the corridor. The travel time savings formula is based on the Highway Capacity Manual (HCM) 2000 equation for delay (Equation 16-11 Chapter 16). When signals are synchronized, it is assumed that delay is reduced by a factor of 0.55.[4]

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

Where:

C = Cycle length; and

g/C = Green time to cycle ratio.[5]

The travel time savings is the difference in seconds per vehicle per signal. It is multiplied by the number of signals and divided by 60 to get the benefit in minutes per vehicle for the total length of the arterial. Finally, the approach multiplies this by the volume to get the total saving in minutes.

[3] Caltrans (2008), *Traffic Light Synchronization Program (TLSP) Evaluation and Scoring Methodology*, California Department of Transportation, available on-line at: http://www.catc.ca.gov/programs/tlsp.htm.

[4] HCM (2000), *Highway Capacity Manual*, Transportation Research Board (TRB), Exhibit 16-12. 0.55 is calculated as the average adjustment factor for arrival type 4 (0.767) and arrival type 5(0.333) at a green ratio of 0.5. Exhibit 16-12 available in "Other Variables" tab of the calculator.

[5] To avoid users having to enter time-to-cycle ratios for each intersection, g/C is assumed to be 0.5 for the corridor. This is a recommended practice per HCM (2000).

2.3 Intersection Improvement

Project Types

This approach evaluates a number of at-grade intersection improvement projects:

- **TYPE A – New Signal** – An unsignalized intersection approaching failure due to intolerable levels of delays is improved to a signalized intersection with an acceptable level of service.
- **TYPE B – New Phase –** Enabling a specific turn or movement at the intersection that was nonexistent or making a permissive turn into a protected turn by changing the signal phasing and/or timing.
- **TYPE C – Capacity and Phase –** Changes to the signalized intersection positively impacting level of service including improvements to geometry, approach redesign, or increased capacity.

NOTE: In project definitions where both a new phase and added capacity are included (i.e., a mix of project type B and C), the following approach is recommended:

1. For projects adding only turn-lane capacity and new turn phasing, only apply the project type B approach, entering the new number of turn lanes as an input.
2. For projects adding both turn-lane and through-lane capacity, apply both the project type B and project type C approach separately.

In each case, average reduction in delay per vehicle due to the improvement is estimated to determine the emission reduction benefits as a result of the improvement. A major overarching assumption is that the design methodology considers the signals as pre-timed, given the difficulty of accounting for the dynamics of changes to signal times and phases under an actuated setting.

Methodology Limitations

The intersection improvement methodology calculates delay at a single intersection level, and is not equipped to estimate improvement benefits for multiple intersections or systemwide improvements. Intersection delay studies are the best source for delay measurements, if available. In the absence of observed intersection delay information, guidance to estimate delay is provided based on LOS, as presented in HCM tables found in the "Other Variables" tab of the calculator and in

Table 2.5 below. This methodology is not applicable in case of a staggered (five-legged or more) intersection.

In the absence of accurate delay data, estimation through vehicle approach and progression should be made as accurately as possible. LOS corresponding to delay windows may only be used to approximate control delay due to the difference in lower and upper bounds of each

LOS (for example, LOS F corresponds to a delay between 55 to 80 seconds per vehicle, which might not be precise enough to provide an accurate estimation of emission reduction benefits).

User-Defined Inputs

The three unique intersection project approaches requires the set of project-specific, user-defined inputs presented in Table 2.4.

Table 2.4 Intersection Improvement Project User-Defined Inputs

User-Defined Input	Default Values	Input Guidance
A. Unsignalized (two-way of four-way stop) to Signalized Intersection		
Area Type		Five options are available (CBD, Urban, Suburban, Mountain, Rural)
Facility Type (Street 1 and Street 2)		Four options are available (Interstate, Expressway, Primary, Secondary)
Total number of lanes (Street 1 and Street 2)		Note: Each turn lane, auxiliary lane or reversible lane equals ½ lane. Input total lanes for both directions of the street.
Peak Hour Volume (Approach Street 1 and 2)		Enter the average weekday peak hour volume (sum of both directions) for each street
Percent Trucks (Street 1 and 2)		Input the percentage of trucks on each street from traffic counts or the travel demand model.
Proposed Signalized Intersection Cycle Length (sec)	60 – 120	Guidance based on FHWA signal timing manual (see Table 2.4)
Peak Hour Intersection Delay before Improvement (s/veh)	50	50 second per vehicle is the default assumption for LOS F at unsignalized intersections. Higher values may be entered if supported by a recent study. Lower value may be entered for LOS A-E based on Table 2.5.
B. New or Protected Turn Phasing at Existing Signalized Intersection		
Type of Turn Affected by Project		Input the turn movement (left or right) enabled by the new phase. Project approach can measure the benefit of adding a single phase only.
Proposed Total Cycle Length (sec) (including impact from new or extended turn phases)	60 – 120	Guidance based on FHWA signal timing manual[2].
Total number of turn lanes on improved turn movements		The total number of turn lanes for all of the improved turn movements. For example, say 2 left turns at the intersection are being improved, each with 1 turn lane. The user should enter 2 lanes.
Percentage of Trucks		Input the percentage of trucks in the turn lanes being impacted.

User-Defined Input	Default Values	Input Guidance
C. Improvement in Overall Intersection Capacity		
Area Type		Five options are available (CBD, Urban, Suburban, Mountain, Rural)
Facility Type (Street 1 and Street 2)		Four options are available (Interstate, Expressway, Primary, Secondary)
Total number of lanes (Street 1 and Street 2)		Note: Each turn lane, auxiliary lane or reversible lane equals ½ lane. Input total lanes for both directions of the street.
Total number of lanes after improvement (Street 1 and Street 2)		Note: Each turn lane, auxiliary lane or reversible lane equals ½ lane. Input total lanes for both directions of the street.
Peak Hour Volume (Approach Street 1 and 2)		Enter the average weekday peak hour volume for each intersection approach
Existing Cycle Length (sec)	60-120	See signal complexity guidance from FHWA Signal Timing Manual (see Table 2.6)

Table 2.5 Unsignalized Intersection Delay by LOS

Level of Service	Unsignalized Intersection Delay	Progression Criteria (Unsignalized Intersection)
A	<10	Very low control delay 10 or less seconds per vehicle. All drivers find freedom of operation. Very rarely more than one vehicle in queue.
B	10 to 15	Control delay greater than 10 and up to 15 seconds per vehicle. Some drivers begin to consider the delay troublesome. Seldom there is more than one vehicle in queue.
C	15 to 25	Control delay greater than 15 and up to 25 seconds per vehicle. Most drivers feel restricted, but tolerably so. Often there is more than one vehicle in queue.
D	25-35	Control delay greater than 25 and up to 35 seconds per vehicle. Drivers feel restricted. Most often, there is more than one vehicle in queue.
E	35-50	Control delay greater than 35 and up to 50 seconds per vehicle. Drivers find delays approaching intolerable levels. There is frequently more than one vehicle in queue. Level denotes a state in which the demand is close or equal to the probable maximum number of vehicles that can be accommodated by the movement.
F	>50	Control delay in excess of 50 seconds per vehicle. Very constrained flow. Represents an intersection failure situation that is caused by geometric and/or operational constraints external to the intersection.

Source: HCM 2000.

Table 2.6 FHWA Signal Timing Manual Reference

Signal Complexity	Commonly Assumed Cycle Lengths
Permissive left turns on both streets	60 seconds
Protected left turns, protected-permissive left turns, or split phasing on one street	90 seconds
Protected left turns, protected-permissive left turns, or split phasing on both street	120 seconds

Source: FHWA Traffic Signal Timing Manual, 2008.

Methodology

Intersection improvements that provide additional turn lanes, better geometric design, improved signal timing and phasing can reduce vehicle delay in navigating the intersection. This delay reduction results in lower vehicle emissions due to less vehicle time spent decelerating, accelerating, or idling. Existing vehicle hours of delay for each intersecting street (by each approach) must be estimated separately, either via an intersection delay study or data from a traffic management center. Alternatively, estimation through vehicle approach and progression should be instrumental in estimating the average delay for each approach, and thereby for intersecting streets.

Delay at the intersection is calculated given the delays for individual approaches and flow rates as follows:

$$\frac{\sum_{i=1}^{n}\left(v_i \cdot d_i\right)}{\sum_{i=1}^{n} v_i}$$

Where:

d = Delay for the approach;

v = Approach flow rate (vehicles per hour); and

n = Number of approaches to the intersection.

This reduction in average delay per vehicle approaching the intersection equates to less time spent idling, where emission rates are highest. Since control delay takes into consideration the time elapsed for deceleration, queuing, and idling, the difference in travel speeds for noncongested conditions before-and-after improvements are not included in the emission reduction calculation. The total change in vehicle hours of delay at the intersection, before and after the improvement, is calculated as follows:

$$\Delta D_{int} = D_{intnb} - D_{intb}$$

Where:

D_{intnb} = Total delay at the intersection for the no-build condition; and

D_{intb} = Total delay at the intersection for the build condition.

The change in delay (ΔD_{int}) is multiplied by the idle emissions factor (g/hr) to estimate emission reductions.

Project Type A – New Signal

For estimating the delay at a planned signalized intersection, short of obtaining basic design parameters of the intersection including turning movements and the lane configuration changes, the user is prompted to provide peak hour volumes for intersecting streets, respective capacity at the intersection and the total signal cycle length at the intersection. Delay at the intersection is calculated using the following formula (this formula is used within each project type approach):

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

Where C = is the cycle length, g/C = is the green time to cycle ratio = 0.5 (for simplicity) and X is the highest volume to capacity ratio of any turning movement or a lane group at the intersection.

The improvement in delay experienced per vehicle due to signalization is transformed into total delay in vehicle hours and thereby used for estimation of emission reductions.

Estimated delay in this methodology is assumed to be uniform delay resulting due to uniform arrival of traffic at the intersection, which is an ideal assumption. In the absence of detailed turning movement data and proposed signal timing and phasing details, green time to cycle ratio is assumed to be 0.5. It should be recognized that the mid-block capacity of a street is different from the capacity at the intersection due to turning traffic and effects of signal controls on the traffic. Hence, intersection capacity should be input keeping view that it is not exactly the same as the mid-block capacity.

