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Methodology for Estimating Greenhouse Gas Emissions and Assessing Mitigation Options for Project Level Applications for On-Road Mobile Sources

Volume 1 – Documentation of Research Approach, Work Performed, and Results Achieved

Prepared for

Houston-Galveston Area Council

Prepared by

Texas Transportation Institute and Houston-Galveston Area Council

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ABOUT THIS REPORT

This report documents the research approach, work performed and results achieved for the project "Methodology for Estimating Greenhouse Gas Emissions and Assessing Mitigation Options for Project Level Applications for On-Road Mobile Sources." This is a joint project conducted by the Texas Transportation Institute (TTI), and the Houston-Galveston Area Council (H-GAC), in consultation with the Texas Department of Transportation (TxDOT) and Houston Advanced Research Center (HARC). The project was conducted through direct funding from H-GAC and leverage funding from TxDOT.

Graciela Lubertino of H-GAC was the Project Director and Principal Investigator. Josias Zietsman of TTI was the co-Principal Investigator. The TTI project team included Tara Ramani, Jinpeng Lv, Nicolas Norboge and Reza Farzaneh. William Knowles of TxDOT and David Hitchcock of HARC contributed through in-kind support.

The other project deliverables include Volume 2 of the report, which contains a white paper on greenhouse gas emissions and climate change, and a spreadsheet-based analysis tool which can be used to evaluate the effectiveness of greenhouse gas reduction strategies.

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1. Introduction

On-road mobile sources are a major contributor to greenhouse gas (GHG) emissions, contributing nearly 30 percent of U.S. GHG emissions (*1*). While other environmental concerns such as pollutant emissions and ecological health have been addressed for decades in the transportation sector, there is relatively less knowledge about GHGs, climate change, and the implications for transportation agencies.

State and localities, including state departments of transportation (DOTs) and metropolitan planning organizations (MPOs) are recognizing the importance of this issue – many are incorporating GHG emissions in planning documents, policies, and strategies. There are two aspects to addressing the transportation/GHG climate change problem from the perspective of transportation agencies: 1) mitigation; and 2) adaptation. Mitigation refers to the reduction in GHG emissions, with a view of pre-empting climate change impacts. The scientific community recommends an 80 percent reduction from 1990 GHG emissions levels by 2050 to avoid the worst impacts of climate change (*2*). Adaptation refers to long-term actions taken by transportation agencies to accommodate future climate change impacts such as increased flooding, precipitation, and storms.

This project focuses on the issue of GHG mitigation, specifically the reduction of GHG emissions from on-road mobile sources. In this context, carbon dioxide (CO_2) emissions are the primary focus, being the major GHG associated with mobile sources. Mitigation options for transportation are generally classified as vehicle measures, fuel options, activity reduction, or system operation improvements (*3*). The main objectives of this project are to provide transportation agencies and air quality agencies with an approach and methodology to address the issue of GHG emissions and mitigation for on-road mobile sources.

The main project objectives were to:

1. Understand the current critical issues regarding greenhouse gas emissions from a transportation agency perspective; and
2. To develop an approach and methodology for transportation agencies (specifically Houston-Galveston Area Council [H-GAC]) to assess the GHG emissions impact of various GHG “control strategies.”

The first project objective was achieved through a review of literature relating to on-road mobile GHG emissions sources, the types of mitigation options possible, and the available analytical tools and methodologies for estimating/inventorying GHG emissions focusing on project level applications. The literature review also covered broader policy and legislative issues related to GHG emissions. The findings from this background and literature study were summarized in the form of a “white paper” used to describe the issues involved for transportation and air quality agencies with regard to GHG emissions, with a focus on Texas. This white paper is included in a companion piece (Volume 2) to this report.

The second research objective was achieved through the following steps:

- Identifying GHG control strategies for on-road mobile sources that are potentially applicable for the Houston-Galveston-Brazoria (HGB) region. As mentioned previously, the focus of the analysis is specifically on CO_2 emissions, which are considered to be synonymous with mobile-source GHG emissions for purposes of this project;
- Selecting control strategies for final analysis in consultation with H-GAC, and considering other factors such as cost effectiveness, potential for emission reductions, and applicability to the HGB region; and
- Developing analytical methodologies for evaluating the impact of the selected control strategies and integrating them into a generic analytical tool which can be used to quantify the impacts of applying selected control strategies, based on user input data. The control strategies can be evaluated at the present year and a future year to estimate the emission reductions attributable to these control strategies.

This report summarizes the methodology and findings from the selection of control strategies and development of a generic analytical tool for use by H-GAC in quantifying the impact of various GHG reduction strategies. The remainder of this report is organized as follows: Chapter 2 discusses the criteria to select GHG control strategies in the context of this project. For each strategy selected, Chapter 3 develops computation methods and describes the implementation in the analysis tool. Chapter 4 then describes the development of the analytical tool in the form of a spreadsheet-based calculator, with examples applications. Chapter 5 summarizes conclusions and findings.

2. Selection of GHG Control Strategies

The selection of control strategies for final analysis was an iterative process conducted in consultation with H-GAC staff, and with the Texas Department of Transportation (TxDOT) and the Houston Advanced Research Center (HARC) project advisors. As a first step, the Texas Transportation Institute (TTI) research team identified a list of potential strategies based on a review of various literature sources, including a previous compilation of strategies assembled by the research team (*4*, *5*). The types of strategies originally tabled can be categorized into the following broad categories:

- Transportation and land use strategies;
- Vehicle and fuel standards and technologies;
- Transportation control measures, including vehicle miles of travel (VMT) reduction and fuel use reduction strategies;
- Fleet strategies for emissions reduction; and
- Incentive and voluntary programs.

The research team also considered the project types as listed in H-GAC's regional transportation plan (RTP), which would enable the evaluation of the GHG emissions impacts due to the implementation of specific projects. The types of projects included the following categories:

- Air quality projects;
- Pedestrian/bicycle projects;
- Port/airport projects;
- Roadway projects;
- Traffic flow improvements; and
- Transit projects.

The research team made a final set of recommendations of strategies for analysis based on considerations of: 1) H-GAC's interest in the strategy; 2) whether the GHG impacts of the strategies could be scientifically quantified; and 3) whether the strategies could potentially achieve a reasonable magnitude of GHG reductions. These recommended strategies were further discussed among the research team and the H-GAC principal investigator before finalization. The following lists the eight strategies selected for final inclusion in the analysis tool with a detailed description in the following chapter:

- Implementation of anti-idling policy;
- Idle reduction for long-haul trucks;
- Vehicle fleet electrification;

- Transit facilities;
- High occupancy vehicle (HOV) facilities;
- Mixed-use developments;
- Retiming of traffic signals; and
- Bicycle facilities.

Two strategies initially considered for inclusion but later eliminated were eco-driving and carbon sequestration. Eco-driving refers to the process by which drivers modify their behavior to reduce emissions and fuel use by eliminating hard accelerations, reducing idling, avoiding frequent starts and stops, and, where possible, optimizing their gear shifting. While existing research has shown that eco-driving can reduce pollutant and GHG emissions, the strategy was eliminated from consideration due to the lack of sufficient scientific data to quantify the benefits of eco-driving and to establish rates of compliance among various fleets. Carbon sequestration refers to the process by which vegetation (specifically trees) can absorb CO_2. Due to this process, roadside vegetation could potentially be considered as a GHG control strategy. However, this strategy was eliminated from consideration at this stage due to difficulties in tracking changes in vegetation levels and attribution to a specific transportation corridor. An additional analysis, for highway capacity addition, is also included to allow for the analysis of capacity addition projects in the RTP. This strategy is not listed as a control strategy, but included separately in the analysis tool.

