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16. Abstract

A quick-response project-planning tool can be extremely valuable in anticipating the congestion, safety, emissions, and other impacts of large-scale network improvements and policy implementations. This report identifies the advantages and limitations of existing methods and toolkits for sketch-planning project evaluation. The report also describes the design and application of a new project evaluation toolkit, to assist transportation agencies and their consultants in the project planning phase. The toolkit is a spreadsheet-based application that offers users a familiar and powerful data manipulation interface for evaluation of abstracted networks' improvements and modifications, versus a base case scenario, relying largely on traffic counts. The toolkit includes a travel demand prediction module for destination, mode, time of day and route choices, across multiple user classes and implemented as a set of external C++ programs. The toolkit estimates vehicle emissions using an extensive spreadsheet database of EPA's MOBILE 6.2 emissions rates. Crash rates come from Texas-based models, and changes in traveler/consumer surplus (versus base case scenarios) are estimated using the Rule of Half. Estimates of link reliability also are available, and can be included in comprehensive benefit-cost metrics, which discount future impacts over time. The toolkit enables planners to comprehensively yet quickly anticipate and analyze the various impacts of diverse network improvement strategies.

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Comprehensive Evaluation of Transportation Projects: A Toolkit for Sketch Planning

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Products

Products associated with this project include the provision of a Toolkit User Workshop for TxDOT engineers and MPO planners held on June 30, 2010 at the TxDOT Planning Conference, held at the Hyatt Lost Pines in Bastrop, Texas. Though not a formally listed deliverable, a documentation guidebook for Toolkit use (described in Appendix G in this report) and associated code files are attached to this report on a CD, and will be useful to the reader.

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Chapter 1. Introduction

1.1 Background

Mobile source emissions, such as oxides of nitrogen, reactive organic gases, fine particulate matter, carbon monoxide, and various hazardous air pollutants, constitute a major fraction of anthropogenic emissions and are responsible for air quality concerns in hundreds of U.S. counties. The great majority of these counties lie in congested regions, where travel delays are rising steadily, and transportation systems are in need of improvement. Consequently, many states and regions must regularly and carefully consider the emissions impacts of proposed congestion mitigation strategies, vis-à-vis new roadway investments, transportation control measures (TCMs), and other policies and programs. Such emissions accounting is central to state implementation plans to ensure conformity with Clean Air Act Amendments and ultimately comply with National Ambient Air Quality Standards, which have been tightening. In addition, national energy and climate change policies loom on the horizon, in order to address natural resource depletion, energy security, and global warming considerations. Of course, adequate project financing and optimal resource allocation remain major goals of all departments of transport and related public agencies.

Within this context, it is important to anticipate, quantify, and communicate the benefits and costs of new, congestion-abating projects and strategies. While capacity additions to existing transportation systems may facilitate new and longer trips, thereby increasing total vehicle-miles traveled (VMT) in a region, these miles tend to occur at preferred times of day, to more attractive destinations and/or at lower cost. The travel time and cost savings, as well as added choice benefits for personal and commercial travelers, can be sizable, along with crash reductions and other benefits. Moreover, congestion mitigating projects can have important emissions benefits, by reducing stop-and-go driving; reducing energy demands; providing incentives for the use of transit, shared rides, and non-motorized modes; and encouraging more efficient travel patterns. Finally, as higher emitting vehicles are retired and those benefiting from more stringent emissions standards and better emissions control technologies are introduced, mobile source emissions are falling in nearly all urban regions. Procedures and tools are needed to permit early evaluation of transportation-project proposals, facilitate project prioritization, and enhance communication with all stakeholders.

As described in Chapter 2, a number of software packages with different functionalities and varying degrees of complexity are available to evaluate the traffic and emissions impacts of traffic control measures and network modifications. However, these tools are limited in their ability to examine the impacts of large infrastructure projects of the type being considered here. Specifically, the traffic flow impacts of large-scale infrastructure projects may result in changes to trip destination patterns, travel mode, route, and time of day choices. These traffic effects need to be evaluated at a network or sub-network level by time-of-day (TOD) rather than for a single corridor during a single TOD.

1.2 Objectives and Tasks

Sketch planning offers a quick and cost-effective approach for evaluating the economic and environmental impacts of congestion mitigation and other network improvement projects. A sketch network may be an abstracted or simplified topology, synthesizing only major arterials in the region, or it may be a sub-network, with most/all details of a neighborhood's or corridor's links, within a larger roadway system. Sketch planning approaches are especially appealing when evaluation of a regional network requires specialized expertise and/or is computationally demanding (and potentially distracting), possibly prohibiting evaluation of one or more scenarios within a limited timeframe. Sketch planning tools seek to provide planners with less complex platforms, facilitating quick-response and relatively informed decision making early on (e.g., before the NEPA review process).

This project addresses such aims by providing a sketch planning toolkit to assess the myriad impacts associated with a variety of network changes (including tolling). The toolkit's development process included synthesizing, extending, and enhancing existing and emerging knowledge on travel demand modeling, vehicle emissions modeling, vehicle crash prediction, and economic evaluation measures. Existing project evaluation tools emphasize impact estimation for traffic control measures and/or travel demand measures (TDMs), for small to moderate size projects, entailing a corridor perspective. To develop a successful tool for large-scale projects, the research team reviewed existing models and tools, as well as Texas project contexts. New methods were developed to estimate trip tables and traffic flow changes for abstracted network cases, and the means for converting these to emissions, crash, reliability, and traveler welfare impacts.

1.3 Report Outline

Due to the multi-disciplinary nature of the project, this report synthesizes knowledge and findings from multiple specializations, including constrained maximum entropy optimization, travel demand modeling, vehicle emissions modeling, economic benefit-cost analysis, and traffic safety analysis. All these modeling components and computational procedures are coded into or can be accessed through the resulting toolkit's spreadsheet-based platform.

Chapter 2 summarizes the research team's survey of previous methods and software experiences for evaluating travel demand and vehicle emissions. Chapter 3 presents a traffic-count-based travel demand estimation procedure for abstracted or "sketch" networks, for use in the toolkit's travel demand module. Chapter 4 describes the methodology for developing the toolkit's comprehensive list of MOBILE 6.2 emissions rates. Chapter 5 outlines the toolkit's overall design, structure, and functionality. Chapter 6 presents performance measures used for project evaluation, along with results of two multi-scenario case studies. Finally, Chapter 7 summarizes experts' comments during review of the toolkit's development, along with experiences during a practitioners' workshop for toolkit use and the team's recommendations for extending and refining the toolkit's capabilities. A variety of supplementary yet important information is provided in the appendices. Appendix A describes the link travel time variance function and the method of estimating the parameters of this function. Appendix B elaborates a solution algorithm for estimating the trip matrix based on traffic counts. Appendix C provides a list of demand elasticity values estimated based on the travel demand data from the Austin regional network. Appendix D presents a chart of emission rates used in the toolkit's vehicle emission database. Appendix E lists all the transportation-related parameter values used in the case studies. Appendix F summarizes all the external reviewers' comments and the project team's responses to these comments. Appendix G gives an introduction of the toolkit's user's guide, a detailed version of which can be found on the CD that accompanies this report.

Chapter 2. Synthesis of Existing Methods

2.1 Existing Methods of Estimating Travel Demand Changes

The traffic effects of network changes may be assessed using several different modeling approaches. Each is associated with a certain level of detail for required inputs, including existing flow rates, behavioral parameters, and project attributes. These inputs determine the underlying methods that can be adopted, which then influence necessary user expertise and the accuracy of the traffic and emissions estimates.

A number of different approaches were identified that span the gamut of input data needs (low resolution to a high resolution), methodologies (computationally simple to relatively sophisticated), necessary staff expertise, and impact assessment accuracy. The team identified five broad approaches within this domain, including (a) a simple elasticity approach for a single-corridor's traffic levels, (b) a sub-network-based elastic-demand approach, (c) a sub-network travel demand modeling approach, (d) a sub-network traffic simulation approach, and (e) full-network demand modeling. Table 2.1 provides details of input data needs for each approach, as well as the necessary staff expertise and assessment accuracy.