Project Type B – New Phase

Enabling a specific turn or movement at the intersection that was nonexistent or permissive before into a protected turn by providing a new phase or include the movement in an existing phase by changing the time allocated to such phase can reduce overall intersection delay. If the movement is not allowed at the intersection in the existing set-up, the existing delay is assumed to reflect a level of service F or more, which translates into a delay of 80 seconds or more. By providing protected phase to this movement, we are not only changing the signal timing plan, but also potentially adding to the cycle length. Because the delay at the intersection will be reduced for this movement, due to the provision of a green time to serve this movement, delay can be calculated based on the new cycle time and the effective green time for that movement.

The same formula presented in project type 1 is used to calculate before and after intersection delay. This methodology relies on assuming several constants for estimation of delay at the intersection for the turning lane group. Saturation flow rate is adjusted to area type and based on the type of turn. Saturation flow rate in CBDs and urban areas is assumed to be 1,700 veh/hr/lane[6]. Further, this saturation rate needs to be adjusted for the type of turn, which is lower for right and left turns compared to the through movement. For right turns, the adjustment factor is 0.85 and for left turns, it is 0.95. The default v/c ratio for the turning movement is 0.9.[7]

Project Type C – Capacity and Phase

Physical changes to the intersection for increasing capacity or geometric design will include provision of new lanes (through or turning lanes). These changes to the capacity will be reflected in estimating delay due to easing capacity restrictions due to changes caused by the improvement. Volume is considered constant for practical purposes, since it is hard to estimate the quantity of traffic which gets re-routed from other facilities due to improvement in delay at this intersection. Given the added capacity and geometric redesign resulting in delay reduction, a comparative analysis of intersection configuration before and after the improvement can be conducted to estimate the reduction in greenhouse gas emissions due to physical intersection design changes.

The same formula presented in project type 1 is used to calculate before and after intersection delay. Effective green to cycle ratio is assumed to be 0.5 for simplification in absence of turning movement and signal timing data to calculate it. Traffic is assumed to arrive in a uniform fashion at the intersection and improvement in uniform delay is estimated for calculating reductions in total greenhouse gas emissions as a result of improved geometric design and approach changes at the intersection.

[6] Highway Capacity Manual (HCM 2000), Adjustments for Saturation Flow Rate, Chapters 16 to 11.

[7] Highway Capacity Manual (HCM 2000), Chapter 16-99, Signalized Intersections, Design Strategies for Signal Timing Plan Design for Pre-timed control.

2.4 Roundabouts

Project Types

This approach evaluates the emission benefits of constructing a roundabout at either an unsignalized or signalized intersection. Projects can have a maximum of four approaches and can be analyzed as a one-lane or two-lane roundabout. The average delay reduction per vehicle due to the roundabout improvement is estimated to determine the emission reduction benefit.

Methodology Limitations

The modern roundabout can have numerous design considerations including the size and shape of the roundabout based on the street layout and surrounding area. This approach does not completely consider the design elements of roundabouts, which can affect average vehicle delay. A user-change of the impedance factor when calculating capacity can account for any design considerations that may greatly influence the average critical gap or follow-up time.

The approach does not alter the capacity of the intersection due to an increase in driver's familiarity. Generally, capacity at a roundabout is initially lower when first installed until drivers gain more experience traversing the intersection.

When the Degree of Saturation (v/c) becomes greater than one, the intersection has failed and does not produce accurate delay calculations. The cells indicating v/c turns red when this occurs. Users should be mindful to test roundabouts that do not exceed a circulating flow greater than 1,800 veh/h.

User-Defined Inputs

The methodology requires the set of project-specific, user-defined inputs presented in Table 2.8.

Table 2.7 Roundabout Project User-Defined Inputs

User-Defined Input	Default Values	Input Guidance
Total Hourly Volume of Each Approach		• Enter average peak hour weekday passenger vehicle traffic.
Percentage of Left Turns for Each Approach		• Enter the average percentage of left turns for each approach
Percentage of Right Turns for Each Approach		• Enter the average percentage of right turns for each approach
Truck Percentage (using the roundabout)		• Enter the average percentage of trucks using the roundabout
Peak Hour Factor (PHF)	0.95	• Enter the Peak Hour Factor for the intersection, if known • Default value based on the NCHRP Report 599,[8] PHFs for Uninterrupted Flow Facilities, Page 4 (Urban = 0.95; Rural = 0.88)
Proposed Number of Lanes for Roundabout		• Select either a 1 Lane or 2 Lane Roundabout
Peak Hour Intersection Delay before Improvement		• Enter the current peak hour intersection delay

Methodology

Roundabouts can improve traffic flow and decrease delay under certain conditions. Delay reduction results in lower vehicle emissions due to less time spent waiting to traverse the intersection, specifically the time spent idling. Each approach into the intersection must be analyzed separately due to the unique nature of how roundabout delay is calculated.

The source used to calculate the average intersection delay at roundabouts was derived from the National Cooperative Highway Research Program (NCHRP) Report 672, *Roundabouts: An Informational Guide, Second Edition*, which provides instructions on what information and steps are necessary for the calculations[9]. This source was also the basis for the fifth edition of the Highway Capacity Manual (HCM 2010).

[8] Kittelson & Associates, Inc. (2008), *NCHRP Report 599: Default Values for Highway Capacity and Level of Service Analyses,* Transportation Research Board, accessed at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_599.pdf.

[9] Kittelson & Associates, Inc. (2010), *NCHRP Report 672: Roundabouts: An Informational Guide, Second Edition*, Transportation Research Board, accessed at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_672.pdf.

The delay calculation begins with the calculation of the entering, circulating, and exiting flow rates for each roundabout leg. This adjusts for the percentage of heavy vehicles into the number of passenger cars per hour.

$$v_{i,pce} = \frac{v_i}{f_{HV}}$$

$$f_{HV} = \frac{1}{1 + P_T\left(E_T - 1\right)}$$

Where:

$v_{i,pce}$ = demand flow rate for movement *i*, pc/h;

v_i= demand volume for movement *i,* veh/h;

f_{HV} = heavy vehicle adjustment factor;

P_T = proportion of demand volume that consists of heavy vehicles; and

E_T = passenger car equivalent for heavy vehicles (default is 2.0).

Following the conversion from entry volumes to roundabout volumes, the capacity of each approach is then calculated. The opposing volumes passing by the approach contribute to how many vehicles can transverse the roundabout in an hour due to the need for a gap between opposing vehicles in order to enter the intersection. The equation for estimating the capacity of a one lane roundabout is:

$$c_{e,pce} = 1{,}130e^{\left(-1.0 \times 10^{-3}\right)v_{c,pce}}$$

Where:

$c_{e,pce}$ = lane capacity, adjusted for heavy vehicles, pc/h; and

$v_{c,pce}$ = conflicting flow, pc/h.

For a two lane roundabout, where two entry lanes are opposed by two conflicting lanes, the average impedance factor between right (-0.007) and left (-0.0075) were used for the capacity equation. Therefore, the equation for estimating a two lane roundabout is:

$$c_{e,pce} = 1{,}130e^{(-0.7 \times 10^{-3})v_{c,pce}}$$

Where all variables are as given previously.

The degree of saturation (v/c) is calculated similarly to other intersection improvements, dividing the roundabout entry flow rate by the approach capacity.

The control delay for each approach was calculated separately, as described in the NCHRP Report 672. The calculation of this delay includes the total time the driver spends decelerating when approaching the intersection, waiting in queue, waiting for an acceptable gap, and accelerating out of the queue. The delay calculation for each approach is:

$$d = \frac{3,600}{c} + 900T\left[x - 1 + \sqrt{(x-1)^2 + \frac{\left(\frac{3,600}{c}\right)x}{450T}}\right] + 5 \cdot \min[x,1]$$

Where:

d = average control delay, s/veh;

x = volume-to-capacity ratio of the subject lane;

c = capacity of subject lane, veh/h; and

T = time period, h (T = 1 for 1-h analysis, T = 0.25 for 15-min analysis).

The improved intersection peak hour delay for roundabout improvements is then calculated similarly to other intersection improvements, where:

$$d_{intersection} = \frac{\sum d_i v_i}{\sum v_i}$$

Where:

$d_{intersection}$ = control delay for the entire intersection, s/veh;

d_i = control delay for approach i, s/veh; and

v_i = flow rate for approach I, veh/h.

2.5 Incident Management

Project Types

This approach evaluates the emission benefits of implementing incident management along a corridor to improve incident clearance time over the existing highway patrol response and clearance times. Emission benefits are based on a reduction in vehicle delay (and therefore idling emissions) since incident management usually provides faster response and clearance time than the existing highway patrol.

Methodology Limitations

This method makes the simplifying assumption that all emissions benefits are from a reduction of vehicle idling (estimated using delay calculations); however, in the real world delay is due to a combination of being stopped (idling) and traveling at lower than normal speeds (slowing down at the bottleneck caused by the incident). It would be difficult to calculate the reduced speed associated with a partial highway closure due to the incident.

Each incident likely results in a different number of lanes being closed (e.g., a freeway with eight lanes in one direction could have anywhere from one to eight lanes closed). Therefore, in reality each incident would have a different capacity of open lanes and a different calculated delay. This method makes the simplifying assumption that on average somewhere between 1/3 and ½ of the total lanes will be open for vehicles to get by an incident during a partial closure. Table 2.9 below shows the exact assumptions on the number of open lanes depending on the total number of lanes in one direction.

User-Defined Inputs

The methodology requires the set of project-specific, user-defined inputs presented in Table 2.8. The calculator is set up to only consider one direction of the corridor at a time. If incident management will be implemented for both directions on a corridor, the incident management tab should be copied and repeated for the second direction.