3. Quantification of GHG Reductions for Selected Control Strategies

One of the objectives of this project is to develop a spreadsheet-based estimation tool that can be used to estimate reductions in GHG emissions achieved by various mitigation strategies. As discussed in Chapter 2, eight GHG control strategies were selected for further analysis and inclusion in the tool. Generic estimation methodologies have been developed for the strategies that would allow for GHG reductions to be calculated based on user inputs. Depending on the type of strategy, the inputs may be for a region (such as a county) or for a specific transportation facility. The estimation of some of the control strategies, such as HOV projects, transit projects, and mixed-use developments ("livable centers") enable specific projects listed in H-GAC's RTP to be evaluated where sufficient project-level data is available. Default inputs, which include the MOVES model emissions rates for the HBG region and other assumptions, are included, and may be changed by the user if desired. An additional analysis, for highway capacity addition, is also included to allow for the analysis of capacity addition projects in the RTP. This strategy is not listed as a control strategy, but included separately in the analysis tool.

This chapter describes each of the strategies in detail, and provides information about the quantification of GHG emissions reduction (specifically CO_2 reduction – or, in some cases the increase) attributable to the strategy, the scope of implementation, assumptions made and default data used as part of the analysis tool. These are described further in Chapter 4.

The outputs generated in the analysis tool for each strategy include the daily CO_2 emission reduction due to the implementation of the strategy for a base and future year. For all strategies except the bike facility strategy (where the input data does not allow for this computation), the emissions in the base and future year without implementation of the control strategy ("Business as Usual") scenario and with the implementation of the strategy are provided. The difference in emissions between the base year "Business as Usual" scenario with the future year control strategy scenario is also displayed, which provides an indication of the overall future year benefits of the strategy.

The remainder of this chapter describes each strategy in detail.

Strategy 1: Implementation of Anti-Idling Policy

This strategy considers the implementation of an anti-idling policy targeting local heavy-duty fleets (i.e., short-haul truck fleets). The reduction of emissions is evaluated by considering the effect of placing restrictions on idling time, for example, the implementation of a "five minute" idle restriction, which would reduce the overall time these vehicles idle, and consequently, the associated emissions.

This strategy can be applied at a regional level (e.g., a county) and requires identifying a target fleet (e.g., short-haul diesel trucks) and knowledge of compliance and existing idling levels. The levels of compliance, number of target vehicles, and average idling time per vehicle prior to implementation of an idling restriction vary significantly from one county to another; however, many counties in Texas such as Bastrop, Caldwell, Hays, Travis, and Williamson allow a maximum idling time of 5 minutes from April to October (*6*).

General Quantification Approach

Equations 1 through 3 show the general quantification of the impact of this strategy.

$$\text{Daily Emission Reduction (gram/day)} = A \times B \qquad (1)$$

$$A = N_V \times F_C \qquad (2)$$

$$B = EF_I \times (t_B - t_A) \qquad (3)$$

Where,

EF_I = Idling emissions factor, i.e., CO_2 emissions rate for the target fleet (gram/hour);

N_V = Number of vehicles in the target fleet found to idle per day (vehicles per day);

F_C = Compliance factor, i.e. percentage of vehicles in compliance with the strategy (percentage);

t_A = Time vehicles are allowed to idle under new restriction (hours per vehicle); and

t_B = Average idling time per vehicle prior to implementation of restriction (hours per vehicle).

Implementation in Analysis Tool

Required inputs for this strategy include:

- Number of target vehicles (vehicles per day);
- Average idling time per vehicle prior to implementation of restriction (hours per vehicle);
- Time vehicles are allowed to idle under new restriction (hours per vehicle); and
- Compliance factor (percentage).

Optional inputs are the idling emissions factor (grams/hour), which may be input by the user if desired. Currently, default values from the MOVES model for single-unit short-haul trucks are provided for two evaluation years 2011 and 2040. These defaults may be changed to target different vehicle types or different analysis years. Additionally, the required inputs for the base year such as the number of target vehicles and compliance factors are included as optional future year inputs, which can be entered if different from the base year values.

The output of this strategy is expressed in the CO_2 emissions reductions in gram per day (or ton per day).

Strategy 2: Idle Reduction for Long-Haul Trucks

This strategy can reduce emissions by reducing the extended idling of long-haul trucks during mandatory rest periods. The estimation of this is based on usage of electrified parking spaces (i.e., truck stop electrification, TSE) or auxiliary power units (APUs) as an alternative to idling the truck engine. This strategy can be applied to all truck stops at a regional or county level. The target fleet is heavy-duty diesel long-haul trucks. TTI has performed previous research on utilization of truck spot parking spaces, including those with and without TSE. Average occupancy rates of parking spaces with and without TSE are 0.27 and 0.50 according to a TTI study (*7*), and these values are used as suggested defaults in the analysis tool.

General Quantification Approach

Equations 4 through 6 shows the general quantification of the impact of this strategy.

Daily Emission Reduction = $A + B$ *(4)*

$$A = 24 \times N_1 \times AVR_1 \times P_{APU} \times (EF_I - EF_{APU}) \quad (5)$$

$$B = 24 \times N_2 \times AVR_2 \times EF_I \quad (6)$$

Where,

- AVR_1 = Average daily utilization of parking spaces without TSE (percentage);
- AVR_2 = Average daily utilization of parking spaces with TSE (percentage);
- EF_I = Idling emissions factor for trucks (gram/hour);
- EF_{AUP} = Emissions factor of using APU (gram/hour);
- N_1 = Number of parking spaces without TSE;
- N_2 = Number of parking spaces with TSE; and
- P_{AUP} = Percentage of vehicles in non-TSE spaces using APU (percentage).

Implementation in Analysis Tool

Required inputs for this strategy include:

- Number of available parking spaces with and without TSE;
- Average daily utilization of parking spaces with and without TSE; and
- Percentage of vehicles in non-TSE spaces using APU.

Optional inputs are emission factors for truck idling and for APU (gram/hour), which may be input by the user if desired. Note that no emissions are associated with the use of TSE. Currently, default values of emissions factors for idling from the MOVES model for combination long-haul trucks are provided for two evaluation years – 2011 and 2040. Default values of emissions factors for APU are based on a TTI study for the HARC (*8*). These defaults may be changed to target different analysis years. Additionally, the required inputs for the base year such as the utilization rates are included as optional future year inputs, which can be entered if different from the base year values.

The output of this strategy is expressed in the CO_2 emissions reductions in gram per day (or ton/day).

Strategy 3: Vehicle Fleet Electrification

This strategy considers the potential impact of increasing the market share of electrified vehicles (hybrids, plug-in hybrids or fully-electric vehicles) over and above the projected fleet penetration levels through implementation of a marketing/incentive program. This strategy can be applied at a regional level. The quantification of emissions reductions is attributed to reduced emissions rates of these vehicles in comparison with the fleet averages. Emission factors of electrified vehicles vary significantly depending on the vehicle make and the electrification type. For example, as a typical hybrid vehicle, the fuel efficiency of 2011 Toyota Prius is 50 miles per gallon (mpg) (*9*), and the corresponding emission rate is 176 grams/mile; as a typical plug-in hybrid vehicle, the fuel efficiency of 2011 Chevrolet volt can reach 93 mpg, and the corresponding emissions rate is 94 grams/mile. These recommended values may be used in the calculations in the absence of specific emissions data.

General Quantification Approach

Equations 7 through 9 show the general quantification of the impact of this strategy.

$$\text{Daily Emission Reduction} = A \times B \qquad (7)$$

$$A = N_E \times VMT_{AVE} \qquad (8)$$

$$B = EF_B - EF_A \qquad (9)$$

Where,

EF_A = Emissions factor after replacement (i.e., for a representative "electrified" vehicle – this value would be zero for purely electric vehicles, but will have a value for hybrids or PHEVs; gram/mile);

EF_B = Emissions factor before replacement – i.e., average emissions factor for a Light-duty vehicle in the fleet (gram/mile);

N_E = Number of electrified vehicles considered to replace existing passenger cars due to incentives/programs put in place (i.e., over and above levels that are ordinarily projected and included in the MOVES model or other emissions rates); and

VMT_{AVE} = Average daily VMT per vehicle (mile).