The elasticity approach is based on simplifying the existing transportation network to include the link of improvement and key parallel facilities within a certain distance (say one or two miles) of the improved facility. The traffic and project-related inputs for this approach are likely readily available to analysts. The methodology in this first approach is based on pivoting off current flows and speeds using elasticity measures to estimate "after-project" traffic flows and speeds, which can be translated into emissions changes.[1] Even an analyst with no special training should be able to apply a set of pre-defined elasticity measures that are likely to cover the range of possible "after-project" traffic scenarios to predict the direction and potential range of emissions changes and other project impacts.

At the other extreme, the full network demand modeling approach needs substantial input detail and staff expertise. This is the kind of analysis that is routinely undertaken as part of the Environmental Impact Assessment (EIA) process to show conformity with National Environment Policy Act (NEPA) requirements. Discussions with Project Monitoring Committee (PMC) indicated that the intent of the project was to develop a sketch-planning tool that could screen projects to identify those that appear promising to take further into the NEPA process for EIA. In other words, the intent is for the sketch-planning tool to be applied before or in the very early stages of a NEPA process. Thus, this fifth approach was ruled out as not viable for this project.

The intermediate (second, third and fourth) approaches in Table 2.1 correspond to methods that employ an abstracted (simplified) sub-network of the region's complete transportation network in the vicinity of the project (but not as simplified as in the first approach where only certain parallel facilities in very close proximity are considered). The second approach uses elasticity measures on certain sub-network flows to estimate "after-project" impacts, while the third applies a multi-step travel demand model on the sub-network. This approach involves estimating a sub-network trip table, followed by traffic assignment to estimate new link flows, or estimating trip table and link flows of the sub-network simultaneously. The fourth method uses microscopic traffic simulation. Given the data expectations for users of the toolkit developed here (e.g., only access to link flows and network link attributes), the fourth approach was pursued under this research project, with substantial success and a user-friendly interface (but requiring rather sophisticated coding).

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[1] The term "elasticity measures" is used loosely here, to provide a mechanism to pivot off current flows and/or speeds based on the project characteristics. For instance, these "elasticity measures" may be based on a percentage change in link flows due to a percentage change in level of service (obtained, for example, through repeated application of elasticities across destination, mode, and route dimensions) or may be based on a shift in link flows due to a certain change in level of service (obtained, for example, through the repeated application of level of service model coefficients or trade-off values across different travel dimensions to obtain an estimate of link flow change).

2.2 Emission Estimation Models

The collection of models reviewed includes a relatively long list of 22 models (in addition to MOBILE6.2 and MOVES). The list is shown below (in no particular order, and with developer/source shown in parentheses).

- MOSERS (Texas Transportation Institute/TxDOT)
- BenMAP (University of North Carolina at Chapel Hill)
- TDM Evaluation Model (FHWA/McTrans)
- TCM/Commuter Choice Model (COMMUTER developed by EPA)
- TCM Analyst (Texas Transportation Institute)
- CM/AQ Evaluation Model (University of North Carolina at Chapel Hill)
- CUTR_AVR (University of South Florida)
- TCM Tools (Sierra Research, JHK Associates, FHWA)
- Off-Net/PAQNE (COMSIS Corporation, PennDOT)
- ECO/Regulation XV Software (COMSIS Corporation, Cambridge Systematics)
- California Standard Methodology (COMSIS Corp.)
- RAQC Workbook (Regional Air Quality Council)
- MWCOG Sketch-Planning Methods (MWCOG)
- NCTCOG Sketch-Planning Methods (NCTCOG)
- IDAS (FHWA)
- SMART (COMSIS Corporation, Cambridge Systematics)
- STEAM (FHWA)
- SMITE (FHWA)
- IMPACTS (FHWA)
- TRIMMS (University of South Florida)
- HERS-ST (FHWA)
- Traffic Simulation Models (e.g., CORSIM, Paramics, Synchro/SimTraffic)
- Cal-B/C (System Metrics & Cambridge Systematics, for Caltrans)

Table 2.1: Existing Approaches for Estimating Travel Demand Changes

Analytical Approach	Input Requirements		Staff Expertise Needed	Impact Assessment Accuracy
	Existing Traffic Network	Project Characteristics		
Simple Elasticity Approach	Capacities and flows on key existing facilities (ex: substitute corridors within 2-mile radius).	Standard project details: Capacity, network connections, and demand management strategies employed (e.g., tolled or HOT) of new facilities.	Simplest of all approaches; no special background required by the analyst for using the tool.	Should be able to predict direction as well as range of the change in emissions.
Sub-network Elasticity Approach	A connected sub-network surrounding the new facility with link flows and capacities for the design year, ideally by time of day.	Standard project details. (See above.)	Slightly more complex, and analyst will have to identify the sub-network.	Should be able to predict the direction as well as range of change in emissions.
Sub-network Demand Travel Model Approach	A connected sub-network surrounding the new facility with link flows and capacities for the design year, ideally by time of day, trip table for the entire network.	Standard project details. (See above.)	Slightly more complex, and analyst will have to identify the sub-network and estimate sub-network trip table.	Should be able to predict the direction of change in emissions but accuracy of magnitude of change depends on the availability of trip table of entire network.
Sub-network Traffic Simulation Approach	A connected sub-network surrounding the new facility with link flows and capacities for the design year, ideally by time of day, trip table for the entire network.	Standard project details along with more detailed information, like lane and intersection geometries.	More complex, and analyst will have to identify sub-network and estimate sub-network trip table.	Should be able to predict the direction of change in emissions but accuracy of magnitude of change depends on the availability of trip table of entire network.
Full Scale Network Travel Demand Model	Entire coded network and trip table, travel time and cost skims, zone information (on jobs and household) and existing TDM parameters for the region.	Standard project details along with more detailed information, like lane and intersection geometries.	Most complex, and the analyst must be knowledgeable of various components of the travel demand model.	Should be able to predict the direction as well as magnitude of change in emissions.

The methodologies range from relatively statistically robust techniques to user-assumed parameters, for estimating changes in traffic flows. Each model was initially reviewed to assess whether its approach is transferable to and relevant for this project. Those using feasible, theoretically sound, and potentially applicable methods were identified as the most applicable points of reference. These are the following seven models (in alphabetical order):

- COMMUTER
- HERS-ST (Highway Economic Requirements System—State Version)
- IDAS (Intelligent Transportation Systems Deployment Analysis System)
- IMPACTS
- SMITE (Spreadsheet Model for Induced Travel Estimation)
- TCM Analyst (Traffic Control Measures Analyst)
- TRIMMS (Trip Reduction Impacts for Mobility Management Strategies)

Table 2.2 provides an overview of key characteristics for each of the seven models, and the remaining discussion in this section describes their methodologies. The models reflect a range of applications and analytical detail. While aspects of each appear potentially useful to this research project, all require significant modifications for applicability to the research topic at hand.

Five of the seven models noted in Table 2.2 estimate emissions and other impacts or changes due to a specific project, set of projects, and/or traffic control measures. These models are COMMUTER, TCM Analyst, IMPACTS, and HERS-ST. Each of the five models uses a similar approach to estimating emissions impacts. The basic procedure estimate changes in VMT, number of trips, vehicle types, and speeds, and then predict emissions changes and other impacts, typically using emission rates generated from MOBILE. In each of the models, users are permitted to provide regionally or locally applicable emission rates rather than use the default values provided in the model. When applicable, the models estimate changes in emissions due to changes in VMT and changes in the number of trips.

At a broad level there are two basic sources of emissions as related to vehicle travel. These are VMT-based emissions impacts and trip-based emissions impacts. The VMT-based emissions impacts are those resulting from changes in VMT due to extended vehicle trips and/or additional vehicle trips. These are calculated separately from trip-based emissions impacts because vehicles are assumed to already be in a "running" mode, which means their rate of emissions is less than the rate when a vehicle is started (e.g., cold start mode). The trip-based emissions estimate is based on the change in the number of trips, which is equated to the change in the number of cold starts. Models that predict both sources of emissions calculate these impacts separately until the final step and then sum the results. The VMT-based emissions impacts tend to be applicable to all projects; however, trip-based emissions estimates are only applicable to projects with the potential to change the number of trips occurring (e.g., carpool incentives).