Table 2.8 Incident Management Project User-Defined Inputs

User-Defined Input	Default Values	Input Guidance
Facility Type	Interstate/ Freeway Free-flow	• Select the facility type for the incident management project from the drop down list • Normally interstate/freeway or expressway would be chosen for this strategy • The facility type and area type is used to look up the capacity per lane
Area Type		• Select the area type for the incident management project from the drop down list • The facility type and area type is used to look up the capacity per lane
Number of Lanes (one direction)		• Enter the number of lanes in one direction along the corridor where incident management will be deployed

User-Defined Input	Default Values	Input Guidance
Hourly Volume Along Facility (Veh/hr for one direction)		• Enter the total volume for all lanes in one direction on the corridor (vehicles/hour) • This should be preferably at the time of the incident, but averaging events makes it less significant
Annual Number of Incidents (in one direction)		• Enter the annual number of incident in the corridor in the single direction that is being analyzed
Average IMS Response and Clear-up Time (minutes)		• Enter the estimated average time that it will take incident management vehicles to respond to and clear an incident (average time of lane blockage)
Average Highway Patrol Response and Clear-up Time (minutes)		• Enter the current average time that it takes the existing highway patrol to respond to and clear an incident (average time of lane blockage)
Share of Incidents Resulting in Total Closures		• Enter the percentage of total incidents that result in all lanes in that direction being closed (the remaining share of incidents will be assumed to result in partial lane closures)
Truck Percentage in the Corridor		• Enter the average truck percent in the corridor (used to get a composite emission rate)

Methodology

The methodology for calculating emission reductions from the incident management strategy is based upon reduced vehicle delay due to special incident management vehicles responding to and clearing the incident faster than is normally done by the highway patrol. The following equation[10] calculates total vehicle-hours of delay for each incident based upon the response and clear up time of the incident management vehicles or highway patrol. Additional variables related to the volume and capacity of the roadway are defined below.

$$d_T = \frac{t^2 * (v - c_R) * (c - c_R)}{2 * (c - v)}$$

Where:

d_T = total delay due to incident (vehicle-hours).

t= duration of incident (response+clear-up time).

[10]Garber, Nicholas and Lester Hoel, Traffic and Highway Engineering – SI Version, page 252.

v= hourly volume (vehicles/hour).

c_R =capacity of open lanes (vehicles/hour).

c=total roadway capacity(vehicles/hour).

Average delay per incident is calculated for four cases:

- Average delay per incident resulting in partial blockage with Incident Management,
- Average delay per incident resulting in complete blockage with Incident Management,
- Average delay per incident resulting in partial blockage with existing Highway Patrol, and
- Average delay per incident resulting in complete blockage with existing Highway Patrol.

This method allows for the user to input the percent of annual incidents that result in a total closure of all lanes of traffic. For these cases the capacity of open lanes becomes zero. The method assumes that the remaining incidents result in a partial closure of lanes and uses the values in Table 2.9 to determine how many lanes remain open during a partial closure. For partial closure incidents the capacity of open lanes is the capacity of a single lane multiplied by the number of lanes that remain open.

Table 2.9 Assumptions for Number of Lanes Open During Partial Closure

Number of Lanes	Lanes Open During Partial Closure
8	3
7	3
6	2
5	2
4	2
3	1
2	1

Once the average delay per incident is calculated for the four cases the total annual delay for all incidents is calculated for the existing highway patrol strategy and the implementation of incident management strategy. The annual number of partial closure and complete closure incidents is calculated based on the two user inputs: total annual incidents and share of incidents resulting in total closure. These annual incident estimates are multiplied by the appropriate average delay per incident (partial or complete closure) and then summed together to estimate total annual delay due to all incidents. The total annual delay for the incident management strategy is subtracted from the total annual delay for the existing highway patrol strategy to estimate the reduction in annual delay due to the implementation of incident management. This reduction in annual vehicle-hours of delay is multiplied by a composite gram/hour idle emission rate that includes both trucks and light duty vehicles. The composite rate is derived by using the truck percent entered by the user.

2.6 Diverging Diamond Interchange

Project Types

This approach evaluates the emission benefits of constructing a diverging diamond interchange in place of any number of traditional interchange designs. Emission benefits are based on a reduction in delay since diverging diamond interchanges have fewer turning movements that experience delay. Diverging diamond interchanges also have fewer conflict points, which leads to traffic signals with fewer phases and shorter waiting times (less delay).

Methodology Limitations

This method does not automatically calculate the delay reduction associated with a diverging diamond interchange. Instead it relies on the user to enter average delay by turning movement for both a no build and build scenario. Separate modeling through a traffic simulation model or similar tool is necessary to obtain the delay information and volume information to input into the emissions calculator.

The method assumes that benefits are realized only on weekdays and multiplies average weekday benefits by the number of weekdays in a year. It also calculates benefits based on peak hour information and then scales them up using a peak hour to daily conversion factor.

User-Defined Inputs

The methodology requires the set of project-specific, user-defined inputs presented in Table 2.10.

Table 2.10 Diverging Diamond Interchange Project User-Defined Inputs

User-Defined Input	Default Values	Input Guidance
Percent Trucks through the interchange		• Enter the average percent of trucks over all 16 movements through the intersection. • The same percentage will be used for before and after the project
Existing/Traditional Interchange Turning Movements Peak Hour Volume		• Enter the no build peak hour volume for up to 16 movements through the interchange (not necessary to use all 16 movements; many traditional interchanges only have 12 movements) • See figures in "Other Variables" tab of calculator for several examples of traditional interchange turning movements
Existing/Traditional Interchange Peak Hour Average Delay (s/veh)		• Enter the no build average delay in seconds per vehicle associated with each of the turning movements
Diverging Diamond Interchange Turning Movement Peak Hour Volumes		• Enter the build condition peak hour volume for up to 16 movements through the interchange (not necessary to use all 16 movements; many diverging diamond interchanges only have 8 movements that experience delay) • See figure in "Other Variables" tab of calculator for an example of diverging diamond interchange turning movements
Diverging Diamond Interchange Peak Hour Average Delay (s/veh)		• Enter the build condition average delay in seconds per vehicle associated with each of the turning movements

Methodology

Diverging diamond interchanges can improve traffic flow and decrease delay under certain conditions. A delay reduction results in lower vehicle emissions due to less time spent waiting to traverse the interchange, specifically the time spent idling.

The methodology employed in this calculator calculates total vehicle hours of delay by multiplying the average delay per vehicle by the volume of vehicles conducting that movement and summing over all movements. This is done for both the no build condition (traditional interchange) and build condition (diverging diamond interchange). A composite light duty and truck idle emission rate is calculated using the truck percentage entered. This is multiplied by the vehicle-hours of delay, a peak hour to daily conversion factor, and the number of weekdays in a year to calculate annual emissions for the build and no build conditions. The annual build emissions are subtracted from the annual no build emissions to calculate the annual emission reduction.

3.0 Transit Start-Up Operations and Expansion

3.1 New Transit Service and/or Transit Technology

Project Types

Transit expansion projects, such as new or extended bus routes and rail lines, can cause shifts from auto travel, resulting in reductions in VMT and thus reductions in emissions. This methodology also estimates the emission reduction benefits of real-time transit arrival information by estimating additional ridership due to shorter wait associated with having this arrival information. Increased frequency of service (or reducing headways) and fleet expansions could also be modeled using the “percent of travel time spent waiting” constants associated with the real-time arrival information calculations.

Methodology Limitations

Some transit improvements, such as general enhancement of transit amenities (stops, sidewalks, benches); transit signal priority; queue jumper lanes; or bus rapid transit (BRT) are beyond the scope of this strategy. For transit improvements that utilize transit signal priority, queue jumper lanes, or bus rapid transit (BRT), please refer to the “Transit Signal Priority” improvement.

Reduction in VMT due to real-time information is due to the reduction in total time spent waiting for the bus. This reduction in total travel time spent waiting has been investigated for bus travel, but not for rail. Caution is advised for applying this methodology for rail travel until further research is conducted in this area.

User-Defined Inputs

The methodology requires the set of project-specific, user-defined inputs presented in Table 3.1.

Table 3.1 Transit Expansion Project User-Defined Inputs

User-Defined Input	Default Values	Input Guidance
Type of New/Current Transit Service		• Select the type of transit fuel/technology that will be used for the new/expanded transit service • Four types of buses plus electric light rail and heavy rail are available
Average Daily Headways (minutes)	15 minutes	• Enter average daily headways (minutes) of the new transit service • Default value of 15 minute headways represents a mid-level value for typical transit service frequencies
Transit Corridor Length (miles)		• Enter average peak-period headway (minutes) after the project
Transit Corridor Hours of Service Per Day	18 hours	• Enter the number of hours per day (max 24) that regularly scheduled transit service will be available in the transit corridor • Default value of 18 hours represents service from 6 AM to midnight.
Does project include real-time arrival information?		• Select "Y" if project involves real-time arrival information
Daily Transit Ridership		• Enter average daily transit ridership added due to improvements

Methodology

The ridership for the new transit project must be estimated separately and input into the calculator. Once the ridership of the new service is known, it is used to calculate the VMT reduction. The equation to calculate decrease in light-duty VMT is as follows:

$$VMT = \frac{(R)}{AVO} \times TL$$

Where:

VMT = Reduction in daily light-duty VMT;

R = Ridership associated with new transit service;

AVO = Average passenger vehicle occupancy; and

TL = Average passenger vehicle trip length.

Additional Ridership Due to Real-Time Arrival Information

The reduction in single-occupant vehicle emissions is the driving force behind estimating how real-time information will improve air quality. The methodology is based on an increase in transit ridership due to a decrease in wait time for the bus.

According to the 2001 National Household Travel Survey, approximately 26 percent of the total travel time while riding transit is spent waiting[11]. The implementation of real-time information allows users to know exactly when the next bus is arriving at their stop. This reduces the user's wait time for the bus by removing the need to arrive early in case the bus is running ahead of schedule. It also allows riders to utilize their time more efficiently in case the bus is running late. A recent study found that riders who use real-time information wait almost two minutes less than those who use traditional schedule information[12]. This decrease results in approximately 21 percent of total travel time spent waiting when real-time information is available.