Implementation in Analysis Too

Required inputs for this strategy include:

- Number of electrified vehicles considered to replace existing passenger cars due to implementation of specific incentives/programs;
- Average daily VMT per vehicle (mile); and
- Emissions factor after replacement (gram/mile) – in the case of a mix of vehicles being considered (for example, hybrids and electric vehicles), a weighted average value may be used.

Optional inputs are emissions factors before the replacement (gram/mile), which can be input by the user, or can be calculated from look-up tables by selecting the roadway type (1 represents arterial; 2 represents freeway), and speed (from 5 to 75 mph) most representative of the vehicles' operation. The emissions look-up table is developed using the MOVES model for passenger cars in the evaluation year of 2011 and 2040. Currently, the road type is assumed to arterial, and the speed 30 mph. These defaults may be changed to target different vehicle types or different analysis years. Additionally, the required inputs for the base year such as the number of target vehicles are included as optional future year inputs, which can be entered if different from the base year values.

The output of this strategy is expressed in the CO_2 emissions reductions in gram per day (or ton/day).

Strategy 4: Transit Facilities

This strategy considers the expansion of existing transit (specifically, bus) facilities or service, or introduction of new service. The emissions reductions are attributed to the VMT reduced by transit users who were originally automobile users. This strategy can be applied to selected projects listed in the RTP, or quantified at a regional level. This strategy will require knowledge of the new transit ridership, additional daily transit VMT, and the percentage of those new users that previously were automobile drivers. This percentage varies significantly from city to city; for example, it is as low as 60 percent in Washington D.C., but it can reach 100 percent in Denver (*10*).

General Quantification Approach

Equations 10 through 12 show the general quantification of the impact of this strategy.

Daily Emission Reduction = $VMT_R \times EF_C - VMT_T \times EF_T$ *(10)*

$$VMT_R = VT_R \times L \quad (11)$$

$$VT_R = N_{TR} \times F_{T,SOV} \quad (12)$$

Where,

EF_C	=	Emissions factor for passenger cars on affected roadway or region before implementation of transit service (gram/mile);
EF_T	=	Emissions factor for transit buses (gram/mile);
$F_{T,SOV}$	=	Percentage of users of new/expanded transit services that previously were automobile drivers (percentage);
N_{TR}	=	New transit ridership (person/day);
L	=	Average auto trip length (mile);
VMT_R	=	Reduction in daily automobile VMT (VMT/day);
VMT_T	=	New transit VMT (VMT/day); and
VT_R	=	Reduction in number of daily automobile vehicle trips (trip/day).

Implementation in Analysis Tool

Required inputs for this strategy include:

- New transit ridership (person/day);
- New transit VMT; and
- Percentage of users of new/expanded transit services that previously were automobile drivers (percentage).

Optional inputs are emissions factors for passenger cars (gram/mile), emissions factor of transit buses (gram/mile), and the average trip length (mile) for passenger cars. Emissions factors for passenger cars and transit buses can be input by the user, or can be calculated from look-up tables by selecting the roadway type (1 represents arterial; 2 represents freeway), and speed (from 5 to 75 mph) most representative of the vehicles' operation. The emissions look-up table is developed using the MOVES model in the evaluation years of 2011 and 2040. Currently, the road type is assumed to arterial, and the speed 30 mph. The percentages of gasoline and diesel buses are both 50%. These defaults may be changed to target different analysis years. The 8.6 mile average trip length is provided by a previous H-GAC livable center project (*11*). Additionally, the required inputs for the base year such as the ridership are included as optional future year inputs, which can be entered if different from the base year values. If an analysis is to be performed for rail transit, the emissions factors for transit can be considered as zero (i.e. no on-road mobile emissions).

The output of this strategy is the emissions reduction in gram/day (or ton/day).

Strategy 5: High Occupancy Vehicle (HOV) Facilities

This strategy considers HOV facilities – separate lanes on controlled access highways are created for vehicles containing a specified minimum number of passengers. In this case, emissions reductions computed are based on reduced VMT due to increased occupancy. This strategy can be applied to existing HOV facilities or planned facilities as contained in RTP.

General Quantification Approach

Equation 13 through 15 shows the general quantification of the impact of this strategy.

$$\text{Daily Emission Reduction} = EF \times L \times N_P \times AVO_A / AVO_B - EF \times L \times N_P \qquad (13)$$

Where,

AVO_A = HOV occupancy requirement (person/vehicle);

AVO_B = Existing average passenger car occupancy (person/vehicle);

EF = Emissions factor for passenger cars (gram/mile);

N_P = Total number of vehicles using/expected to use HOV lanes (vehicle per day); and

L = Average trip length on HOV facility (mile).

Implementation in Analysis Tool

Required inputs for this strategy include:

- Total number of vehicles using/expected to use HOV lanes (vehicle per day);

- Average trip length on HOV facility (mile);
- Existing average passenger car occupancy (person/vehicle); and
- HOV occupancy requirement (person/vehicle).

Optional inputs are emissions factors for passenger cars (gram/mile), which can be input by the user, or can be calculated from look-up tables by selecting the roadway type (1 represents arterial; 2 represents freeway), and speed (from 5 to 75 mph) most representative of the vehicles' operation. The emissions look-up table is developed using the MOVES model for passenger cars in the evaluation years of 2011 and 2040. Currently, the road type is assumed to freeway, and the speed 70 mph. These defaults may be changed to target different vehicle types or different analysis years. Additionally, the required inputs for the base year such as the HOV usage and occupancy requirements are included as optional future year inputs, which can be entered if different from the base year values.

The output of this strategy is the emissions reduction in gram/day (or ton/day).

Strategy 6: Mixed-Use Developments

Mixed land uses can reduce vehicle trips through "internal trip capture" by locating various land uses adjacent to each other. This measure can be applied to "livable centers" being planned in the Houston-Galveston area, or to other planned or existing mixed-use developments. The estimation method for internal trips comes from Institute of Transportation Engineers (ITE) recommendations (*12*). In addition, the calculation process adopts trip generation rates and internal capture rates in (*12*). Advanced users can also modify these rates.

General Quantification Approach

- Step 1- Document Characteristics of Multi-Use Development (three use types).
- Step 2 - Compute Baseline Trip Generation for Individual Land Uses (based on size/number of units and standard trip generation rates).
- Step 3- Estimate Anticipated Internal Capture Rate between Each Pair of Land Use.
- Step 4 -Estimate "Unconstrained Demand" Volume by Direction.
- Step 5 -Estimate "Balanced Demand" Volume by Direction.
- Step 6 - Estimate the Internal and External Trips for Each Land Use.
- Step 7 -Estimate the reduction of VMT and translate to emissions (i.e., emissions reduced = daily trips reduced x average trip length x emissions factor).

Implementation in Analysis Tool

Required inputs for this strategy include:

- Area of office land use (square foot);
- Area of retail land use (square foot); and
- Units of residential land use.

Optional inputs are emissions factors for passenger cars (gram/mile) and the average trip length (mile) for passenger cars, which can be input by the user, or can be calculated from look-up tables by selecting the roadway type (1 represents arterial; 2 represents freeway), and speed (from 5 to 75 mph) most representative of the vehicles' operation. The emissions look-up table is developed using the MOVES model for passenger cars in the evaluation years of 2011 and 2040. Currently, the road type is assumed to arterial, and the speed 30 mph. These defaults may be changed to target different vehicle types and different analysis years. Internal trip generation rates may also be changed by the user. The 8.6 mile average trip length is provided by a previous H-GAC livable center project (*11*).

The output of this strategy is the emissions reduction in gram/day (or ton/day).