As noted earlier, most of the models reviewed are either limited in scope to single corridor analysis (such as HERS-ST or Cal-BC) or very detailed (such as regional transportation planning models). The FHWA's Highway Economic Requirements System—State Version (HERS-ST) evaluates project impacts based on pavement quality, operating costs, safety costs, travel time changes, and emissions. Emissions of VOC, NOx, SOx, and $PM_{2.5}$ are estimated based on vehicle speeds and use MOBILE-generated emissions rates (FHWA, 2005). HERS-ST estimates changes in travel demand using elasticities (i.e., the "rebound effect," or latent demand effects, as network travel times fall). HERS-ST estimates simple link-level demand (ignoring link connections) but does not contain an embedded travel demand model to account for shifting traffic patterns on parallel or alternate routes between origin-destination pairs and is therefore more suited for corridor analysis, rather than network analysis. Another model that the project team drew upon when developing the project toolkit was the California Life-Cycle Benefit/Cost Analysis Model (Cal-B/C), developed by System Metrics Group in association with Cambridge Systematics for the California Department of Transportation (2009). This spreadsheet-based toolkit quickly estimates changes in crashes, emissions, travel time savings, and operating costs. Cal-B/C requires users to input before and after traffic link volumes, thus requiring additional (travel-demand) analysis outside the tool. Among all the tools, however, Cal-B/C comes closest to the style and rigor of the toolkit developed under this project—but without any demand modeling and with simpler calculations of emissions, crashes, and traveler welfare impacts.

Many transportation planning models are customized for specific metropolitan planning organizations (MPOs). Individual models vary widely in methodology and capabilities, from detailed traveler activity-based models, to simpler zonal production-attraction gravity models with logit models or fixed shares for mode and time of day (TOD) choices. Such models require many detailed inputs and often rely on trip generation information obtained from area demographics. They also can contain tens of thousands of highway links and take significant time and processing power to run a single scenario alternative. While they seek to provide robust and defensible traffic volume estimates, they do not directly offer key summary measures for project analysis, including crash prediction and travel time reliability. Of course, they can be integrated with other toolkits, such as the Environmental Protection Agency's (EPA) new MOVES to assess vehicle emissions.

As noted above, project analysis toolkits that were examined include EPA's COMMUTER (Carlson et al., 2005), which analyzes emissions impacts from commuter-related strategies (e.g., carpools, transit, bicycle programs, etc.) but does not use any direct network information; DeCorla-Souza's IMPACTS (1999), which focuses on corridor capacity expansion, tolling, transit, and bicycle projects to estimate congestion, emissions (HC, CO, and NOx), fuel consumption, and vehicle crash impacts; and FHWA's STEAM (Cambridge Systematics, 2000), which uses a four-step planning model to anticipate changes in congestion, accessibility, crashes, and emissions. STEAM relies on a user-specified trip table, as well as zonal production and attraction information, as key inputs.

All these existing models are limited in some important ways, such as emphasizing corridor calculations at just one or two times of day (rather than recognizing network impacts, including route changes) and relying on fixed trip tables (rather than allowing for latent demand by origin-destination pair). Other modeling options (e.g., MPO demand models) require too much detail (such as trip productions and attractions by zone, rather than simply link counts [which all U.S. regions should have]). None recognizes reliability, safety impacts, emissions, and traveler welfare all together. A new modeling paradigm is needed, and the research team's approach to this problem is detailed in the following sections of this report.

Table 2.2: Summary of Features of the Emissions Estimation Models

Models	Format	Application	Methodologies		
			Traffic Demand Estimates	**Traffic Flow Estimates**	**Emissions Calculations**
COMMUTER	Spreadsheet developed by the EPA	Tool for analyzing travel and emissions impacts of employer-based voluntary TDM strategies.	Uses an incremental logit procedure to determine the change in VMT. For some strategies uses look-up tables based on empirical evidence.	Does not estimate changes in traffic flow characteristics.	Uses look-up tables containing factors derived from MOBILE based on changes in number of trips, VMT, and speed (input provided by user).
HERS-ST	Software program created by the FHWA	Engineering economic analysis tool used to identify the most cost-effective mix of improvements.	Calculates a generalized price of travel and uses price elasticity measures (short-run and long-run) to quantify the relationship between generalized price of travel and traffic volume.	Calculates average effective speed by modifying unconstrained speeds to account for effects of congestion and traffic control devices.	Calculates emissions based on vehicle class, average effective speed, and functional roadway class. Look-up table with parameters included in model.
IDAS	Software program developed by the FHWA	Sketch-planning analysis tool used to assess the relative benefits and costs of ITS investments.	Uses an incremental logit procedure, which ideally is able to make use of coefficients from the regional travel demand model.	Uses trip assignment algorithm to reach user-equilibrium. Estimates travel time based on BPR method. Speeds are based on volume-delay curves and facility type.	User inputs MOBILE emissions factors by speed range or model defaults are used.
IMPACTS	Series of spreadsheets distributed by the FHWA	Screening tool to evaluate the impacts of multimodal alternatives. Produces benefits/cost estimate for each alternative.	Same methodology as SMITE.	Same methodology as SMITE.	Calculates emissions based on changes in VMT, speed and number of cold starts. User provides emissions rates or model includes a set of default rates.
SMITE	Spreadsheet created by the FHWA	Sketch-planning tool used to evaluate highway capacity expansions in an urban setting. Produces benefits/cost estimate for each alternative.	Accounts for diverted traffic by redistributing traffic to achieve relatively similar levels of congestion on facilities in the study area (based on principles in NCHRP 255). Accounts for induced traffic using elasticity measures.	Estimates changes in speeds using relationship between speed and ADT/Capacity ratio.	Does not directly calculate emissions impacts. Outputs can be used to calculate change in emissions.
TCM Analyst	Spreadsheet developed by TTI	Sketch-planning tool to estimate emissions benefits of TCMs.	Uses elasticity measures to relate change in cost/travel time to changes in VMT.	Uses elasticity measures to relate changes in VMT to changes in speed.	Uses MOBILE emissions factors based on VMT, speed, and number of trips.
TRIMMS	Spreadsheet created and distributed by University of South Florida	Sketch-planning tool used to perform benefits/cost assessment for travel demand management strategies.	Uses elasticity measures of car fuel demand, car travel demand, and car travel time with respect to transit travel time to calculate changes in traffic volume.	Does not estimate changes in traffic flow characteristics.	Does not directly calculate emissions impacts. Outputs can be used to calculate change in emissions.

Chapter 3. The Toolkit's Travel Demand Model Specification

This chapter provides a detailed description for the models and solution algorithms for the sub-network travel demand modeling procedure used in the toolkit (Figure 3.1). The aim of developing this procedure is to provide a cost-effective modeling tool that can closely mimic full-network demand estimation results across different roadway facilities, time-of-day periods, and changed network conditions, while reducing computing time and demands on staff expertise. Demand model outputs include distributions of traffic flows by O-D pair, route, and mode, over individual links and times of day. The computational effort required to run the sub-network model is much lower than for its full-network counterpart; however, the code runs fast enough that one could conceivably have 1,000 or more links coded, elastic demand modeled, and networks equilibrated (with impacts analysis and economic accounting [e.g., cost-benefit ratios] quickly computed in sequence).