Using this decrease in total time spent waiting, a travel wait time elasticity of -0.54 is applied to predict the increase in transit ridership due to this new technology[13]. This reduces the number of annual single-occupant vehicle trips, in turn, reducing the total annual emissions.

Also, a second source estimated the direct effects of real-time information on transit ridership. This study concluded that, when all other variables are controlled, there is a ridership increase of approximately 2 percent when real-time information is introduced to transit service.[14] This 2 percent increase was applied to the user-inputted/calculated transit ridership and compared to the previously discussed wait time methodology. The results were very comparable, with ridership estimates different by less than 0.2 percent. In the calculator, estimating the increase in ridership is based on the wait time methodology.

[11] National Center for Transit Research (20051). *Public Transit in America: Results from the 2001 National Household Travel Survey*. Accessed from: http://www.nctr.usf.edu/pdf/527-09.pdf.

[12] Watkins, K. E., Ferris, B., Borning, A., Rutherford, G. S., Layton, D. (2011). Where Is My Bus? Impact of mobile real-time information on the perceived and actual wait time of transit riders. *Transportation Research Part A: Policy and Practice 45*(8) 839-848.

[13] Iseki, H., Taylor, B. D., Miller, M. (2006). The Effects of Out-of-Vehicle Time on Travel Behavior: Implications for Transit Transfers. *Tool Development to Evaluate the Performance of Intermodal Connectivity (EPIC) to Improve Public Transportation.* Access at http://www.its.ucla.edu/wp-content/uploads/sites/6/2014/06/Appendix-A.pdf.

[14] Tang, L., Thakuriah, P. V. (2012). Ridership effects of real-time bus information system: A case study in the City of Chicago. *Transportation Research Part C 22*(2012) 146-161. Accessed from http://foresight.ifmo.ru/ict/shared/files/201311/1_149.pdf.

3.2 Transit Signal Priority

Project Types

This approach evaluates the emission benefits of providing transit signal priority (TSP) along a signal intersection or corridor. Bus Rapid Transit and Express Bus Services are the most likely project types to benefit from this analysis.

Methodology Limitations

This calculator can only estimate emission reductions from transit services with bus vehicles; rail technologies cannot be used in this analysis.

In many cases, Transit Signal Priority is supplemented with additional preferential treatments such as queue jump lanes. In these instances, emission benefits should only be calculated for the transit vehicle and not include general traffic along the same route. The calculator currently assumes the green extension/red truncation can be utilized by both the transit vehicle and the general traffic, only applying a negative emission benefit to the cross street traffic.

User-Defined Inputs

The methodology requires the set of project-specific, user-defined inputs presented in Table 3.2.

Table 3.2 Transit Signal Priority User-Defined Inputs

User-Defined Input	Default Values	Input Guidance
Area Type		• Seven different area types are available: Urban Very High Density, Urban High Density, Urban Medium Density, Urban Low Density, Suburban, Exurban, and Rural.
Facility Type (Street 1 and Street 2)		• Enter what best describes the type of facility for Street 1 and Street 2
Average Existing Number of Lanes (Street 1 and Street 2)		• Enter the average existing number of lanes for both approaches
Average Peak Hour Volume (Street 1 and Street 2)		• Enter the average peak hour volume for Street 1 (main TSP corridor) and Street 2 (intersecting streets)
Percent Trucks		• Enter the average percentage of trucks along the corridor
Average Existing Intersection Signal Cycle Length (sec)		• Enter the average intersection signal cycle length for the entire corridor

User-Defined Input	Default Values	Input Guidance
Average Daily Headway (mins)		• Enter the average transit headway along the corridor with proposed TSP
Transit Signal Priority Hours of Service Per Day		• Enter the total number of hours TSP is implemented in a day. • If activation is not dependent on the time of day (peak vs nonpeak) enter total hours of transit service per day
Average Corridor Travel Time for Buses (one direction, mins)		• Enter the current, average corridor travel time along the proposed TSP route
Change in Green to Cycle Length Ratio with addition of TSP, *or*	10%[a]	• Enter the proposed change in percentage of the green to cycle length ratio when TSP is activated
Maximum Green Time Extension + Maximum Red Time Truncation (seconds)		• Enter the maximum number of seconds a green time extension and red time truncation can be implemented during a TSP activation.

[a] Smith, H. R., B. Hemily, and M. Ivanovic, M, 2005, *Transit Signal Priority (TSP): A Planning and Implementation Handbook*, U.S. Department of Transportation, Federal Transit Administration, accessed at http://www.fta.dot.gov/documents/TSPHandbook10-20-05.pdf.

Methodology

Transit Signal Priority improves overall travel time to transit vehicles along a corridor or when traveling through a congested intersection. When approaching an intersection, the bus is detected and either a green time extension or red time truncation is granted to the transit vehicle. The extension or truncation is granted depending on at what point in the cycle the bus is detected. For example, if the cross street has the green signal, the phase will shorten by a pre-determined number of seconds, effectively truncating the red time for the transit vehicle.

In determining the potential emission benefits of implementing transit signal priority, the current delay and other intersection characteristics are calculated. This methodology is similar to what is implemented for other intersection improvement strategies, where the delay for each approach is:

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

Where C = is the cycle length, g/C = is the green time to cycle ratio = 0.5 (for simplicity) and X is the volume to capacity ratio. It was assumed the delay for Street 1 was the same as the current delay for the transit vehicle.

The same methodology is then applied to calculate the change in delay when TSP is activated. Only the green time to cycle ratio (*g/C)* was changed for this calculation due to TSP altering this ratio for Street 1 and Street 2. When TSP is activated, Street 1's green time increases by a user-defined amount while the green time for Street 2 decreases. This increases the overall delay for Street 2 and decreases the delay for Street 1.

The total delay per vehicle hour is then calculated multiplying the peak hour delay and the total hourly volume and then converting to hours. However, TSP is only activated when a bus is detected; therefore, this improvement in Street 1 delay is not a permanent, continuous occurrence. The probability of a bus arriving during a cycle was calculated, taking into effect the transit hours of service, headway, and average cycle length[15]:

$$P_{bus} = \frac{C}{H}$$

Where:

P_{bus} = probability of bus arriving during a cycle;

$C = \frac{c}{(3600*24)}$ where c = average signal cycle length, s;

$H = \frac{(h*0.5)*60}{3600*s_{hours}}$ where h = average daily headway, mins; and

s_{hours} = TSP hours of service per day.

This probability was used as a weight to factor that not every cycle will have TSP activated; therefore, the intersection peak hour delay when TSP is granted is defined as:

$$D = \frac{\left((v_1 * d_{1,act}) + (v_2 * d_{2,act})\right) * (P_{bus}) + \left((v_1 * d_{1,cur}) + (v_2 * d_{2,cur})\right) * (1 - P_{bus})}{3600}$$

Where:

D = intersection peak hour delay with TSP granted, Veh-hr;

v_1 = average peak hour volume of Street 1, veh/h;

v_2 = average peak hour volume of Street 2, veh/h;

$d_{1,act}$ = peak hour Street 1 & transit delay with TSP granted, s/veh;

$d_{2,act}$ = peak hour Street 2 delay with TSP granted, s/veh;

[15] Skabardonis, A. & Christofa, E. (2011). Impact of Transit Signal Priority of Level of Service at Signalized Intersections. *Procedia Social and Behavioral Sciences (16)* 612-619.

$d_{1,cur}$ = current peak hour Street 1 & transit delay, s/veh; and

$d_{2,cur}$ = current peak hour Street 2 delay, s/veh.

These delay calculations were used to estimate the increase and decrease in emissions of the general traffic due to the implementation of TSP. Overall decreases in emissions for the transit vehicle were also used assuming the change in delay is the same for Street 1 and for the transit vehicle.

In addition to the decrease in delay, improvements in emissions were also considered from the potential increase in transit ridership due to the addition of TSP. The additional riders would be due to the overall increase in travel time along the route, making it more viable for certain individuals to switch from single-occupancy vehicles to transit. With a travel time elasticity of -0.40[16], estimates in the increase in annual transit ridership were calculated. In other words, for every 1 percent decrease in travel time, there is an average 0.40 percent increase in ridership. The improvement in travel time was calculated where

$$C_{TT} = \frac{N_{TT} - O_{TT}}{O_{TT}}$$

Where:

C_{TT} = Percentage change in travel time; and

N_{TT} = new corridor travel time or $O_{TT} - (d_c - d_i)$

Where:

d_c = current average intersection delay to buses, minutes per trip;

d_i = improved average intersection delay to buses, minutes per trip; and

O_{TT} = current average corridor travel time, minutes.

This improvement in travel time was then multiplied by the elasticity of -0.40 to estimate the percent increase in ridership due to the improved travel time along the corridor.

In calculating the total emission benefits, the change due to delay improvements, as well as the increase in ridership, were both considered. Specifically, the emission benefits due to the decreased delay to Street 1 and the transit vehicle were added to the emission benefits from the increase in transit ridership. These factors when then subtracted by the delay increase on Street 2 due to the shortened green phase.

[16] ICF International, 2011, *Analyzing Emission Reductions from Travel Efficiency Strategies: A Guide to the TEAM Approach*. United States Environmental Protection Agency, accessed at http://www.epa.gov/otaq/stateresources/policy/420r11025.pdf.

4.0 Managed Lanes

4.1 Managed Lanes

Project Types

This approach evaluates the emission benefits of constructing new managed lane(s) in a freeway corridor or converting existing HOV lane(s) to managed lane(s). The calculator is set up to assume that the new managed lane has the ability to limit the number of vehicles that enter the lane so that a maximum volume to capacity (v/c) ratio is not exceeded and a minimum operating speed can be maintained. Managed lanes with a pricing mechanism, such as toll lanes or High-Occupancy Toll (HOT) lanes, are the most likely types of managed lanes that could ensure this requirement for the calculator. It is possible to model a reversible lane system by configuring lanes in only one direction in the morning and the opposite direction in the evening.