Strategy 7: Retiming of Traffic Signals

This measure considers the potential improvement of signal timing at intersections that can reduce emissions by reducing vehicle delay. This strategy can be applied on a project basis, for example for an arterial or corridor, or for a region. The quantification methodologies are based on a the Texas Guide to Accepted Mobile Source Emission Reduction Strategies (*13*). This strategy requires knowledge of traffic conditions before and after signal retiming, such as VMT, total delay and stops, and cruise speed along the corridor.

General Quantification Approach

Equations 14 through 18 show the general quantification of the impact of this strategy.

$$\text{Daily Emission Reduction} = A + B + C + D \qquad (14)$$

$$A = (D_B - D_A) \times EF_I \times V_{D,P} \qquad (15)$$

$$B = (D_B - D_A) \times EF_I \times V_{D,OP} \qquad (16)$$

$$C = V_{D,P} \times (EF_{B,P} - EF_{A,P}) \times L \qquad (17)$$

$$D = V_{D,OP} \times (EF_{B,P} - EF_{A,P}) \times L \qquad (18)$$

Where,

A = Change in idling emissions from reduced vehicle delay during the peak period

B = Change in idling emissions from reduced vehicle delay during the off-peak period

C = Change in running exhaust emissions from improved traffic flow during the peak period

D = Change in running exhaust emissions from improved traffic flow during the off-peak period

D_A = Average vehicle delay at intersections (hours) after implementation

D_B = Average vehicle delay at intersections (hours) before implementation

$EF_{A,OP}$ = Speed based CO_2 running exhaust emission factor during off-peak period (grams/mile) after implementation

$EF_{A,P}$ = Speed based CO_2 running exhaust emission factor during peak period (grams/mile) after implementation

$EF_{B,OP}$ = Speed based CO_2 running exhaust emission factor during off-peak period (grams/mile) before implementation

$EF_{B,P}$ = Speed based CO_2 running exhaust emission factor during peak period (grams/mile) before implementation

EF_I = Idling emission factors for CO2 (grams/hour)

L = length of corridor affected by signalization project (miles)

$V_{D,OP}$ = Average daily volume for the corridor during off-peak period

$V_{D,P}$ = Average daily volume for the corridor during peak period

Implementation in Analysis Tool

Required inputs for this strategy include:

- Length of corridor (mile);
- Total delay before and after retiming (hour);
- Cruise speeds before and after retiming (mph).
- Volumes of peak and off-peak periods (vehicle/hour)

The idling emission factors (grams/hour) can be selected from look up tables already included in the tool for years 2011 and 2040. The running exhausts emission factors can be estimated from look up tables by selecting the road type and speed, or input manually to override the default values.

The output of this strategy is the emissions reduction in gram/day (or ton/day).

Strategy 8: Bicycle Facilities

This measure considers the potential impact of a new bicycle facility that can attract more cyclists. Based on this increasing number of cyclists, the reduction of VMT and emissions are estimated. This strategy can be applied on a project level or for a region, and the estimation methodology for increased bicycle trips is from a National Cooperative Highway Research Program Report NCHRP 552 (*14*).

General Quantification Approach

Equations 19 through 22 shows the general quantification of the impact of this strategy.

$$\text{Daily Emission Reduction} = EF \times \frac{BT_1 + BT_2 + BT_3}{AVO} \times L \quad (19)$$

$$BT_1 = AR \times BR \times P_1 \times IR_1 \quad (20)$$

$$BT_2 = AR \times BR \times P_2 \times IR_2 \quad (21)$$

$$BT_3 = AR \times BR \times P_3 \times IR_3 \quad (22)$$

Where,

AR = Percentage of adults in population;

AVO = Average passenger car occupancy (adult persons per vehicle);

BR = Bicycling rates; (0.02 for low estimation, 0.028 for moderate estimation, and 0.066 for high estimation);

BT_1 = Increased bicycle trips within 0.25 mile from the bicycle facility;

BT_2 = Increased bicycle trips within 0.25 to 0.50 mile from the bicycle facility;

BT_3 = Increased bicycle trips within 0.50 to 1.00 mile from the bicycle facility;

EF = Emissions factor (gram/mile);

IR_1 = Trip increase rate within 0.25 mile from the bicycle facility (1.93);

IR_2 = Trip increase rate within 0.25 to 0.50 mile from the bicycle facility (1.11);

IR_3 = Trip increase rate within 0.50 to 1.00 mile from the bicycle facility (0.39);

L = Average trip length;

P_1 = Population for area within 0.25 mile from the bicycle facility;

P_2 = Population for area within 0.25 to 0.50 mile from the bicycle facility; and

P_3 = Population for area within 0.50 to 1.00 mile from the bicycle facility.

Implementation in Analysis Tool
Required inputs for this strategy include:

- Percentage of adults in population;
- Average passenger car occupancy (adult persons per vehicle);
- Bicycle rates; and
- Populations for areas within 0.25, 0.25 to 0.50, and 0.50 to 1.00 mile from the bicycle facility.

Optional inputs are emissions factors (gram/mile) and the average trip length (mile). By selecting the road type (1 represents arterial; 2 represents freeway), and speed (from 5 to 75 mph), emissions factors can be estimated from look-up tables with respect to speed. The emissions look-up tables contain rates from the MOVES model for passenger cars in the evaluation years of 2011 and 2040. Currently, the road type is assumed to arterial, and the speed 30 mph. These defaults may be changed to target different vehicle types and different analysis years. The 8.6 mile average trip length is provided by a previous H-GAC livable center project (*11*).

In addition to the emissions factor and the average trip length, other optional inputs include bicycling rates and trip increase rate within 0.25, 0.25 to 0.50, and 0.50 to 1.00 mile from the bicycle facility, which currently adopt the values suggested in the NCHRP report (*14*). Additionally, the required inputs for the base year such as populations in different areas are included as optional future year inputs, which can be entered if different from the base year values.

The output of this strategy is the emissions reduction in gram/day (or ton/day)

Analysis for Highway Capacity Addition
Adding highway capacity provides higher road capacities and mitigates traffic congestion. However, as noted previously, it is not a viable long-term emissions control strategy on account of induced demand, and will remain an emissions benefit only if traffic volumes do not increase in future years. However, its estimation has been included to allow for the evaluation of capacity addition projects from the RTP and to show how these projects will affect the greenhouse gas emissions in future years. These projects could bring short term emission benefits due to improved travel speed, and as a consequence, reduced fuel consumption. However, in the long term they bring large disbenefits due to induced demand and, as a consequence, increased traffic volumes.

General Quantification Approach
Equation 23 shows the general quantification of the impact of this strategy.

Daily Emission Reduction = $D_p \times (V_B \times L \times EF_B - V_A \times L \times EF_A)$ (23)

Where,

D_P = Duration of peak hours (hours);

EF_A = Emissions factor after adding lanes (gram/mile);

EF_B = Emissions factor before adding lanes (gram/mile);

L = Length of facility (mile);

V_A = Average peak hour traffic volume after adding lanes (vehicle/hour); and

V_B = Average peak hour traffic volume before adding lanes (vehicle/hour).

Implementation in Analysis Tool

Required inputs for this strategy include:

- Duration of peak period (hours);
- Traffic volumes with and without the capacity addition, for base and future years. (vehicle/hour); and
- Length of facility (mile).

Given the importance of considering induced demand due to the capacity addition in both base and future years, the inputs of this strategy include separate volume entries for the base and future years, for both a “build” and “no-build” scenario, to allow for this to be appropriately included in the estimation.

Optional inputs are the speeds and roadway type for each scenario, or the emissions factors, which may be entered directly instead. By selecting the roadway type (1 represents arterial; 2 represents freeway), and speed (from 5 to 75 mph), emissions factors are estimated from look-up tables with respect to speed. The emissions look-up tables contain rates from the MOVES model for passenger cars in the evaluation years of 2011 and 2040. Alternatively, the user can directly enter the required emissions factors.

The output of this strategy is the emissions reduction in gram/day (or ton/day).