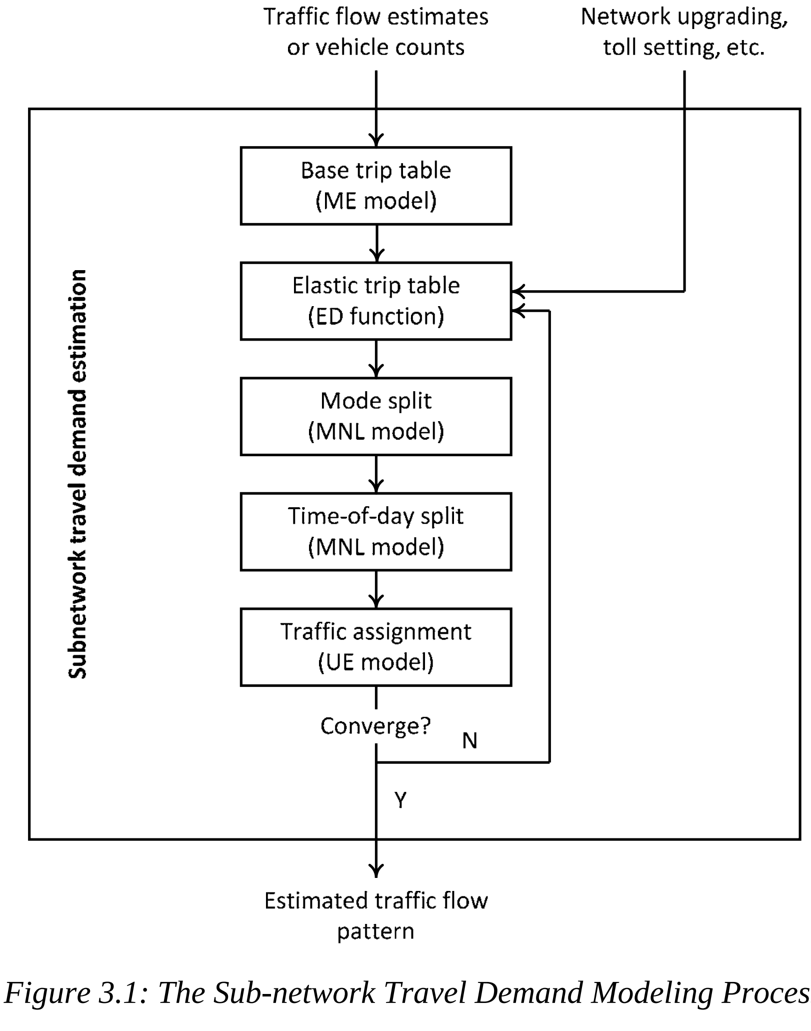
Traffic flow estimates or vehicle counts
Network upgrading, toll setting, etc.
Subnetwork travel demand estimation
Base trip table (ME model)
Elastic trip table (ED function)
Mode split (MNL model)
Time-of-day split (MNL model)
Traffic assignment (UE model)
Converge?
N
Y
Estimated traffic flow pattern

Figure 3.1: The Sub-network Travel Demand Modeling Process

As an overview, the demand modeling procedure in the sub-network model is depicted by the sequential steps and iterative process shown in Figure 3.1. The first step estimates the base O-D trip table, based on the link flow rates from a complete-network traffic assignment or link traffic counts from field measurements (e.g., the Highway Performance Monitoring System's AADT values). Future-year travel demands between each O-D pair for the base-case (no-build) option are based on a user-assumed growth rate. The second step estimates cost-dependent elastic O-D trip rates for all other scenarios, by pivoting off of the base-case trip rates. The third step, mode split, distributes the O-D trip rates (as developed in the second step) into different transportation modes, such as drive-alone, shared-ride (including two travelers and three-plus travelers in a vehicle, if further split is needed [for HOV lane settings, for example]), and transit. The fourth step produces trip tables by time of day for each transportation mode. The fifth step assigns these various trip tables (by vehicle type, traveler class, travel mode, and time of day) to the abstracted/coded network under the user-equilibrium principle. It should be noted here that the last four steps (i.e., the second through fifth steps) form a supply-demand interaction loop and are conducted iteratively, so that computations of trip shares in the second, third, and fourth steps are consistent with the time-and-cost outputs of the fifth step. In other words, supply-demand interactions are treated with "full feedback" (rather than just equilibrating travel times and costs in the fifth step, across routes, leaving trip tables fixed).

While the first step involves a one-time, one-period trip table estimation event (i.e., typically an aggregate estimation over different times of day, travel modes and routes for a 24-hour period), all other steps are part of an iterative process with feedback, to ensure that flows and costs are in equilibrium, between different time-of-day periods, between different travel modes, and between alternative travel routes connecting all O-D pairs. This feedback process iterates over the last four steps until equilibrium between traffic flows and travel costs is reached. In particular, the consistency can be evaluated by checking whether the average difference of the traffic flows between consecutive iterations satisfy a pre-specified gap criterion ε: $\sum_d \sum_a \frac{|v_{a,d}^{n+1} - v_{a,d}^{n}|}{v_{a,d}^{n+1}} / (|A||D|) < \varepsilon$, where n is the iteration number, $v_{a,d}^{n}$ is the traffic flow rate of link a during time-of-day period d at iteration n, and A and D are the sets of links and time-of-day periods, respectively.

3.1 Modeling Assumptions and Settings

For the discussion convenience, we first introduce the notation used throughout this chapter, including data sets, parameters, and variables. Both the input data sets and parameters should be specified by users in the Excel interface. A set of default parameter values are also provided.

Table 3.1: Notation Used in the Travel Demand Model

Sets	
N	Set of nodes, $N = \{n\}$
A	Set of links, $A = \{a\}$
I	Set of origin nodes, $I = \{i\}$
J	Set of destination nodes, $J = \{j\}$
P_{ij}	Set of paths connecting origin node i and destination j, $P_{ij} = \{p\}$
K	Set of traveler value-of-time (and value-of-reliability) classes, $K = \{k\}$, where, for example, $k = 1$ (high value of time), $k = 2$ (medium value of time), and $k = 3$ (low value of time)
M	Set of transportation modes, $M = \{m\}$, where, for example, $m = 1$ (drive-alone), $m = 2$ (shared-ride), and $m = 3$ (transit),
D	Set of time-of-day periods, $D = \{d\}$, where, for example, $d = 1$ (morning peak period), $d = 2$ (midday period), $d = 3$ (afternoon peak period), and $d = 4$ (other time-of-day period)
Variables	
x_{ij}	Flow rate from origin i to destination j
$x_{ij,d}^{b}$	Flow rate from origin i to destination j during time-of-day period d in the base network scenario
$y_{ij,d}^{b}$	Auxiliary flow rate from origin i to destination j during time-of-day period d in the base network scenario
$f_{ij,p,d}^{b}$	Flow rate along path p connecting origin i to destination j during time-of-day period d in the base network scenario
$x_{ij,d}$	Flow rate from origin i to destination j during time-of-day period d
$f_{ij,p,d}$	Flow rate along path p connecting origin i to destination j during time-of-day period d
$v_{a,d}$	Flow rate on link a during time-of-day period d
$x_{ij,d}^{k}$	Flow rate of traveler class k from origin i to destination j during time-of-day period d
q_{ij}^{k}	Trip rate of traveler class k from origin i to destination j
w_{ij}^{k}	Average vehicle occupancy rate of traveler class k from origin i to destination j
$x_{ij,m}^{k}$	Flow rate of traveler class k in transportation mode m from origin i to destination j
$w_{ij,m}^{k}$	Average vehicle occupancy rate of traveler class k in transportation mode m from origin i to destination j

$x_{ij,d}^{b,k}$	Flow rate of traveler class k from origin i to destination j during time-of-day period d in the base network scenario
$f_{ij,p,d}^{k}$	Flow rate of traveler class k along path p connecting origin i to destination j during time-of-day period d
$v_{a,d}^{k}$	Flow rate of traveler class k on link a during time-of-day period d
$x_{ij,m,d}^{k}$	Flow rate of traveler class k in transportation mode m from origin i to destination j during time-of-day period d
$f_{ij,p,m,d}^{k}$	Flow rate of traveler class k in transportation mode m along path p connecting origin i to destination j during time-of-day period d
$v_{a,m,d}^{k}$	Flow rate of traveler class k in transportation mode m on link a during time-of-day period d
$t_{ij,p,d}$	Travel time along path p connecting origin i to destination j during time-of-day period d
$t_{a,d}$	Travel time on link a during time-of-day period d
$r_{ij,p,d}$	Travel time variance (unreliability) along path p connecting origin i to destination j during time-of-day period d
$r_{a,d}$	Travel time variance (unreliability) on link a during time-of-day period
$s_{ij,p,m,d}$	Monetary cost associated with a traveler in transportation mode m using path p connecting origin i to destination j during time-of-day period d
$s_{a,m,d}$	Monetary cost associated with a traveler in transportation mode m using link a during time-of-day period d
$g_{ij,d}^{k}$	Average generalized cost (over transportation modes) associated with a traveler of class k from origin i and destination j during time-of-day period d
$g_{ij,d}^{b,k}$	Average generalized cost associated with a traveler of class k from origin i and destination j during time-of-day period d in the base network scenario
$g_{ij,m}^{k}$	Average generalized cost (over time-of-day periods) associated with a traveler of class k in transportation mode m traveling from origin i to destination j
$g_{ij,m,d}^{k}$	Generalized cost associated with a traveler of class k in transportation mode m traveling from origin i and destination j during time-of-day period d
$g_{ij,m,d}^{b,k}$	Generalized cost associated with a traveler of class k in transportation mode m traveling from origin i and destination j during time-of-day period d in the base network scenario
$g_{ij,p,m,d}^{k}$	Generalized cost associated with a traveler of class k in transportation mode m using path p connecting origin i to destination j during time-of-day period d
$g_{a,m,d}^{k}$	Generalized cost associated with a traveler of class k in transportation mode m using link a during time-of-day period d
$P_{ij,m}^{k}$	Probability of a traveler of class k choosing transportation mode m