Methodology Limitations

This methodology assumes that all emissions benefits from the managed lane project will be realized during the weekday peak periods. The calculator does not pick up any emissions benefits during weekend and off peak periods, although these are likely small compared to the weekday peak period benefits. Also, the method is based on calculations for average hourly conditions over the multihour peak period, and then benefits are multiplied by the number of hours in the peak period (the default assumption is four hours in each peak period). In reality conditions that influence v/c ratios and speed may vary over the multihour peak period (possibly in increments as small as 15 minutes as shown by Georgia Tech researchers).

The method assumes the same vehicle fleet (same age distribution and vehicle type mix) before and after the project. Therefore, the same set of emission rates are used when looking up emission rates by speed. In reality, research has shown that managed lanes that use pricing strategies can impact the age of the vehicle fleet (and the associated emission rates) since high income drivers that can afford newer cars are attracted to toll lanes. Also, the calculator assumes the same vehicle type mix after the project is implemented, but some managed lanes projects may include components that provide additional bus transit service or encourage more or less of certain vehicle types.

User-Defined Inputs

The methodology requires the set of project-specific, user-defined inputs presented in Table 4.1. The calculator is set up to accept the inputs for eight columns, which correspond to the combination of morning peak and evening peak; general purpose lanes and HOV/HOT lanes; northbound and southbound or eastbound and westbound. The calculator assumes that the number of general purpose lanes will stay the same after the project is completed so it only asks for the number of general purpose lanes before the project, but not after the project.

Table 4.1 Managed Lanes Project User-Defined Inputs

User-Defined Input	Default Values	Input Guidance
Corridor Length (miles)		• Enter the length of the corridor in miles where the managed lanes will be implemented
Area Type		• Select the area type for the project from the drop down list • The facility type and area type is used to look up the capacity per lane
Number of Lanes – Before Project		• Enter the number of lanes in one direction along the corridor for both general purpose and HOV/HOT lanes • The number of HOV/HOT lanes before the project can be zero in the case of new managed lanes or more than zero in the case of an HOV lane conversion
Number of Lanes – After Project		• Enter the number of lanes in one direction along the corridor for HOV/HOT lanes after the project is implemented (calculator assumes the same number of general purpose lanes for before and after project) • A reversible lane system could be modeled by setting the morning inbound lanes to a certain number and the afternoon outbound lanes to the same number. The morning outbound lanes and afternoon inbound lanes should be set to zero.
Volumes (vehicles/lane/hour) – Before Project		• Enter the average hourly volume (vehicles/lane/hour) during the peak period for each lane type, direction, and morning/evening period.
Percentage of Passenger Vehicles – Before Project		• Enter the percent of passenger vehicles found in the average hourly volume • The calculator assumes the same percentages for before and after the project
Percentage of Buses – Before Project		• Enter the percent of buses found in the average hourly volume • The calculator assumes the same percentages for before and after the project • This could be derived by using a bus schedule to get the number of buses per hour and dividing by the hourly volume.

User-Defined Input	Default Values	Input Guidance
Percentage of Trucks – Before Project		• Enter the percent of trucks found in the average hourly volume • The calculator assumes the same percentages for before and after the project

Methodology

The methodology for calculating emission reductions from managed lanes is based upon changes to the average speed due to different congestion levels (v/c ratios) in certain lanes before and after the project. The method also considers the emissions increases associated with extra volumes in the corridor due to latent demand filling in extra capacity from the implementation of the project.

The Bureau of Public Roads (BPR) equation is used to estimate the average speed both before and after the project:

$$"S = S_f \, [1 + \alpha(V/C]^{\beta}$$

Where:

S = Predicted mean speed;

S_f = Free-flow speed (defined as 1.15 times the speed at “practical capacity”);

V = Volume; and

C = Practical capacity (defined as 80 percent of capacity).

The standard BPR coefficient values for α and β are 0.15 and 4.00, respectively; however, the calculator uses default values for α and β of 0.83 and 5.50, respectively, which are obtained from an NCHRP report[17].

The capacity for each group of lanes (general purpose and HOV/HOT) is calculated by multiplying the number of lanes entered by the user by the default capacity/lane values in the constants section (1,800 veh/lane/hour for general purpose and 1,600 veh/lane/hour for buffer separated HOV/HOT lane). The default free-flow speed in the constants section is set at 55 mph.

[17] NCHRP Report 716 Table 4.25 for Freeways with free flow speed of 60 mph. Table available in the “Other Variables” tab of the calculator.

Estimating the volume for each lane type before and after the project is a complex calculation that uses the following steps:

- Check to see if the current general purpose lane volume is leading to a high v/c ratio (associated with slower speeds) that would be associated with vehicle wanting to jump into the new managed lane (even if they have to pay a toll). In the constants Section 0.9 is used as the default v/c ratio associated with vehicles jumping to the HOT lane, since it is associated with a speed of 38 mph using the BPR equation. The demand for the HOT lane from the general purpose lane is assumed to be the difference between the total volume of vehicles and the volume of vehicles associated with a 0.9 v/c ratio. If the current volume of vehicles leads to a v/c ratio less than 0.9, the GP lane demand for the HOT lane is assumed to be zero.

- If the new HOT lane can handle all of the GP lane demand without exceeding the 0.9 v/c ratio associated with a minimum operating speed, then all of that volume is added to the before volume (the existing HOV lane volume in the case of a conversion); otherwise the HOT lane volume is set to 0.9 times the capacity.

- The additional HOT lane volume is calculated by subtracting the existing HOV lane volume from the new HOT lane volume set in the previous step. In the case of a completely new HOT lane where there was no HOV lane conversion, the additional volume equals the newly set volume.

- The GP lane reduction is calculated as the latent demand factor times the additional HOT lane volume. The default latent demand factor in the constants section is set at 77.2 percent based on an evaluation of an HOT lane project in Minnesota.[18] This calculation assumes that 22.8 percent of the volume that jumped from the GP lane to the HOT lane is actually backfilled by latent demand. Therefore, the GP lane volume reduction is not the full amount of the additional HOT lane volume.

- The GP lane reduction is divided by the number of GP lanes. This number is subtracted by the GP volume/lane for before the project to provide the GP lane volume after the project.

After all of the volume calculations the v/c ratio for each lane type, direction, morning/evening period combination is calculated for both before and after the project. These v/c ratios are used in the BPR equation above to calculate before and after speed. The before and after speeds are used to lookup emission rates. The percent of vehicle types are used to calculate a composite emission rate. The annual VMT is calculated by multiplying the volume by the length of the corridor, the number of hours in the peak period (4 hours default), and the number of weekdays per year (250 default). The annual emissions for before and after the project are calculated by multiplying the annual VMT by the composite emission rate. The

[18] Cambridge Systematics. I-394 MnPass Technical Evaluation. Prepared for Minnesota Department of Transportation. November 2006. Available: http://www.mnpass.org/pdfs/394mnpass_tech_eval.pdf. Accessed June 11, 2008.

emission reductions are calculated by subtracting the after project emission from the before project emissions.

5.0 Travel Demand Management

5.1 Bike/Pedestrian and Transit

Project Types

This approach evaluates bike and pedestrian infrastructure improvements that are parallel to an arterial roadway with known average daily traffic (ADT) volumes. The benefits of increased transit ridership are included for bike and pedestrian projects that provide increased accessibility to transit. Projects can be evaluated individually for bike or pedestrian facilities, or combined.

Pedestrian and bicycle facilities can reduce emissions when auto trips are replaced by walking, biking, and transit trips. The methodology estimates the annual number of vehicle trips reduced, and the annual auto VMT reduced to approximate the emissions reduction.

Methodology Limitations

The approach does not completely account for all elements of pedestrian bridges or multiuse facilities/greenways in exclusive ROW; however, the regional bike/pedestrian project strategy, which is based on total travel demand between an origin and destination, can be used instead.

The approach does not test potential mode shifts to nonmotorized and transit modes as a result of complete street elements (e.g., benches, lighting, improved buffers); traffic-calming strategies; transit station design elements, such as a bike station; employer-based strategies (e.g., bike lockers, showers); or improved transit amenities.

User-Defined Inputs

The methodology requires the set of project-specific, user-defined inputs presented in Table 5.1.

Table 5.1 Bike/Pedestrian and Transit Project User-Defined Inputs

User-Defined Input	Default Values	Input Guidance
ADT on the parallel arterial		• Enter average weekday passenger vehicle traffic on nearest parallel roadway. • Enter the sum of volumes in both directions for the entire day
Capacity of parallel arterial (vph)		• Enter the capacity of all lanes in both directions of the parallel arterial in vehicles/hour • Single lane values can be looked up at the top of the other variables tab (based on area type and facility type) and multiplied by the number of lanes in both directions
Length of project (miles)		• Enter total length of the bike/pedestrian project.
Posted Speed on parallel arterial (mph)		• Enter the speed limit in miles per hour on the parallel arterial • This speed is used to calculate free-flow travel time.
Number of activity centers within ½ mile of project		• Select appropriate number of activity centers. • Activity center examples include banks, churches, hospitals, park-and-ride, office parks, library, shopping, and schools.
Within 2 miles of a university or college (Y/N)?		• Select "Y" if any segment of project is within 2 miles of a university or college.
Area type		• Select from CBD, Urban, Suburban, Mountain, and Rural area types.
Does this project have a bicycle component?		• Enter "Y" if the project provides bicycle infrastructure; otherwise enter "N."
Average length of bicycle trips (miles)	1.8	• Enter estimated average length of bicycle trips in the area; leave blank if a pedestrian project only. • Default value (1.8 mi) is based on 2001 NHTS statistics, excluding purely recreational trips.
Does this project have a pedestrian component?		• Enter "Y" if the project provides pedestrian infrastructure; otherwise enter "N."
Average length of pedestrian trips (miles)	0.5	• Enter estimated average length of pedestrian trips in the area; leave blank if bike project only. • Default value (0.5 mi) is based on 2001 NHTS statistics, excluding purely recreational trips
Does project provide direct access to transit?		• Answer "Y" if any segment of project provides direct access to transit (station or bus stop).