4. Development of an Analysis Tool and Example Applications

Layout of Analysis Tool

Chapter 3 discussed the GHG control strategies analyzed as part of this project, and the methodology by which the CO_2 reductions attributable to the implementation of various strategies are estimated. These methodologies were compiled in the form of a generic, user-friendly analysis tool that could be used to evaluate individual strategies, a "bundle" of strategies, or to compare and contrast various strategies and the potential emissions reductions.

The analysis tool is developed in the form of a Microsoft® Excel workbook, with hyperlinked worksheets that are linked to each other with calculations. Figure 1 shows the main page of the analysis tool, from which users may select a specific strategy that they wish to evaluate.

"Methodology for Estimating Greenhouse Gas Emissions and Assessing Mitigation Options for Project Level Applications for On-Road Mobile Sources"

Analysis Tool to Estimate CO_2 Reductions for Selected Control Strategies

	Select the Strategy to Evaluate:
1	Implementation of Anti-Idling Policy
2	Idle Reduction for Long-Haul Trucks
3	Vehicle Fleet Electrification
4	Transit Facilities
5	HOV Facilities
6	Mixed Use Developments
7	Retiming of Traffic Signals
8	Bicycle Facilities
	Analysis for Capacity Addition Projects

Click on a strategy name to go to individual strategy worksheets.
Click on "Menu" at the top left corner of each worksheet to return to this main menu.

Figure 1. Main Page of Analysis Tool.

Each of the individual strategies has worksheets in which users may input data and generate the outputs. Figure 2 shows the example layout of the sheets. Each strategy contains a brief description, and space for user inputs, default values, and makes use of color-coded cells to distinguish the types of data. Additional calculations for certain strategies, as well as look-up tables for emissions, etc. are included as hidden cells and hidden worksheets. Advanced users may unhide these and modify if they so choose, but note that the formatting and layout of the hidden calculation sheets are not as refined as the interface of the strategy worksheets.

Output

Description	*Symbol*	*Value*	*Units*	*Comments*
Emissions Reduction Due to Control Strategy Implementation				
Daily CO_2 Emission Reduction - Base Year	ER	0	gram/day	
		0.00	ton/day	
Daily CO_2 Emission Reduction - Future Year	ER	0	gram/day	
		0.00	ton/day	
Assessment of Benefits Compared to Business as Usual (BAU) Scenario				
Daily CO_2 Emissions for Base Year - Business as Usual		0	gram/day	
		0.00	ton/day	
Daily CO_2 Emissions for Base Year - With Control Strategy		0	gram/day	
		0.00	ton/day	
Daily CO_2 Emissions for Future Year - Business as Usual		0	gram/day	
		0.00	ton/day	
Daily CO_2 Emissions for Future Year - With Control Strategy		0	gram/day	
		0.00	ton/day	
Daily CO_2 Emissions Reduction over Base Year BAU Scenario				
With Control Strategy in Future Year		0	gram/day	
		0.00	ton/day	

Input

Description	*Symbol*	*Value*	*Units*	*Comments*
Number of target vehicles	N_v		vehicle	
Compliance factor	F_c		percentage	
Time vehicles are allowed to idle under new restriction	t_A		hour	
Average idling time per vehicle prior to implementation of restriction	t_B		hour	
Number of target vehicles (for the future year)	N_v		vehicle	Input only if it is different from current year
Compliance factor (for the future year)	F_c		percentage	Input only if it is different from current year
Time vehicles are allowed to idle under new restriction (for the future year)	t_A		hour	Input only if it is different from current year
Average idling time per vehicle prior to implementation of restriction (for the future year)	t_B		hour	Input only if it is different from current year
Idling emission factor - current year	EF_I	9,591	gram/hour	From MOVES for Year 2011, Short Haul Single Unit Trucks
Idling emission factor - future year		9,504	gram/hour	From MOVES for Year 2040, Short Haul Single Unit Trucks

Figure 2. Example Worksheet for Strategy Analysis.

Example Application for Analysis Tool

This section provides example calculations for each of the strategies being analyzed, in the form of a hypothetical case study for a county where these strategies are being implemented. This section discusses the assumptions and inputs for each strategy, the resulting emissions reductions, and the total estimated for the entire bundle of strategies. The resulting input and output worksheets are provided in Appendix A.

Implementation of Anti-Idling Policy

Table A-1 in Appendix A illustrates the application of an anti-idling policy in the form of a “5-minute” idling restriction. In this county, the number of target vehicles of this strategy is set to 10,000, their average idling time is 30 minutes (0.5 hour), and 45 percent of them comply with the anti-idling regulation (i.e., implementation of a 5-minute idling rule). The GHG emissions reduction associated with this measure is 19.84 tons/day for the year 2011 and 19.66 tons/day for year 2040.

Idle Reduction for Long-Haul Trucks

Table A-2 in Appendix A illustrates the application of the long-haul truck idle reduction. This county establishes a new truck stop. It provides 20 parking spaces with TSE and 100 parking spaces without TSE. The average utilization rate of TSE is 27 percent. For those parking spaces without TSE, the average utilization is 50 percent, and 30 percent of these vehicles use APUs. The GHG emissions reduction associated with this measure is 3.85 tons/day for the year 2011 and 3.81 tons/day for year 2040.

Vehicle Fleet Electrification

Table A-3 in Appendix A illustrates the application of vehicle fleet electrification. In this county, a total of 1,000 vehicles are replaced with the electrified vehicles through the implementation of a marketing or incentive program. For those vehicles, the average daily VMT is 20 miles, and the emissions factor is 176 grams/mile. In the future year, the total number of vehicles to be replaced is considered to increase to 2,000. When considering the default speeds and roadway types, the GHG emissions reduction associated with this measure is 5.02 tons/day for the year 2011 and 6.26 tons/day for year 2040.

Transit Facilities

Table A-4 in Appendix A illustrates the application of transit facilities. This county increases the transit ridership by 1,000 persons, and 80 percent of these new transit users were previously automobile drivers. On the other hand, new transit service causes additional 300 transit VMTs. The GHG emissions reduction associated with this measure is 2.63 tons/day for the year 2011 and 1.98 tons/day for year 2040, when considering the default speeds and emissions factors.

HOV Facilities

Table A-5 in Appendix A illustrates the application of HOV facilities. This county establishes an HOV lane that is 11 miles long and the number of HOV users is 10,000 vehicles/day, with a minimum occupancy requirement of 2 (i.e., HOV 2+). The average general-purpose lane occupancy in this county is 1.1 persons/vehicle. The average general-purpose lane occupancy in this county is 1.1 persons/vehicle. The GHG emissions reduction associated with this measure is 35.10 tons/day for the year 2011 and 27.83 tons/day for year 2040.

Mixed-Use Development

Table A-6 in Appendix A illustrates the application of mixed-use land development. This county proposes a mixed-use land development that includes 771,487 square feet of office space, 141,926 square feet of retail space, and 702 residential apartment units. The GHG emissions reduction associated with this measure is 7.00 tons/day for the year 2011 and 5.51 tons/day for year 2040.

Retiming of Traffic Signals

Table A-7 in Appendix A illustrates the application of retiming traffic signal. The length of the corridor is 10 miles. The traffic volumes during peak hours and off-peak hours are 60,000 and 40,000 vehicles per day. Due to signal retiming, the average delay is reduced from 0.20 to 0.18 hour per vehicle, but the speed remains the same. The GHG emissions reduction associated with this measure is 21.14 tons/day for the year 2011 and 20.95 tons/day for the year 2040.

Bicycle Facilities

Table A-8 in Appendix A illustrates the application of bicycle facilities. This county builds a new 10-mile bicycle facility. In the year 2011, populations for areas within 0.25, 0.25 to 0.50, and 0.50 to 1.00 mile from the bicycle facility are 500, 1,000, and 5,000 persons, respectively; the corresponding populations in the year 2040 are 800, 1,400, and 7,000 persons. The GHG emissions reduction associated with this measure is 0.18 ton/day for the year 2011 and 0.20 ton/day for year 2040.