$P_{ij,m,d}^{k}$	Probability of a traveler of class k in transportation mode m choosing time-of-day period d
Parameters	
α, β	Parameters of the link travel time function (i.e., the link performance or volume-delay function)
σ, γ, τ	Parameters of the link travel time variance function
VOT^{k}	Value of travel time of travelers of class k
VOR^{k}	Value of travel time reliability of travelers of class k
W	Ratio of the value of travel time variance to the value of travel time mean
$\delta_{ij,p}^{a}$	Link-path incidence indicator (equals 1 if link a is part of path p between zones i & j; 0 otherwise)
η_d	Elasticity of O-D flow rate with respect to O-D travel cost during time-of-day period d
$p_{ij,d}^{b,k}$	Proportion of travelers of class k in the traveling population from origin i to destination j during time-of-day period d in the base network scenario
$P_{ij,m}^{b,k}$	Probability of a traveler of class k choosing transportation mode m in the base network scenario
$P_{ij,m,d}^{b,k}$	Probability of a traveler of class k in transportation mode m choosing time-of-day period d in the base network scenario
λ_m	Scale parameter of the incremental logit model of mode choice
λ_d	Scale parameter of the incremental logit model of time-of-day choice

It should be noted that trip or flow rates may be represented in person-trips or vehicle-trips across the travel demand modeling procedure, depending on the requirement of the specific modeling step. In particular, the flow rates in the first, second, fourth, and fifth steps are in vehicle-trips, while trip rates in the third step are in person-trips. For discussion consistency, this report uses the term *flow rates* when referring to *vehicle-trips* and the term *trip rates* when referring to *person-trips*, unless stated otherwise. Because of the mixed use of vehicle-trips and person-trips throughout the modeling procedure, necessary conversions occur at two places: 1) a conversion process for O-D trip rates from vehicle-trips to person-trips is required between the second and third trips; and 2) the third step is designed to produce flow rates in vehicle-trips from person-trips.

While the mode split process is specified in the third step, the framework does not explicitly model a separate transit network because the toolkit assumes all transit travel is by bus, on the coded highway network. Thus, travel times experienced by transit users are assumed to match those of other vehicles in the modeled network, for each O-D pair.

The traffic distribution patterns of each of the four steps in the loop process are aggregated results of individual travel choices. Random utility maximization (or random cost minimization) theory is very common in travel demand modeling and essentially was used to assign mode and time of day user choices, based on incremental logit assumptions. The model controls for (average or expected) travel time, and monetary cost in the observed part of the disutility function (or generalized cost function in this text) for time-of-day, mode, and route choices in the modeling procedure[2]. The monetary cost includes tolls and operating costs (including fuel, maintenance, depreciation, and other mileage-dependent costs) and is evaluated in dollars. The monetary cost may differ across modes on the link and route levels. Flow-dependent link travel time is evaluated based on the popular BPR functional form:

$$t_a = t_a^0 \left(1 + \alpha \left(\frac{v_a}{c_a}\right)^{\beta}\right) \qquad \forall a \qquad (3.1)$$

where t_a^0 is the free-flow travel time of link a, and α and β are function parameters. The default values of these parameters we set for toolkit applications are $\alpha = 0.85$ and $\beta = 5.5$, based on NCHRP Report 365 (Martin and McGuckin, 1998). Meanwhile, characterization of travel time (un)reliability comes via estimates of link travel time variance, which appears to have a flow-dependent functional form similar to the BPR function (though shifted by a term γ):

$$r_a = r_a^0 \left(1 + \delta \left(\gamma + \frac{v_a}{c_a}\right)^{\tau}\right) \qquad \forall a \qquad (3.2)$$

where r_a^0 is the free-flow travel time variance of link a, and σ, γ and τ are function parameters.

We calibrated the parameters of the formula in (3.2) (where $\delta = 2.3$, $\gamma = 0.7$, and $\tau = 8.4$, based on the traffic data provided by Cambridge Systematics (Margiotta, 2009). More details of the parameter calibration for the travel time variance function can be found in Appendix A.

Nevertheless, in terms of the current state of the practice, we do not explicitly incorporate the travel time (un)reliability into individual's travel choice behavior. Thus, the observed parts of the generalized cost function on the link and path levels are as follows:

$$\begin{aligned} g_{a,m,d}^{k} &= VOT^{k} \cdot t_{a,d} + s_{a,m,d} \\ &= VOT^{k} \cdot t_a\big(v_{a,d}\big) + s_{a,m,d} \qquad \forall a, m, d, k \qquad (3.3) \end{aligned}$$

$$\begin{aligned} g_{ij,p,m,d}^{k} &= VOT^{k} \cdot t_{ij,p,d} + s_{ij,p,m,d} \\ &= \sum_{a} \big(VOT^{k} \cdot t_a\big(v_{a,d}\big) + s_{a,m,d}\big)\delta_{ij,p}^{a} \qquad \forall i, j, p, m, d, k \qquad (3.4) \end{aligned}$$

where VOT^{k} is the value of travel time traveler class k, respectively. It is readily known that the path-level cost function given above implies an additive property for all the cost terms, which allows that link travel time and monetary cost are all additive along a route. Thus, $t_{ij,p,d} = \sum_a t_{a,d}\delta_{ij,p}^{a}$ and $s_{ij,p,m,d} = \sum_a s_{a,m,d}\delta_{ij,p}^{a}$.

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[2] A model specification allowing for route choices based on the sum of unreliability across each path's links (using variance in travel time to characterize unreliability) was also tested by the research team, and can be easily coded. However, few travelers have solid information on the variance or unreliability in most links' and routes' travel times, so it seems unrealistic to allow for this. Moreover, the model's equations for variance are based on freeway observations that do not go much past v/c = 1.1, so these may not extrapolate well as networks congest further.

3.2 Base Trip Matrix Estimation

A number of studies have addressed important theoretical and practical issues regarding network abstraction (e.g., Eash et al., 1983; Kaplan et al., 1984; Chan, 1976; Chan et al., 1989; Haghani and Daskin, 1984, 1986; Taylor et al., 1988; and Rogus, 1996). Nevertheless, information on sub-network travel demand analysis remains quite limited (Dowling and May, 1985; Zhou et al., 2006). Given a sub-network extracted from a larger network and known traffic flows (by link only) in the sub-network, the research team needed to determine a methodology to ascertain the sub-network's trip table, as a data prerequisite for later modeling tasks. The following discussion details the method developed for the project's specific sub-network abstracted network requirements.

A trip table is an aggregation of individual trip makers' decisions to travel and destination choices. In a sub-network, trip tables typically are rather small (e.g., with 40 zones, rather than 1,000), and a relatively high share of trips originate from or terminate in "external" (edge) zones (where the true origins and destinations live beyond the sub-network's physical boundaries). In standard travel demand modeling practice, flows to and from these external zones are generally held fixed. This heroic assumption is clearly inadequate within the context of sub-network modeling, because many (or most or nearly all) trips can begin or end well beyond the sub-network's borders. Essentially, trips involving external zones can change routes that lead to different entry and exit points from the sub-network (and new sub-network trips altogether [i.e., trips previously entirely outside the sub-network]); such travelers wish to take advantage of shortened travel times or costs within the sub-network. To accommodate such supply-demand relationships in the sub-network (including local changes in trip generation and attraction), elastic demand equations between all O-D pairs were assumed, as a function of generalized cost and pivoting off base-trip-table demand levels.