User-Defined Input	Default Values	Input Guidance
Average length of transit trips (miles)	5.2	• Enter estimated average length of transit trips in the area. • Default value based on the American Public Transportation Association (APTA) 2009 Factbook,[19] Table 7 (Bus = 3.9 mi; Commuter Rail = 24.3 mi; Heavy Rail = 4.7 mi; Average = 5.2 mi).
Existing daily transit boardings		• Enter estimated total weekday boardings for all transit access points along project corridor.
Provides access to fixed guideway transit?		• Select "Y" if the segment provides direct access to fixed guideway transit.

Methodology

The bike project approach is consistent with *Methods to Find the Cost-Effectiveness of Funding Air Quality Projects*, a handbook prepared by the CARB in 2005. The CARB handbook describes how to evaluate Motor Vehicle Registration Fee Projects and Congestion Mitigation and Air Quality Improvement (CMAQ) projects, and is the basis for determining the amount of emissions reductions from bicycle facility projects.

The 2009 report *Methodologies for Evaluating Congestion Mitigation and Air Quality Improvement Projects*, developed for the Maricopa Association of Governments (MAG), is the basis for determining emissions reductions resulting from auto trips replaced by pedestrian trips. The MAG document adapted the methodology for calculating the impact of pedestrian improvements from the 2005 CARB handbook.

The approaches for bike and pedestrian projects are consistent. Within the general CARB approach, two primary factors drive the calculation of reduced auto trips: 1) the number of activity centers adjacent to the project, and 2) the project location with respect to a nearby university or college.[20]

[19] APTA (2009), *Public Transportation Factbook, 60th Edition,* American Public Transportation Association, accessed at http://www.apta.com/gap/policyresearch/Documents/APTA_2009_Fact_Book.pdf.

[20] Per CARB documentation, adjustment factors were derived from a limited set of bicycle commute mode split data for cities and university towns in the southern and western United States (Source: U.S. DOT (1992), *National Bicycling And Walking Study – Transportation Choices for a Changing America*). This data was then averaged and multiplied by 0.7 to estimate potential auto travel diverted to bikes. On average, about 70 percent of all person trips are taken by auto driving (Source: Caltrans (2002), *2000-2001 California Statewide Travel Survey*), and it is these trips that can be considered as possible auto trips reduced. Finally, this number was multiplied by 0.65 to estimate the growth in bicycle trips from construction of the bike facility. Sixty-five percent represent the average growth in bike trips from a new bike facility, as observed in before and after data for bike projects (Source: U.S. DOT (1994), *A*

(Footnote continued on next page...)

The number of activity centers within one-quarter mile of a pedestrian project and one-half mile of a bike project feed into a lookup table of factors generating percent auto trip reductions. The university/college location factor increases average trip lengths on the assumption that willingness to bike or walk, and the average distances for these trips are greater for college students.

Calculations for auto trips reduced as a result of increased bike and pedestrian trips generated by the project are listed below.

$$\text{Daily auto trips reduced}_{\text{(bike)}} = \text{AWT} * 0.91 * (\text{A}_{\text{½ mile}} + \text{C})$$

$$\text{Daily auto trips reduced}_{\text{(walk)}} = \text{AWT} * 0.91 * (\text{A}_{\text{¼ mile}} + \text{C})$$

Where:

AWT = Average weekday traffic on the adjacent or nearest parallel arterial; and

0.91 = Factor to convert average weekday traffic to AADT.

The additional transit access element within this project approach is addressed through a lookup table quantifying the increase in transit trips, based on type of access and area type (two percent for improved access to bus; four percent for improved access to fixed guideway).

The source for increases in transit trips is the Transit Cooperative Research Program (TCRP) Report 95, *Traveler Response to Transportation System Changes, Chapter 17 – Transit-Oriented Development (TOD)*, which summarizes travel mode shifts of residents upon relocation into TODs. The TCRP report specifically references California results based upon a 2003 study by Lund, Cervero, and Willson.[21] The shift to transit was larger for residents along the Bay Area Rapid Transit District (BART) heavy-rail system (4.2 percent) than for TOD survey respondents statewide (1.8 percent). These results indicated a reasonable estimate for percent increases as a result of improved accessibility: two percent for bus trips and four percent for fixed guideway trips. Results from the *TCRP Report 95* sources are assumed to approximate responses in high-density areas. Increase percentages in suburban, mountain, and rural areas are based on VMT per capita relationships by population density from the 2001 NHTS (see Tables 5.2 and 5.3).

Compendium of Available Bicycle and Pedestrian Trip Generation Data in the United States). Benefits are scaled to reflect differences in project structure, length, traffic intensity, community size, and proximity of activity centers. The scale has been adapted from a method developed by Dave Burch of the Bay Area Air Quality Management District (BAAQMD).

[21] H. Lund, R. Cervero, and R. Willson (2003), *Travel Characteristics of Transit-Oriented Development in California*, accessed at: http://www.csupomona.edu/~rwwillson/tod/Pictures/TOD2.pdf.

Table 5.2 Increase in Transit Trips by Area Type and Transit Mode

Area Type	Bus	Fixed Guideway
CBD/Core	2.0%	4.0%
Urban	2.0%	4.0%
Suburban	1.6%	3.2%
Difficult Terrain/Rural	1.4%	2.8%

Source: NHTS, 2001.

Table 5.3 VMT per Capita by Area Type

Area Type	Population Density People per Square Mile (ppsm)	Annual VMT Per Capita
Difficult Terrain/Rural	0 – 499	11,818
Suburban	500 -1,999	10,435
Urban	2,000 – 3,999	9,678
Urban	4,000 – 9,999	8,285
CBD/Core	10,000+	4,639

Source: NHTS, 2001.

The calculation for auto trips reduced by new transit trips is detailed below.

$$\text{Daily auto trips reduced}_{\text{(transit)}} = B_{\text{(project corridor)}} * I_{\text{(area type \& mode)}}$$

Where:

B **=** Daily transit boarding for all transit access points along bike/pedestrian project corridor; and

I **=** Percent increase in transit trips as presented in Table 5.2.

Auto trips reduced by bike, walk, and transit modes are translated into VMT based on average bike, walk, and transit trip lengths. The methodology uses default average trip lengths based on the NHTS and APTA *2009 Factbook* data, but can be replaced with user-defined, local-specific data. The VMT reductions annualized (assumes a factor of 250 days, since commute benefits are assumed only to accrue during workdays) and summed together. The small increase in congested speed due to slightly lower volumes is calculated using the BPR equation as explained in the Managed Lanes section. Emission rates before and after the project are looked up based on the calculated speeds and multiplied by VMT before and after the project to calculate emissions. The emission reduction is calculated by subtracting the "after project" emissions from the "before project" emissions.

5.2 Regional Bike/Pedestrian Projects

Project Types

This approach evaluates regionally significant bike and/or pedestrian infrastructure projects that are on a separated facility, not necessarily directly adjacent to a roadway. Potential emissions reductions result from the decrease in emissions associated with auto trips being replaced by bicycle and/or pedestrian trips. Projects can be evaluated singularly by mode or combined. The user specifies the average length of the bike and pedestrian trips on the corridor, and the number of activity centers along the corridor for each mode. If the project will only positively impact one mode (for example, a bicycle trail), then the user specifies inputs for that specific mode only. If the project implements both pedestrian and bike improvements (e.g., a multiuse path or trail), the user may input values for each mode.

Methodology Limitations

The approach does not test potential mode shifts to nonmotorized modes as a result of complete street elements (e.g., benches, lighting, improved buffers); traffic calming strategies; or employer-based support strategies (e.g., bike lockers, showers).

User-Defined Inputs

The methodology requires the set of project-specific, user-defined inputs presented in Table 5.4.

Table 5.4 Bike/Pedestrian Project User-Defined Inputs

User-Defined Input	Default Values	Input Guidance
ADT between origin and destination of route		• Use results from travel demand model origin/destination data • Alternatively, enter average weekday passenger vehicle traffic on parallel roadway with generally the same origin and destination
Capacity of parallel arterial (vph)		• Enter the capacity of all lanes in both directions of the parallel arterial in vehicles/hour • Single lane values can be looked up at the top of the other variables tab (based on area type and facility type) and multiplied by the number of lanes in both directions
Posted Speed on parallel arterial (mph)		• Enter the speed limit in miles per hour on the parallel arterial • This speed is used to calculate free-flow travel time.

User-Defined Input	Default Values	Input Guidance
Number of activity centers within ½ mile of project		• Select appropriate number of activity centers. • Activity center examples include banks, churches, hospitals, park-and-ride, office parks, library, shopping, and schools; credit is only given for 3 or more centers
Within 2 miles of a university or college (Y/N)?		• Select "Y" if any segment of project is within 2 miles of a university or college.
Area type		• Select from CBD, Urban, Suburban, Mountain, and Rural area types.
Predicted Total Daily Bicycle Demand (optional input to use in place of first six inputs)		• Enter the estimated number of daily bicycle trips along the facility, if known
Predicted Total Daily Pedestrian Demand (optional input to use in place of first six inputs)		• Enter the estimated number of daily pedestrian trips along the facility, if known
Does this project have a bicycle component?		• Enter "Y" if the project provides bicycle infrastructure; otherwise enter "N."
Does this project have a bicycle component?		• Enter "Y" if the project provides bicycle infrastructure; otherwise enter "N."
Average length of bicycle trips (miles)	1.8	• Enter estimated average length of bicycle trips in the area; leave blank if a pedestrian project only. • Default value (1.8 mi) is based on 2001 NHTS statistics, excluding purely recreational trips.
Does this project have a pedestrian component?		• Enter "Y" if the project provides pedestrian infrastructure; otherwise enter "N."
Average length of pedestrian trips (miles)	0.5	• Enter estimated average length of pedestrian trips in the area; leave blank if bike project only. • Default value (0.5 mi) is based on 2001 NHTS statistics, excluding purely recreational trips
Length of bike/ped project (miles)		• Enter total length of the bike/pedestrian project

Methodology

The bike project approach is consistent with *Methods to Find the Cost-Effectiveness of Funding Air Quality Projects*, a handbook prepared by the CARB in 2005. The CARB handbook describes how to evaluate Motor Vehicle Registration Fee Projects and Congestion Mitigation and Air Quality Improvement (CMAQ) projects, and is the basis for determining the amount of emissions reductions from bicycle facility projects.