Capacity Addition Analysis Example

Table A-9 in Appendix A illustrates the application for a capacity addition project analysis for a 10 mile facility. In the base year, the traffic volumes with and without the capacity addition are 6,000 vehicles per hour and 8,000 vehicles per hour, respectively. The corresponding speeds are 20 mph and 35 mph. In the future year, the volumes with and without capacity addition are 8,000 vehicles per hour and 12,000 vehicles per hour respectively, and the operating speed is the same (20 mph) in both cases. The speeds and roadway type (i.e. arterial) are used to generate the emissions factors. The peak period duration is 4 hours. The results indicate that in the base year (2011), the added capacity results in an emissions reduction of 2.08 ton/day due to improved congestion, despite an increase in traffic volumes. However, in the future year, 2040, the capacity addition results in an increase in GHG emissions, of 71.16 ton/day.

Summary of GHG Emissions Reductions for Example Application

Table 1 summarizes the GHG emissions reduction from the eight different emissions reduction strategies in the study county. The capacity addition example is not considered as part of this bundle of strategies. Additional outputs for each strategy, including, where applicable, the emissions in the base and future year without implementation of the control strategy ("Business as Usual") scenario and with the implementation of the strategy are provided in the result tables in Appendix A. The difference in emissions between the base year "Business as Usual" scenario with the future year control strategy scenario are also included in the Appendix.

Table 1. Summary of GHG Emissions Reduction from Different Strategies.

	Emissions Reduction (ton/day)	
Strategy	**Year 2011**	**Year 2040**
Implementation of Anti-Idling Policy	19.84	19.66
Idle Reduction for Long-Haul Trucks	3.85	3.81
Vehicle Fleet Electrification	5.02	6.26
Transit Facilities	2.11	1.62
HOV Facilities	35.1	27.83
Mixed Use Developments	7.00	5.51
Retiming of Traffic Signals	21.14	20.95
Bicycle Facilities	0.18	0.2
Total	**94.24**	**85.84**

The total GHG emissions reduction is 94.24 tons/day for the year 2011 and 85.84 tons/day for the year 2040. The hypothetical application presented here shows that the anti-idling policy and HOV facilities contribute to the majority of the total emissions reduction.

5. Summary and Conclusions

The aim of this project was to understand the current critical issues regarding GHG emissions from a transportation agency perspective, and to develop an approach and methodology for transportation agencies (specifically H-GAC) to assess the GHG emissions impact of various GHG "control strategies." A "white paper" on background issues was developed, and is included in a companion piece (Volume 2) to this report. A generic analysis tool was developed that can be used to analyze the GHG reductions due to various strategies, and this report summarized the approach and methodology for developing this tool.

This analysis tool can be viewed as a first step in developing an approach to scientifically quantify GHG reductions due to various control strategies. Further refinements and can be made to the tool to customize it to specific projects, regions, or corridors. Some of the assumptions made in quantifying the GHG reductions may also be refined using local data or improved estimation methods. For example, the estimation for the HOV strategy currently does not incorporate the issue of re-distribution of vehicles (i.e., existing HOVs that may use HOV lanes), which could potentially result in over-estimation of emissions reductions. Further local information, even at the project level, regarding average trip lengths, existing truck idling durations, truck stop utilization rates, etc. may be used to enhance the analysis.

As the issue of GHG emissions and climate change are emerging as being of great importance to the transportation sector, the findings from this project will help agencies such as H-GAC take a scientific approach to the evaluation and implementation of GHG control strategies. The analysis tool developed can set the stage for more sophisticated methodologies and tools to be implemented in the future, and will additionally benefit other agencies in Texas and the U.S. who are exploring the area of control strategies for mobile-source GHG emissions.

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Appendix A

Table A-1. Results for Anti-Idling Policy.

Output

Description	Symbol	Value	Units
Emissions Reduction Due to Control Strategy Implementation			
Daily CO_2 Emission Reduction - Base Year	ER	17,997,781	gram/day
		19.84	ton/day
Daily CO_2 Emission Reduction - Future Year	ER	17,835,007	gram/day
		19.66	ton/day
Assessment of Benefits Compared to Business as Usual (BAU) Scenario			
Daily CO_2 Emissions for Base Year - Business as Usual		21,580,073	gram/day
		23.79	ton/day
Daily CO_2 Emissions for Base Year - With Control Strategy		3,582,292	gram/day
		3.95	ton/day
Daily CO_2 Emissions for Future Year - Business as Usual		21,384,900	gram/day
		23.57	ton/day
Daily CO_2 Emissions for Future Year - With Control Strategy		3,549,893	gram/day
		3.91	ton/day
Daily CO_2 Emissions Reduction over Base Year BAU Scenario			
With Control Strategy in Future Year		18,030,179	gram/day
		19.87	ton/day

Input

Description	Symbol	Value	Units
Number of target vehicles	N_v	10000	vehicle
Compliance factor	F_c	45%	percentage
Time vehicles are allowed to idle under new restriction	t_A	0.083	hour
Average idling time per vehicle prior to implementation of restriction	t_B	0.5	hour
Number of target vehicles (for the future year)	N_v		vehicle
Compliance factor (for the future year)	F_c		percentage
Time vehicles are allowed to idle under new restriction (for the future year)	t_A		hour
Average idling time per vehicle prior to implementation of restriction (for the future year)	t_B		hour
Idling emission factor - current year	EF_I	9,591	gram/hour
Idling emission factor - future year		9,504	gram/hour

Table A-2. Results for Long-Haul Truck Idle Reduction.

Output

Description	*Symbol*	*Value*	*Units*
Emissions Reduction Due to Control Strategy Implementation			
Daily CO_2 Emission Reduction - Base Year	ER	3,491,243	gram/day
		3.85	ton/day
Daily CO_2 Emission Reduction - Future Year	ER	3,460,202	gram/day
		3.81	ton/day
Assessment of Benefits Compared to Business as Usual (BAU) Scenario			
Daily CO_2 Emissions for Base Year - Business as Usual		4,463,243	gram/day
		4.92	ton/day
Daily CO_2 Emissions for Base Year - With Control Strategy		972,000	gram/day
		1.07	ton/day
Daily CO_2 Emissions for Future Year - Business as Usual		4,432,202	gram/day
		4.89	ton/day
Daily CO_2 Emissions for Future Year - With Control Strategy		972,000	gram/day
		1.07	ton/day
Daily CO_2 Emissions Reduction over Base Year BAU Scenario			
With Control Strategy in Future Year		3,491,243	gram/day
		3.85	ton/day

Input

Description	*Symbol*	*Value*	*Units*
Number of available parking spaces without TSE	N_1	100	spaces
Average daily utilization rate of parking spaces without TSE	AVR_1	50%	percentage
Percentage of vehicles in non-TSE spaces using APU	P_{AUP}	30%	percentage
Number of available parking spaces with TSE	N_2	20	spaces
Average daily utilization rate of parking spaces with TSE	AVR_2	27%	percentage
Number of available parking spaces without TSE (for the future year)	N_1		spaces
Average daily utilization rate of parking spaces without TSE (for the future year)	AVR_1		percentage
Percentage of vehicles in non-TSE spaces using APU (for the future year)	P_{AUP}		percentage
Number of available parking spaces with TSE (for the future year)	N_2		spaces
Average daily utilization rate of parking spaces with TSE (for the future year)	AVR_2		percentage
Idling emission factor - current year	EF_I	9,116	gram/hour
Idling emission factor - future year	EF_I	9,053	gram/hour
Emission factor of using APU	EF_{AUP}	2,700	gram/hour

Table A-3. Results for Vehicle Fleet Electrification.