Given a complete set of estimated or measured link flow rates, $\hat{v}_{a,d}$, $a \in A$, for each time-of-day d, the model uses the following maximum entropy model for the base trip table estimation problem:

$$\max \quad -\sum_{ij}\left(x_{ij,d}^{b} \ln x_{ij,d}^{b} - x_{ij,d}^{b}\right) \qquad \forall d \qquad (3.5)$$

$$\text{or min} \quad \sum_{ij}\left(x_{ij,d}^{b} \ln x_{ij,d}^{b} - x_{ij,d}^{b}\right) \qquad \forall d \qquad (3.6)$$

$$\text{subject to} \quad \sum_{ij}\sum_{p} f_{ij,p,d}^{b}\delta_{ij,p}^{a} = \hat{v}_{a,d} \qquad \forall a, d \qquad (3.7)$$

$$f_{ij,p,d}^{b} \geq 0 \qquad \forall i, j, p, d \qquad (3.8)$$

and O-D flow rate $x_{ij,d}^{b}$ is defined as

$$x_{ij,d}^{b} = \sum_{p} f_{ij,p,d}^{b} \qquad \forall i, j, d \qquad (3.9)$$

where $f_{ij,p,d}^{b}$ is the flow rate along path p connecting origin i and destination j.

The Frank-Wolfe algorithm (Frank and Wolfe, 1956) was adapted to solve the maximum entropy problem defined above. The modified algorithmic steps for the maximum entropy problem are as follows:

Step 0 **(Initialization):** Find an initial feasible O-D trip matrix. One possible initial trip matrix can be obtained by setting $x_{ij,d}^{b,0} = \hat{v}_{a,d}$, if nodes i and j are the head and tail nodes of some link a, (i.e., $a = (i,j)$, and $x_{ij,d}^{b,0} = 0$, for all other O-D pairs). Set iteration counter to $n = 1$.

Step 1 **(Direction finding):** Find an auxiliary trip matrix $y_{ij,d}^{b}$, $\forall i \in I$, $j \in J$, by solving the following linearized problem:

$$\min \sum_{ij} y_{ij,d}^{b} \ln x_{ij,d}^{b,n} \qquad \forall d \tag{3.10}$$

$$\text{subject to} \quad \sum_{ij} \sum_{p} f_{ij,p,d}^{b} \delta_{ij,p}^{a} = \hat{v}_{a,d} \qquad \forall a, d \tag{3.11}$$

$$f_{ij,p,d}^{b} \geq 0 \qquad \forall i, j, p, d \tag{3.12}$$

where $y_{ij,d}^{b}$ is defined as

$$y_{ij,d}^{b} = \sum_{p} f_{ij,p,d}^{b} \qquad \forall i, j, d \tag{3.13}$$

Step 2 **(Line search):** Find an optimal θ value for $0 \leq \theta \leq 1$ by solving the following line search problem:

$$\min \sum_{rs} \left[x_{ij,d}^{b,n} + \theta\left(y_{ij,d}^{b} - x_{ij,d}^{b,n}\right)\right] \ln\left[x_{ij,d}^{b,n} + \theta\left(y_{ij,d}^{b} - x_{ij,d}^{b,n}\right)\right] - \left[x_{ij,d}^{b,n} + \theta\left(y_{ij,d}^{b} - x_{ij,d}^{b,n}\right)\right] \tag{3.14}$$

$$\text{subject to} \quad 0 \leq \theta \leq 1 \tag{3.15}$$

Step 3 **(Solution update):** Set $x_{ij,d}^{b,n+1} = x_{ij,d}^{b,n} + \theta\left(y_{ij,d}^{b} - x_{ij,d}^{b,n}\right)$.

Step 4 **(Convergence test):** If a prespecified convergence criterion is met (e.g., $\sum_{ij} \frac{\left|x_{ij,d}^{b,n+1} - x_{ij,d}^{b,n}\right|}{x_{ij,d}^{b,n+1}} / \sum_{ij}\left|P_{ij}\right| < \varepsilon$, where $\sum_{ij} \frac{\left|x_{ij,d}^{b,n+1} - x_{ij,d}^{b,n}\right|}{x_{ij,d}^{b,n+1}} / \sum_{ij}\left|P_{ij}\right|$ simply represents the average relative O-D flow difference over the network between consecutive iterations and ε is the prespecified allowable gap error), stop; otherwise, set $n = n + 1$ and go to step 1.

It should be noted that the computational bottleneck of the Frank-Wolfe algorithm in solving the maximum entropy problem is the linearized maximum entropy subproblem specified in step 1. The standard linear programming (LP) solution method—the simplex method—may not be directly applied to this problem, because such methods require the enumeration of all possible path flows between each O-D pair. For this reason, an efficient approach that avoids path enumeration was deemed required; otherwise, algorithm application for this maximum entropy problem will be limited to sub-networks of very small size only (e.g., 50 links). The toolkit relies on a column generation approach to solve the linearized subproblem; this approach generates path flows only as needed, within the solution framework of the revised simplex method (see Dantzig, 1963; and Bazaraa et al., 1990). The detailed solution procedure of the column generation approach is given in Xie and Kockelman (2009) and Xie et al. (2010).

3.3 Elastic Trip Matrix Estimation

As noted earlier, a sub-network's trip table essentially is a synthetic aggregation of different pieces of trips, including internal-internal trips, internal-external trips, external-internal trips, and external-external trips (where modeled external trips originate or end outside the sub-network, but load subnet links). For those modeled trips with either their origin or destination nodes outside the sub-network, traveler choices relate to more than variables arising in the sub-network. Given the many unmodeled opportunities that exist for mode, route, time of day, and trip generation effects outside the modeled sub-network, one can expect higher demand elasticities within the sub-network than when modeling a much larger network. For example, trips can avoid the sub-network all together, or suddenly appear on the subnet once it is enhanced. If one were modeling the larger region, it is unlikely many trips would suddenly emerge (or disappear, in the case of suddenly impaired networks [e.g., reduced capacities during roadway construction projects]). The toolkit assumes the following elastic demand function for anticipating such variable O-D flow rates:

$$\ln \frac{x_{ij,d}^{k}}{x_{ij,d}^{b,k}} = \eta_d \ln \frac{g_{ij,d}^{k}}{g_{ij,d}^{b,k}} \qquad \forall i, j, d, k \qquad (3.16)$$

$$\text{or} \quad x_{ij,d}^{k} = x_{ij,d}^{b,k} \left(\frac{g_{ij,d}^{k}}{g_{ij,d}^{b,k}} \right)^{\eta_d} \qquad \forall i, j, d, k \qquad (3.17)$$

where $x_{ij,d}^{k}$ and $x_{ij,d}^{b,k} = p_{ij,d}^{b,k} x_{ij,d}^{b}$ are the O-D flow rates of traveler class k from origin i to destination j during time-of-day period d in the upgraded-network and base-network scenarios, respectively, and $\Delta x_{ij,d}^{k} = x_{ij,d}^{k} - x_{ij,d}^{b,k}$ is the change in O-D flow rate (due to network upgrading). Here, the fraction of travelers of class k in the population, $p_{ij,d}^{b,k}$, should be provided by the analyst ahead of time. For simplicity, the analyst may provide a common $p_{ij,d}^{b,k}$ value, $p^{b,k}$, between all O-D pairs and across different times of day.

The elasticity of demand in time period d, η_d, is key to determining demand changes as a function of travel cost and time changes. The period-dependent elasticity values were estimated using roughly millions of predicted changes in flow rates between Austin's 1,074 traffic analysis zones (TAZs) from a few network upgrade scenarios (as documented in Lemp and Kockelman, 2009). The following estimates are used as toolkit default values (though they may be over-written by the analyst): $\eta_{d=1}$ = -0.50 (morning peak period), $\eta_{d=2}$ = -0.85 (midday period), $\eta_{d=3}$ = -0.63 (afternoon peak period), and $\eta_{d=4}$ = -0.85 (other time-of-day period). In other words, if travel times for all times of day *fall* uniformly by 10% between an O-D pair, one can expect roughly a 5% demand *increase* in the AM peak on the low side, and an 8.5% increase during the off-peak times of day (mid-day and other). Of course, one may expect more responsiveness, as the sub-network's size falls (as route choices play a larger role than new trips). More details on how these elasticity values were estimated using the Austin data can be found in Appendix C.