The 2009 report *Methodologies for Evaluating Congestion Mitigation and Air Quality Improvement Projects*, developed for the Maricopa Association of Governments (MAG), is the basis for determining emissions reductions resulting from auto trips replaced by pedestrian trips. The MAG document adapted the methodology for calculating the impact of pedestrian improvements from the 2005 CARB handbook.

The approaches for bike and pedestrian projects are consistent. Within the general CARB approach, two primary factors drive the calculation of reduced auto trips: 1) the number of activity centers adjacent to the project, and 2) the project location with respect to a nearby university or college.[22]

The number of activity centers within one-quarter mile of a pedestrian project and one-half mile of a bike project feed into a lookup table of factors generating percent auto trip reductions. The university/college location factor increases average trip lengths on the assumption that willingness to bike or walk, and the average distances for these trips are greater for college students.

Calculations for auto trips reduced as a result of increased bike and pedestrian trips generated by the project are listed below.

$$\text{Daily auto trips reduced}_{(bike)} = AWT * 0.91 * (A_{½\ mile} + C)$$

$$\text{Daily auto trips reduced}_{(walk)} = AWT * 0.91 * (A_{¼\ mile} + C)$$

Where:

AWT = Average weekday traffic on the adjacent or nearest parallel arterial; and

0.91 = Factor to convert average weekday traffic to AADT.

If the average daily vehicular traffic between the origin and destination is not known or does not accurately represent the vehicular path that would be taken if the project was not developed, then a predicted total daily bicycle and pedestrian demand for the facility must be known. This prediction may include commuting and noncommuting trips. From the *2012*

[22] Per CARB documentation, adjustment factors were derived from a limited set of bicycle commute mode split data for cities and university towns in the southern and western United States (Source: U.S. DOT (1992), *National Bicycling And Walking Study – Transportation Choices for a Changing America*). This data was then averaged and multiplied by 0.7 to estimate potential auto travel diverted to bikes. On average, about 70 percent of all person trips are taken by auto driving (Source: Caltrans (2002), *2000-2001 California Statewide Travel Survey*), and it is these trips that can be considered as possible auto trips reduced. Finally, this number was multiplied by 0.65 to estimate the growth in bicycle trips from construction of the bike facility. Sixty-five percent represent the average growth in bike trips from a new bike facility, as observed in before and after data for bike projects (Source: U.S. DOT (1994), *A Compendium of Available Bicycle and Pedestrian Trip Generation Data in the United States*). Benefits are scaled to reflect differences in project structure, length, traffic intensity, community size, and proximity of activity centers. The scale has been adapted from a method developed by Dave Burch of the Bay Area Air Quality Management District (BAAQMD).

National Survey of Bicyclist and Pedestrian Attitudes and Behaviors, approximately 11 percent of bicycle trips and 8 percent of pedestrian trips are for commuting purposes. The inputted daily demand is then multiplied by these percentages to predict the number of automobile trips reduced due to the regionally significant bicycle and pedestrian facility This value may be adjusted under the 'Constants' section or put to 100 percent if the predicted total daily demand includes only commuters.

Auto trips reduced by biking and walking modes are translated into VMT based on average bike and walk trip lengths. Default average trip lengths based on the NHTS shown in Table 5.4 can be used or replaced with user-defined, local-specific data. The VMT reductions annualized (assumes a factor of 250 days, since commute benefits are assumed only to accrue during workdays) and summed together. The small increase in congested speed due to slightly lower volumes is calculated using the BPR equation as explained in the Managed Lanes section. Emission rates before and after the project are looked up based on the calculated speeds and multiplied by VMT before and after the project to calculate emissions. The emission reduction is calculated by subtracting the "after project" emissions from the "before project" emissions.

5.3 Employer Based Commute Strategies

Project Types

This estimation methodology covers employer-based commuter trip reduction programs that entail providing financial incentives that can be used to encourage use of more efficient commute modes. These include parking cash out, travel allowance, transit benefits, and rideshare benefits. They are often provided as an alternative to subsidized employee parking.

Methodology Limitations

Commute trip reductions are based on nationally observed data and need to be customized to Atlanta with local data.

User-Defined Inputs

This method is one of the more input data intensive methods owing to the variability in trip reductions by area type, subsidies and other supporting data requirements like participation rates and mode shares. The methodology requires the set of project-specific, user-defined inputs presented in Table 5.5.

Table 5.5 Employer-Based Commute Strategies Project User-Defined Inputs

User-Defined Input	Default Values	Input Guidance
Total Employment (Site or Areawide)		• The total number of employees that would be eligible to participate in the financial incentive-based program
Share Office/Nonoffice		• The percent of the total employees that are office workers and nonoffice workers. • The two percentages should sum to 100%
Split of Total Employment by Area Type (low density suburb, activity center, regional CBD)		• The percent of total employees that are located in a low density suburb, activity center, and regional CBD) • The three percentages should sum to 100%. • If the strategy is for a single site enter 100% for the area type corresponding to the site and enter 0% for the other two area types.
Mode Shares (single-occupant vehicle, transit, rideshare)		• For each area type (each of three columns) enter the percent of employees that currently arrive by single-occupant vehicle, transit, and rideshare • For each area type (each of three columns) the three percentages should sum to 100%
Base Employer Participation Rate (Office/Nonoffice)		• For each area type (each of three columns) and each worker type (office and nonoffice shown in two different rows) enter the percentage of office employees in that area type that have signed up to participate in the current program (making them eligible for the financial incentive if they take an alternative mode on a particular day)
Current Daily Transit/Rideshare Subsidy (in USD)		• Enter the current subsidy given to an employee for each day that they take an alternative mode
Scenario Employer Participation Rate (Office/Nonoffice)		• For each area type (each of three columns) and each worker type (office and nonoffice shown in two different rows) enter the percentage of office employees in that area type that are expected to sign up to participate in the new program (making them eligible for the financial incentive if they take an alternative mode on a particular day)
New Daily Transit/Rideshare Subsidy (in USD)		• Enter the new subsidy that will be given to an employee for each day that they take an alternative mode

Methodology

This methodology can estimate commute trip reductions across an areawide or a site, given the total office and nonoffice employment by area type. It uses data on reduction in commute trips that can be expected from various combinations of parking charges and financial benefits for alternative modes from the Victoria Transport Policy Institute.[23] The financial subsidies provided as input to the strategy are used to look up single-occupant vehicle (SOV) trip reduction percentages by area type. Different trip reduction rates for the base and new scenario are calculated based on the different financial subsidies. The Daily SOV VMT is estimated for each area type by multiplying the number of employees by area type by the SOV mode share for the area type and the average roundtrip commute length. The percent SOV trip reductions for the base and new scenario are multiplied by the weighted average participation rate (office and nonoffice) since the trip reductions are only possible for employees that have signed up for the program. These trip reductions are then multiplied by the SOV VMT to estimate the SOV VMT reduction for the base and new scenario. The total incremental VMT reduction is calculated as the VMT reduction for all area types under the new scenario minus the VMT reduction for all area types under the base. General light duty emission rates are multiplied by the total incremental VMT reduction to estimate the emissions reduction.

[23] http://www.vtpi.org/tdm/tdm41.htm

6.0 Clean Fuel and Technology

6.1 Retrofits

Project Types

This strategy estimates Particulate Matter (PM) and Volatile Organic Compounds (VOC) emission reductions due to installation of one of two diesel retrofit devices in trucks or buses: Diesel Oxidation Catalysts (DOC) or Diesel Particulate Filters (DPFs).

Diesel oxidation catalysts (DOCs) are exhaust after-treatment devices that reduce emission from diesel engines. Typically packaged with the engine muffler, DOCs are widely used as a retrofit technology because they require little or no maintenance. DOCs consist of a flow-through honeycomb structure that is coated with a precious metal catalyst and surrounded by a stainless steel housing. As hot diesel exhaust flows through the honeycomb (or substrate), the precious metal coating causes a catalytic reaction that breaks down the pollutants.

Diesel particulate filters are exhaust after-treatment devices that significantly reduce emissions from diesel-fueled vehicles and equipment. DPFs typically use metallic filters to physically trap particulate matter (PM) and remove it from the exhaust stream. After it is trapped by the DPF, collected PM is reduced to ash during filter regeneration, which occurs when the filter element reaches the temperature required for combustion of the PM. DPFs work best on engines built after 1995. They are typically effective at reducing emissions of PM by 85 to 90 percent or more[24]. DPFs generally cost between $5,000 to $15,000 or more, including installation, depending on engine size, filter technology and installation requirements.

Methodology Limitations

Percent reductions in emission rates provided by EPA as a range of reductions since results can vary depending on the manufacturer, technology and application of the retrofit device. The midpoint of these ranges is used in the calculator; therefore actual results could be higher or lower than predicted. The range varies from 10 percent to 30 percent depending on pollutant and retrofit technology.

User-Defined Inputs

The methodology requires the set of project-specific, user-defined inputs presented in Table 6.1. The estimation method assumes that this strategy is implemented on a select number of vehicles in a fleet, either operated by a single entity or limited by number. Since DPFs work best for engines built after the year 1995, only these newer trucks and buses should be entered when selecting the DPF technology.

[24] National Clean Diesel Campaign, Technical Bulletin, Disel Particulate Filter, General Information, Accessed@ http://www.epa.gov/cleandiesel/documents/420f10029.pdf.