Output

Description	*Symbol*	*Value*	*Units*
Emissions Reduction Due to Control Strategy Implementation			
Daily CO_2 Emission Reduction - Base Year	ER	4,554,320	gram/day
		5.02	ton/day
Daily CO_2 Emission Reduction - Future Year	ER	5,678,280	gram/day
		6.26	ton/day
Assessment of Benefits Compared to Business as Usual (BAU) Scenario			
Daily CO_2 Emissions for Base Year - Business as Usual		8,074,320	gram/day
		8.90	ton/day
Daily CO_2 Emissions for Base Year - With Control Strategy		3,520,000	gram/day
		3.88	ton/day
Daily CO_2 Emissions for Future Year - Business as Usual		12,718,280	gram/day
		14.02	ton/day
Daily CO_2 Emissions for Future Year - With Control Strategy		7,040,000	gram/day
		7.76	ton/day
Daily CO_2 Emissions Reduction over Base Year BAU Scenario			
With Control Strategy in Future Year		1,034,320	gram/day
		1.14	ton/day

Input

Description	*Symbol*	*Units*	*Value*
Number of electrified vehicles	N_E	1000	vehicle
Number of electrified vehicles (for the future year)	N_E	2000	vehicle
Average daily VMT per vehicle	VMT_{AVE}	20	mile/day
Emission factor after replacement	EF_A	176	gram/mile
For Direct Input of Emissions Factors:			
Emission factor - current year	EF_B		gram/mile
Emission factor - future year			gram/mile
For Estimation from Lookup Tables:			
Select a speed to determine EF_B		30	mph
Select a road type to determine EF_B		1	
Emission factor - current year from the lookup table	EF_B	404	gram/mile
Emission factor - future year from the lookup table		318	gram/mile

Table A-4. Results for Transit Facilities.

Output

Description	Symbol	Value	Units
Emissions Reduction Due to Control Strategy Implementation			
Daily CO_2 Emission Reduction - Base Year	ER	2,387,449	gram/day
		2.63	ton/day
Daily CO_2 Emission Reduction - Future Year	ER	1,796,175	gram/day
		1.98	ton/day
Assessment of Benefits Compared to Business as Usual (BAU) Scenario			
Daily CO_2 Emissions for Base Year - Business as Usual		2,777,566	gram/day
		3.06	ton/day
Daily CO_2 Emissions for Base Year - With Control Strategy		390,117	gram/day
		0.43	ton/day
Daily CO_2 Emissions for Future Year - Business as Usual		2,187,544	gram/day
		2.41	ton/day
Daily CO_2 Emissions for Future Year - With Control Strategy		391,370	gram/day
		0.43	ton/day
Daily CO_2 Emissions Reduction over Base Year BAU Scenario			
With Control Strategy in Future Year		2,386,197	gram/day
		2.63	ton/day

Input

Description	Symbol	Value	Units
New transit ridership	N_{TR}	1000	person
Percentage of users of new/expanded transit services that previously were automobile drivers	$F_{T,SOV}$	80%	percentage
New transit VMT	VMT_T	300	VMT
New transit ridership (for the future year)	N_{TR}		person
Percentage of users of new/expanded transit services that previously were automobile drivers (for the future year)	$F_{T,SOV}$		percentage
New transit VMT	VMT_T		VMT
Average trip length	L	8.6	mile
For Direct Input of Emissions Factors:			
Emission factor of passenger vehicles - current year	EF_C		gram/mile
Emission factor of passenger vehicles - future year			gram/mile
Emission factor of transit buses - current year	EF_T		gram/mile
Emission factor of transit buses - future year			gram/mile
For Estimation from Lookup Tables:			
Select a speed to determine EF_B		30	mph
Select a road type to determine EF_B		2	
Emission factor - current year from the lookup table	EF_C		gram/mile
Emission factor - future year from the lookup table			gram/mile
Select a speed to determine EF_T		30	mph
Select a road type to determine EF_T		2	
Emission factor for gasoline transit buses - current year from the lookup table	$EF_{T,g}$	1,319	gram/mile
Emission factor for gasoline transit buses - future year from the lookup table		1,320	gram/mile
Emission factor for diesel transit buses - current year from the lookup table	$EF_{T,d}$	1,282	gram/mile
Emission factor for diesel transit buses - future year from the lookup table		1,289	gram/mile
Proportion of gasoline vehicles		50%	gram/mile
Proportion of diesel vehicles		50%	gram/mile
Emission factor for transit buses - current year from the lookup table	EF_T	1,300	gram/mile
Emission factor for transit buses - future year from the lookup table		1,305	gram/mile

Table A-5. Results for HOV Facilities.

Output

Description	*Symbol*	*Value*	*Units*
Emissions Reduction Due to Control Strategy Implementation			
Daily CO_2 Emission Reduction - Base Year	ER	31,844,610	gram/day
		35.10	ton/day
Daily CO_2 Emission Reduction - Future Year	ER	25,243,380	gram/day
		27.83	ton/day
Assessment of Benefits Compared to Business as Usual (BAU) Scenario			
Daily CO_2 Emissions for Base Year - Business as Usual		70,765,800	gram/day
		78.01	ton/day
Daily CO_2 Emissions for Base Year - With Control Strategy		38,921,190	gram/day
		42.90	ton/day
Daily CO_2 Emissions for Future Year - Business as Usual		56,096,400	gram/day
		61.84	ton/day
Daily CO_2 Emissions for Future Year - With Control Strategy		30,853,020	gram/day
		34.01	ton/day
Daily CO_2 Emissions Reduction over Base Year BAU Scenario			
With Control Strategy in Future Year		39,912,780	gram/day
		44.00	ton/day

Input

Description	*Symbol*	*Value*	*Units*
Total number of vehicles using HOV lanes	N_p	10000	vehicle/day
HOV occupancy requirement	AVO_A	2	person/veh
Existing average car occupancy	AVO_B	1.1	person/veh
Total number of vehicles using HOV lanes (for the future year)	N_p		vehicle/day
HOV occupancy requirement (for the future year)	AVO_A		person/veh
Existing average car occupancy (for the future year)	AVO_B		person/veh
Length of average trip length	L	11	mile
For Direct Input of Emissions Factors:			
Emission factor - current year	EF_B		gram/mile
Emission factor - future year			gram/mile
For Estimation from Lookup Tables:			
Select a speed to determine EF_B		70	mph
Select a road type to determine EF_B		2	
Emission factor - current year from the lookup table	EF_B	354	gram/mile
Emission factor - future year from the lookup table		280	gram/mile

Table A-6. Results for Mixed Use Developments.

Output			
Description	***Symbol***	***Value***	***Units***
Emissions Reduction Due to Control Strategy Implementation			
Daily CO_2 Emission Reduction - Base Year	ER	6,351,744	gram/day
		7.00	ton/day
Daily CO_2 Emission Reduction - Future Year	ER	5,002,481	gram/day
		5.51	ton/day
Assessment of Benefits Compared to Business as Usual (BAU) Scenario			
Daily CO_2 Emissions for Base Year - Business as Usual		66,502,508	gram/day
		73.31	ton/day
Daily CO_2 Emissions for Base Year - With Control Strategy		60,150,764	gram/day
		66.30	ton/day
Daily CO_2 Emissions for Future Year - Business as Usual		52,375,774	gram/day
		57.73	ton/day
Daily CO_2 Emissions for Future Year - With Control Strategy		47,373,293	gram/day
		52.22	ton/day
Daily CO_2 Emissions Reduction over Base Year BAU Scenario			
With Control Strategy in Future Year		19,129,215	gram/day
		21.09	ton/day

Input			
Description	***Symbol***	***Value***	***Units***
Land use 1: Area of office	LU_1	771487	sq. ft.
Land use 2: Area of retail	LU_2	141926	sq. ft.
Land use 3: Units of apartment	LU_3	702	unit
Average trip length	L	8.6	mile
For Direct Input of Emissions Factors:			
Emission factor - current year	EF_B		gram/mile
Emission factor - future year			gram/mile
For Estimation from Lookup Tables:			
Select a speed to determine EF		30	mph
Select a road type to determine EF		1	
Emission factor - current year from the lookup table	EF_B	404	gram/mile
Emission factor - future year from the lookup table		318	gram/mile

Table A-7. Results for Traffic Signal Retiming.