O-D flow rates are then summed over all time-of-day periods and average vehicle occupancy rates are applied (with rates obtained from step 3 of the last iteration) to convert the flow rates in vehicle trips to the trip rates in person trips such that:

$$q_{ij}^{k} = w_{ij}^{k} \sum_{d} x_{ij,d}^{k} \qquad \forall i, j, k \qquad (3.18)$$

where w_{ij}^{k} is the average vehicle occupancy rate for travelers of class k from origin i to destination j.

3.4 Mode Split

The trip table (in person-trips for each traveler class) is segmented by mode and time of day. This section describes the incremental logit model used to determine the mode split, and time-of-day split is discussed in the next section.

The toolkit uses an incremental version of a multinomial logit (MNL) model for transportation mode splits, and these are specified for each traveler class k as follows. Given the base mode choice probability $P_{ij,m}^{b,k}$ for each mode m and O-D pair i-j, the changed mode split probability $P_{ij,m}^{k}$, due to some change in generalized travel cost, can be estimated as follows (Ben-Akiva and Lerman, 1985):

$$P_{ij,m}^{k} = \frac{P_{ij,m}^{b,k} e^{-\lambda_m \Delta g_{ij,m}^{k}}}{\sum_m P_{ij,m}^{b,k} e^{-\lambda_m \Delta g_{ij,m}^{k}}} \qquad \forall i, j, m, k \qquad (3.19)$$

where λ_m is the scale parameter of the incremental logit model and $\Delta g_{ij,m}^{k}$ is the change of the average generalized travel cost of travelers of class k from origin i to destination j:

$$\Delta g_{ij,m}^{k} = g_{ij,m}^{k} - g_{ij,m}^{b,k} \qquad \forall i, j, m, k \qquad (3.20)$$

where $$g_{ij,m}^{k} = \sum_{d} x_{ij,m,d}^{k} g_{ij,m,d}^{k} \Big/ \sum_{d} x_{ij,m,d}^{k} \qquad \forall i, j, m, k \qquad (3.21)$$

While the model allows users to specify their own base mode choice probabilities, a set of default values are provided: $P_{ij,m=1}^{b,k} = 0.68$ (drive-alone), $P_{ij,m=2}^{b,k} = 0.19$ (2-people shared-ride), $P_{ij,m=3}^{b,k} = 0.094$ (3-or-more-people shared-ride), and $P_{ij,m=4}^{b,k} = 0.036$ (public transit). These default values are obtained from Bhat (2004) and Parsons Brinkerhoff (2009).

The mode split process produces a set of O-D flow tables in vehicle trips for each traveler class k and transportation mode m. Specifically, the O-D flow tables for the drive-alone and shared-ride modes are:

$$x_{ij,m=1}^{k} = P_{ij,m=1}^{k} q_{ij}^{k} \qquad \forall i, j, k \qquad (3.22)$$

$$x_{ij,m=2}^{k} = P_{ij,m=2}^{k} q_{ij}^{k} / w_{ij,m=2}^{k} \qquad \forall i, j, k \qquad (3.23)$$

where $w_{ij,m=2}^{k}$ is the average occupancy rate of the shared-ride mode. The default values of average occupancy rates of all transportation modes used in our model are $w_{ij,m=1}^{k} = 1.0$ (drive-alone), $w_{ij,m=2}^{k} = 2.0$ (2-people shared-ride), $w_{ij,m=3}^{k} = 3.2$ (3+-people shared-ride), and $w_{ij,m=4}^{k} = 12.0$ (public transit). As for the O-D flow table for the transit mode, bus loadings are typically fixed (by routes and schedules of the local transit agency); and the model does not distinguish transit flows by traveler class k (as value of time will not play a role in transit route or time of day choices). If the transit flow rate is negligible, as compared to the general traffic flow rates, the toolkit can ignore the transit flow in the subsequent modeling steps. Heavy trucks are accounted for separately with an assumed average occupancy rate of 1.0 person.

After obtaining the O-D flow rates for each traveler class k by mode m, $x_{ij,m}^{k}$, the average occupancy rates w_{ij}^{k} across traveler classes k can be calculated as follows:

$$w_{ij}^{k} = q_{ij}^{k} \Big/ \sum_{m} x_{ij,m}^{k} \qquad \forall i, j, k \qquad (3.24)$$

3.5 Time-of-Day Split

A similar discrete choice process to the mode split is applied here to split the O-D flow rates $x_{ij,m}^{k}$ into different time-of-day periods. The incremental logit model for the time-of-day choice has the following functional form:

$$P_{ij,m,d}^{k} = \frac{P_{ij,m,d}^{b,k} e^{-\lambda_d \Delta g_{ij,m,d}^{k}}}{\sum_d P_{ij,m,d}^{b,k} e^{-\lambda_d \Delta g_{ij,m,d}^{k}}} \qquad \forall i, j, m, d, k \qquad (3.25)$$

where λ_d is the scale parameter of the incremental logit model and $\Delta g_{ij,m,d}^{k}$ is the change of the average generalized travel cost of travelers of class k from origin i to destination j in mode m during time-of-day d:

$$\Delta g_{ij,m,d}^{k} = g_{ij,m,d}^{k} - g_{ij,m,d}^{b,k} \qquad \forall i, j, m, d, k \qquad (3.26)$$

The base time-of-day split probabilities are specified by the time-of-day travel demand patterns, which are estimated based on the time-of-day traffic counts. The time-of-day split process produces a set of O-D flow tables in vehicle trips for each traveler class k, transportation mode m, and time-of-day period d:

$$x_{ij,m,d}^{k} = P_{ij,m,d}^{k} x_{ij,m}^{k} \qquad \forall i, j, m, d, k \qquad (3.27)$$

3.6 Traffic Assignment

Traffic assignment involves an iterative process of assigning O-D flows over all competing routes to achieve network equilibrium setting (where no traveler can unilaterally improve his/her travel time by changing routes). An equilibrium flow pattern implies that all travelers of the same class and the same mode between an O-D pair enjoy equal generalized travel cost; however, travelers from different classes or different modes can (and regularly do) experience different travel costs (because different classes relate time and money differently and the logit specification allows for unobserved factors impacting mode choice).

The following multi-class, multi-mode optimization problem describes the traffic assignment result for each time-of-day d:

$$\min \quad \sum_a \int_0^{v_{a,d}} [t_a(\omega) + W \cdot r_a(\omega)] d\omega + \sum_a \sum_k \sum_m \frac{v_{a,m,d}^k s_{a,m,d}}{VOT^k} \tag{3.28}$$

$$\text{subject to} \quad \sum_p f_{ij,p,m,d}^k = x_{ij,m,d}^k \qquad \forall i, j, m, d, k \tag{3.29}$$

$$f_{ij,p,m,d}^k \geq 0 \qquad \forall i, j, p, m, d, k \tag{3.30}$$

where $v_{a,d}$ and $v_{a,m,d}^k$ are the total flow rate on link a and the flow rate of traveler class k and transportation mode m on link a, respectively, during time-of-day period p, W is the ratio of the value of travel time variance to the value of travel time mean (where, as we aforementioned, we assume a fixed W value across different traveler classes, i.e., $W = VOR^k/VOT^k$), $s_{a,m,d}$ is the monetary cost associated with link a for travelers class m in transportation mode m during time-of-day period d. Link flow rate $v_{a,d}$ is the sum of all path flows going through link a:

$$v_{a,d} = \sum_{ij} \sum_p \sum_k \sum_m f_{ij,p,m,d}^k \delta_{ij,p}^a \qquad \forall a, d \tag{3.31}$$

and link flow rate $v_{a,m,d}^k$ of traveler class k and transportation mode m is the sum of all path flows of class k and mode m going through link a:

$$v_{a,m,d}^k = \sum_{ij} \sum_p f_{ij,p,m,d}^k \delta_{ij,p}^a \qquad \forall a, m, d, k \tag{3.32}$$

Several existing solution algorithms can be adapted to solve the classical user-equilibrium traffic assignment problem, in which the Frank-Wolfe method is most widely used. A detailed treatment of this algorithm implementation can be found in Sheffi (1985). Because the model assumes a multi-class, multi-mode traffic assignment, as described above, and because different classes of travelers have different values of time and different modes of travelers could potentially experience (in a near-future version of the toolkit) different toll and fare charges, a modified Frank-Wolfe solution method was used. The algorithmic procedure of the modified Frank-Wolfe method was implemented, as follows:

Step 0 **(Initialization):** Find an initial feasible flow pattern. This can be done by performing an all-or-nothing assignment for each combination of traveler class and transportation mode based on free-flow travel costs:

$$g_{a,m,d}^{k,0} = VOT^k \cdot t_a^0 + VOR^k \cdot r_a^0 + s_{a,m,d} \qquad \forall a, m, d, k \tag{3.33}$$

$$g_{ij,p,m,d}^{k,0} = \sum_a \left(VOT^k \cdot t_a^0 + VOR^k \cdot r_a^0 + s_{a,m,d}\right) \delta_{ij,p}^a \qquad \forall i, j, p, m, d, k \tag{3.34}$$

This generates the initial flow pattern, $\{v_{a,m,d}^{k,1}\}$ and $\{v_{a,d}^1\}$. Set iteration counter $n = 1$.