Table 6.1 Clean Fuel and Technology Project User-Defined Inputs

User-Defined Input	Default Values	Input Guidance
Retrofit Technology		• Select Diesel Oxidation Catalyst (DOC) or Diesel Particulate Filter (DPF) from the drop down list.
Number of trucks proposed to be retrofitted (built after 1995 if using DPF)		• If using DOC retrofit technology enter the number of trucks from any model year that the DOC retrofit will be installed on. • If using the DPF retrofit technology enter the number of trucks built after 1995 that the DPF retrofit will be installed on (DPFs have minimal impact on engines built in 1995 or earlier; therefore another retrofit technology should be considered for these older vehicles)
Number of diesel buses proposed to be retrofitted (built after 1995 if using DPF)		• If using DOC retrofit technology enter the number of buses from any model year that the DOC retrofit will be installed on. • If using the DPF retrofit technology enter the number of buses built after 1995 that the DPF retrofit will be installed on (DPFs have minimal impact on engines built in 1995 or earlier; therefore another retrofit technology should be considered for these older vehicles)
Average annual miles traveled by each truck	26,609	• Enter the average annual miles driven for each truck in the fleet that will be retrofitted. • Default value obtained from FHWA Highway Statistics VMT tables.
Average annual miles traveled by each bus	37,009	• Enter the average annual miles driven for each bus in the fleet that will be retrofitted. • Default value obtained from FHWA Highway Statistics VMT tables.

Methodology

The method first multiplies annual VMT/truck by the number of trucks in the fleet and annual VMT/bus by the number of buses in the fleet to calculate annual VMT for the truck fleet and bus fleet respectively. The total emissions for PM and VOC without retrofit are calculated by multiplying the MOVES emission rates by the VMT for both trucks and buses and them summing the result together. The total emissions for PM and VOC with retrofit are calculated by multiplying the emission without retrofit by an appropriate percent reduction factor depending on retrofit technology. The reduction factors are obtained from the EPA's National

Clean Diesel Campaign.[25] The emissions reduced are the without retrofit emissions minus the with retrofit emissions.

6.2 Alternative Fuel Vehicles

Project Types

This strategy estimates emission reductions due to purchasing new alternative fuel/advanced technology vehicles to replace a fleet of traditional gasoline or diesel vehicles.

Methodology Limitations

Emission rates included in the calculator for alternative fuel/advanced technology vehicles are compiled from a variety of different sources to cover 24 vehicle/fuel types. Therefore, there may be a lack of consistency on the method for computing the emission rates since there was not a single source that covered all 24 vehicle/fuel types. Also, most of the sources refer to an average on-road fleet during a particular calendar year, but some sources refer to a specific model year[26] (assuming that the newest model year vehicle would be purchased in a particular calendar year).

User-Defined Inputs

The methodology requires the set of project-specific, user-defined inputs presented in Table 6.2

[25] http://www.epa.gov/cleandiesel/technologies/retrofits.htm.

[26] The July 2014 version of the calculator uses model year specific emission rates for CNG bus, LNG bus, hybrid electric bus, and CNG refuse truck. It uses average onroad fleet emission rates for all other vehicle/fuel types.

Table 6.2 Alternative Fuel Vehicles Project User-Defined Inputs

User-Defined Input	Default Values	Input Guidance
Existing Fuel Type Vehicle		• Select the existing vehicle type/fuel type from the list of 24 vehicles/fuels
Alternative Fuel Type/Technology Vehicle		• Select the proposed vehicle type/fuel type from the list of 24 vehicles/fuels
Number of Vehicles		• Enter the number of vehicles in the fleet that will be replaced
Annual Miles Traveled per Vehicle	37,009 for buses	• Enter the fleet average annual miles traveled per vehicle • Default value for buses obtained from FTA report • MOVES defaults by vehicle type could be used as a default for other vehicles if no project specific information is available

Methodology

2010 and 2020 emission rates for the 24 vehicle/fuel types are found in the "Transit-AltFuelER" tab in the calculator. Sources for these rates are also documented on this tab. Some of the sources used include MOVES, a TCRP report[27], and the U.S. Department of Energy Alternative Fuels Data Center.[28]

The calculator looks up 2010 and 2020 emission rates for the existing vehicles and proposed vehicles and then interpolates between 2010 and 2020 using the calendar year selected. The average annual miles traveled per vehicle is multiplied by the number of vehicles to calculate the annual fleet VMT. This VMT is multiplied by the emission rates to calculate emissions for the existing fleet and proposed fleet. The emission reductions are equal to the emission from the existing fleet minus the emissions from the proposed fleet.

[27] TCRP H-41 Appendix B and C (http://onlinepubs.trb.org/onlinepubs/tcrp/tcrp_w55.pdf).

[28] http://www.afdc.energy.gov/vehicles/natural_gas_emissions.html.

7.0 Other Tabs in Calculator

7.1 Preparation of Running Emission Rates from MOVES

Running emission rates can be found in the blue table on the left hand side of the "2010ER" and "2020ER" tab. These rates are based on MOVES runs that use all of the current planning assumptions and MOVES inputs for the 13 county portion of the Atlanta nonattainment area. Four separate MOVES runs are used: 2010 annual, 2010 summer, 2020 annual, and 2020 summer. The annual runs are for CO2eq, $PM_{2.5}$, and PM-related NO_x, while the summer runs are for NO_x and VOC associated with ozone. The rates in the calculator are aggregated versions of the "rateperdistance" output from a MOVES rate mode run. MOVES is used in rate mode since emission rates are desired by speed, and inventory mode does not provide outputs by speed bins. The emission rates from MOVES must be aggregated to eliminate the hour level of detail, combine multiple source types into general vehicle types used in the calculator, and in some cases combine road types. The following steps explain the aggregation process used:

- New columns are added to the movesacitivity output table for:
  - Aggregate vehicle type (light duty, buses, trucks; assigned using lookup function referencing table of source type and aggregate vehicle types);
  - Average speed bin (last two digits of link ID);
  - Lookup code A (concatenation of hour, source type, road type, and speed bin);
  - Lookup code 1 (concatenation of aggregate vehicle type, road type, and speed bin);
  - VMT associated with lookup code 1 (sums all rows with the same aggregate vehicle type and sums all 24 hours);
  - Lookup code 2 (concatenation of aggregate vehicle type and speed bin); and
  - VMT associated with lookup code 2 (sums all rows with the same aggregate vehicle type, sums all 24 hours, and sums all road types).
- New columns are added to the rate per distance output table for:
  - Aggregate vehicle type (light duty, buses, trucks; assigned using lookup function referencing table of source type and aggregate vehicle types);
  - Pollutant Name (assigned using lookup function referencing table of pollutant IDs and pollutant names);
  - Lookup code A (concatenation of hour, source type, road type, and speed bin; same as used in the movesactivity output table);

- VMT associated with lookup code A (lookup code used to lookup VMT on movesactivity output table);
- Lookup code 1 (concatenation of aggregate vehicle type, road type, and speed bin; same as found on movesactivtyoutput table);
- VMT associated with lookup code 1 (looks up aggregated VMT from movesactivityoutput table);
- VMT Fraction 1 (VMT associated with lookup code A/VMT associated with lookup code 1);
- Rate Per Distance Weighted Average 1 (rateperdistance multiplied by VMT Fraction 1);
- Lookup code 2 (concatenation of aggregate vehicle type and speed bin; same as found on movesactivtyoutput table);
- VMT associated with lookup code 2 (looks up aggregated VMT from movesactivityoutput table);
- VMT Fraction 2 (VMT associated with lookup code A/VMT associated with lookup code 2); and
- Rate Per Distance Weighted Average 2 (rateperdistance multiplied by VMT Fraction 2).

- A pivot table is created on the new rate per distance table with the following set up to provide rates by road type:
  - Row labels contain pollutant name and avgSpeedBin ID.
  - Column labels contain aggregate vehicle type and road type.
  - Values contain sum of Rate Per Distance Weighted Average 1.
  - For a check the sum of VMT Fraction 1 can also be added to values. The result should be an even number, but will vary depending on the number of processes associated with a pollutant (1 for CO2eq, 2 for NO_x, 8 for $PM_{2.5}$, etc.).
- A pivot table is created on the new rate per distance table with the following set up to provide rates over all road types:
  - Row labels contain pollutant name and avgSpeedBin ID.
  - Column labels contain aggregate vehicle type.
  - Values contain sum of Rate Per Distance Weighted Average 2.

- For a check the sum of VMT Fraction 2 can also be added to values. The result should be an even number, but will vary depending on the number of processes associated with a pollutant (1 for CO2eq, 2 for NO_x, 8 for $PM_{2.5}$, etc.)

- The weighted average emission rates from the two pivot tables are copied and pasted into the 2010 ER and 2020 ER tabs of the emissions calculator.

- The process is repeated for each of the four MOVES runs: 2010 annual, 2010 summer, 2020 annual, and 2020 summer.

7.2 Preparation of Idle Emission Rates from MOVES

The CMAQ Calculator calculates idle emission rates using MOVES in project level mode with links set to zero miles per hour average speed. EPA has recommended this method to get more accurate idle emission rates from MOVES. The following steps were used:

- Since MOVES project level can only handle one hour per run, 24 runs are required for each year/season. Therefore, 96 runs are conducted (24 runs x 4 year/seasons (2010 annual, 2010 summer, 2020 annual, 2020 summer)).

- Set up a project level MOVES run with the appropriate year, geographic bounds, pollutants, and other run specifications. Use inventory mode to produce grams per hour idle emission rates.

- For the link data input file include 13 links, one for each of the 13 MOVES source types. For each link assign an average speed of 0 and volume of 1. Use the appropriate road type for the location where the idle emission rates will be used, such as road type 5 (urban unrestricted access) for an urban intersection.

- Set the link source type hour fractions to 1 for the appropriate source type on each link and set the remaining fractions to zero. For example, link 1 is used for motorcycles (source type 11) so link 1 will have a distribution of 1 under source type 11 and zero under all other source types.

- Provide the rest of the inputs using standard regional scale planning assumptions (meteorology, age, fuel, etc.).

- Run MOVES and retrieve the grams/hour idle emission rates.

- Follow an aggregation process similar to that described in Section 7.1 to aggregate over hours and aggregate vehicle types.

7.3 Other Variables

This tab contains a number of constants and other variables often applied in the strategy lookup tables.

7.4 Sources and Comments

This tab compiles sources and comments for all strategies associated with default values and other constants.