Output

Description	***Symbol***	***Value***	***Units***
Emissions Reduction Due to Control Strategy Implementation			
Daily CO_2 Emission Reduction - Base Year	ER	19,182,287	gram/day
		21.14	ton/day
Daily CO_2 Emission Reduction - Future Year	ER	19,008,800	gram/day
		20.95	ton/day
Assessment of Benefits Compared to Business as Usual (BAU) Scenario			
Daily CO_2 Emissions for Base Year - Business as Usual		615,056,869	gram/day
		677.98	ton/day
Daily CO_2 Emissions for Base Year - With Control Strategy		595,874,582	gram/day
		656.83	ton/day
Daily CO_2 Emissions for Future Year - Business as Usual		523,502,201	gram/day
		577.06	ton/day
Daily CO_2 Emissions for Future Year - With Control Strategy		504,493,401	gram/day
		556.10	ton/day
Daily CO_2 Emissions Reduction over Base Year BAU Scenario			
With Control Strategy in Future Year		110,563,468	gram/day
		121.87	ton/day

Input

Description	***Symbol***	***Value***	***Units***
Facility length	L	10	mile
Average daily traffic volume during peak hours	$V_{D,P}$	60000	vehicle/day
Average daily traffic volume during off-peak hours	$V_{D,OP}$	40000	vehicle/day
Average vehicle delay at intersection before retiming	D_B	0.2	hour/veh
Average vehicle delay at intersection after retiming	D_A	0.18	hour/veh
Average daily traffic volume during peak hours (for the future year)	$V_{D,P}$		vehicle/day
Average daily traffic volume during off-peak hours (for the future year)	$V_{D,OP}$		vehicle/day
Average vehicle delay at intersection before retiming (for the future year)	D_B		hour/veh
Average vehicle delay at intersection after retiming (for the future year)	D_A		hour/veh
Idling emission factor from MOVES for Year 2011	EF_I	9,591	gram/hour
Idling emission factor from MOVES for Year 2040		9,504	gram/hour
For Direct Input of Running Emissions Factors:			
Emission factor from MOVES for Year 2011	$EF_{B,P}$		gram/mile
Emission factor from MOVES for Year 2040			gram/mile
Emission factor from MOVES for Year 2011	$EF_{B,OP}$		gram/mile
Emission factor from MOVES for Year 2040			gram/mile
Emission factor from MOVES for Year 2011	$EF_{A,P}$		gram/mile
Emission factor from MOVES for Year 2040			gram/mile
Emission factor from MOVES for Year 2011	$EF_{A,OP}$		gram/mile
Emission factor from MOVES for Year 2040			gram/mile
For Estimation of Running Emissions Factors from Lookup Tables:			
Select a speed to determine emission factor (peak before retiming)		25	mph
Select a road type to determine emission factor (peak before retiming)		1	
Emission factor from MOVES for Year 2011	$EF_{B,P}$	453	gram/mile
Emission factor from MOVES for Year 2040		357	gram/mile
Select a speed to determine emission factor (off-peak before retiming)		35	mph
Select a road type to determine emission factor (off-peak before retiming)		1	
Emission factor from MOVES for Year 2011	$EF_{B,OP}$	379	gram/mile
Emission factor from MOVES for Year 2040		299	gram/mile
Select a speed to determine emission factor (peak after retiming)		25	mph
Select a road type to determine emission factor (peak after retiming)		1	
Emission factor from MOVES for Year 2011	$EF_{A,P}$	453	gram/mile
Emission factor from MOVES for Year 2040		357	gram/mile
Select a speed to determine emission factor (off-peak after retiming)		35	mph

Table A-8. Results for Bicycle Facilities.

Output

Description	***Symbol***	***Value***	***Units***
Daily Emission Reduction for Current year	ER	159,710	gram/day
		0.18	ton/day
Daily Emission Reduction for Future Year		182,129	gram/day
		0.20	ton/day

Input

Description	***Symbol***	***Value***	***Units***
Population (<0.25)	P_1	500	person
Population (0.25~0.50)	P_2	1000	person
Population (0.50~1.00)	P_3	5000	person
Bicycling rate	BR	2.0%	percentage
Increase rate (<0.25)	IR_1	1.93	constant
Increase rate (0.25~0.50)	IR_2	1.11	constant
Increase rate (0.50~1.00)	IR_3	0.39	constant
Population (<0.25) (for the future year)	P_1	800	person
Population (0.25~0.50) (for the future year)	P_2	1400	person
Population (0.50~1.00) (for the future year)	P_3	7000	person
Increase rate (<0.25) (for the future year)	IR_1		constant
Increase rate (0.25~0.50) (for the future year)	IR_2		constant
Increase rate (0.50~1.00) (for the future year)	IR_3		constant
Pecentage of adults in population	AR	80.0%	percentage
Average passenger car occupancy	AVO	1.4	adult person per ve
Average trip length	L	8.6	mile
For Direct Input of Emissions Factors:			
Emission factor - current year	EF_B		gram/mile
Emission factor - future year			gram/mile
For Estimation from Lookup Tables:			
Select a speed to determine EF		30	mph
Select a road type to determine EF		1	
Emission factor - current year from the lookup table	EF_B	404	gram/mile
Emission factor - future year from the lookup table		318	gram/mile

Table A-9. Highway Capacity Addition

Output			
Description	***Symbol***	***Value***	***Units***
Emissions Reduction Due to Control Strategy Implementation			
Daily CO_2 Emission Reduction - Base Year	ER	1,882,800	gram/day
		2.08	ton/day
Daily CO_2 Emission Reduction - Future Year	ER	-64,556,480	gram/day
		-71.16	ton/day
Assessment of Benefits Compared to Business as Usual (BAU) Scenario			
Daily CO_2 Emissions for Base Year - Business as Usual		123,045,360	gram/day
		135.63	ton/day
Daily CO_2 Emissions for Base Year - With Control Strategy		121,162,560	gram/day
		133.56	ton/day
Daily CO_2 Emissions for Future Year - Business as Usual		129,112,960	gram/day
		142.32	ton/day
Daily CO_2 Emissions for Future Year - With Control Strategy		193,669,440	gram/day
		213.48	ton/day
Daily CO_2 Emissions Reduction over Base Year BAU Scenario			
With Control Strategy in Future Year		-70,624,080	gram/day
		-77.85	ton/day

Input			
Description	*Symbol*	*Value*	*Units*
Facility length	L	10	mile
Duration of peak period	D_p	4	
Duration of peak period (for the future year)			
Average peak hour traffic volume - Base Year, without capacity addition	V_B	6000	vehicle/hour
Select a speed to determine emission factor		20	mph
Select a road type to determine emission factor		1	
Emission factor from MOVES for Year 2011	EF_B	513	gram/mile
Running emissions factors (Direct Input, Optional)			gram/mile
Average peak hour traffic volume - Base year, with capacity addition	V_A	8000	vehicle/hour
Select a speed to determine emission factor		35	mph
Select a road type to determine emission factor		1	
Emission factor from MOVES for Year 2011	EF_A	379	gram/mile
Running emissions factors (Direct Input, Optional)			gram/mile
Average peak hour traffic volume - Future Year, without capacity addition	V_B	8000	
Select a speed to determine emission factor		20	mph
Select a road type to determine emission factor		1	
Emission factor from MOVES for Year 2040	EF_B	403	gram/mile
Running emissions factors (Direct Input, Optional)			gram/mile
Average peak hour traffic volume - Future year, with capacity addition	V_A	12000	vehicle/hour
Select a speed to determine emission factor		20	mph
Select a road type to determine emission factor		1	
Emission factor from MOVES for Year 2040	EF_A	403	gram/mile
Running emissions factors (Direct Input, Optional)			gram/mile