Step 1 **(Cost update):** Calculate the updated generalized travel cost on the link level:

$$g_{a,m,d}^{k,n} = VOT^k \cdot t_a\left(v_{a,d}^n\right) + VOR^k \cdot r_a\left(v_{a,d}^n\right) + s_{a,m,d} \qquad \forall a, m, d, k \tag{3.35}$$

Step 2 **(Direction finding):** Find an auxiliary flow pattern $\{u_{a,m,d}^{k}\}$ and $\{u_{a,d}\}$ by performing an all-or-nothing assignment for each combination of traveler class and transportation mode based on the updated travel costs in step 1.

Step 3 **(Line search):** Find an optimal θ value for $0 \leq \theta \leq 1$ by solving the following line search problem:

$$\min \sum_{a} \int_{0}^{v_{a,d}^{n}+\theta(u_{a,d}-v_{a,d}^{n})} [t_a(\omega) + W \cdot r_a(\omega)] d\omega + \sum_{a}\sum_{k}\sum_{m} \frac{\left(v_{a,m,d}^{k,n} + \theta\left(u_{a,m,d}^{k} - v_{a,m,d}^{k,n}\right)\right) s_{a,m,d}}{VOT^{k}} \tag{3.36}$$

$$\text{subject to} \quad 0 \leq \theta \leq 1 \tag{3.37}$$

Step 4 **(Solution update):** Set $v_{a,m,d}^{k,n+1} = v_{a,m,d}^{k,n} + \theta\left(u_{a,m,d}^{k} - v_{a,m,d}^{k,n}\right)$.

Step 5 **(Convergence test):** If a convergence criterion is met, e.g., $\sum_a \frac{|v_{a,d}^{n+1} - v_{a,d}^{n}|}{v_{a,d}^{n+1}} \Big/ |A| < \varepsilon$, $\forall a \in A$, where ε is the allowable convergence error, stop; otherwise, set $n = n + 1$ and go to step 1.

To ensure consistency across model components (e.g., to ensure that travel times used to predict mode split are the same as those at the end of this sequence of sub-models), a feedback process is required. This links the final stage of network assignment back to trip generation and destination (via elastic demands between all O-D pairs), as well as the mode and time-of-day choice models. These program modules are iteratively executed until a satisfactory convergence is obtained (e.g., a relative gap of 0.0001 or less is achieved [as per TransCAD recommendations, to avoid spurious noise in results]). This is not overly time consuming, given the size of the sketch planning networks (which are expected to be on the order of 200 (to 400) one-way links or fewer). The most time-consuming part of the overall model sequence lies in the maximum-entropy trip table estimation, because the Frank-Wolfe algorithm iteratively resorts to a linearized subproblem.

Chapter 4. Vehicle Emissions Estimation

On-road vehicles are an important source of anthropogenic air pollution in the United States. In total, on-road vehicles emit approximately 34% of total oxides of nitrogen (NOx), 10% of particulate matter with a diameter less than 2.5 micrometers ($PM_{2.5}$—this total does not including road dust), 50% of carbon monoxide (CO), and 30% of hydrocarbons (HC) (EPA, 2000). Consequently, agencies monitoring air quality and transportation planners must understand the impacts of planned changes in transportation infrastructure on emissions. In order to provide that capability within the framework of the tool, an emissions rate lookup table was developed. This table, when combined with estimates of VMT and other traffic characteristics, allows tool users to estimate emissions changes due to alternative transportation scenarios. This report outlines the development of that table and important issues that may arise when developing mobile-source emissions inventories.

The emissions rates listed in the lookup table were computed by running MOBILE6.2 many, many times. MOBILE is the mobile source emissions model that has been used by the U.S. EPA and Texas Commission on Environmental Quality (TCEQ) since 1978 (EPA, 2003). EPA publicly released its new mobile source emissions model (MOVES) at the end of 2009, after the toolkit development timeframe of this project. Preliminary analyses with the MOVES model conducted by the U.S. EPA (and others, anecdotally) indicate that PM and NOx emissions rates are higher in MOVES than MOBILE6.2, but HC emissions rates are lower in MOVES than MOBILE6.2 (see, e.g., Beardsley [2009]).

This chapter provides information about the assumptions used to run the MOBILE model to generate the emission rates used in the toolkit. When appropriate and available, Texas-specific inputs were used. Sensitivity studies were conducted on some input parameters in order to provide a range of emissions rates for different conditions. In other instances, it was determined that parameters did not have a large enough impact on the rates to justify considering multiple input values. This chapter describes each of those decisions.

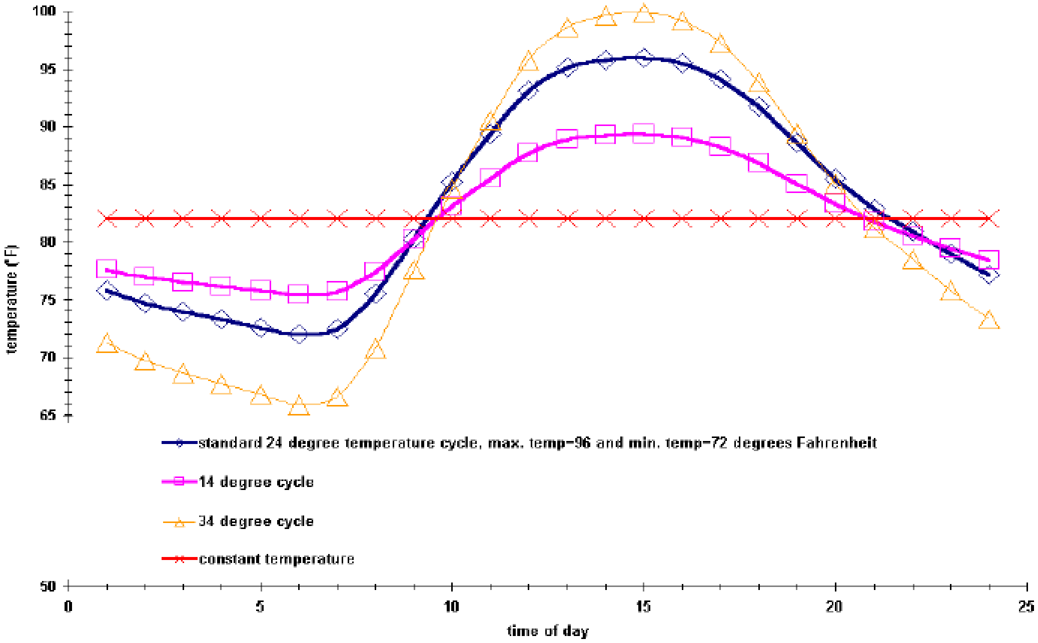
4.1 Input Parameters

4.1.1 MOBILE 6.2 Input Variables

Sensitivity studies with variable values of the following input parameters were undertaken in the development of the toolkit's emissions rate lookup table. The MOBILE model was run once for each unique combination of the following six variable inputs.

1. *Average Daily Temperature*: Four average daily temperatures were chosen based on average and extreme winter and summer temperatures: 80°F and 95°F represent two average daily temperatures common during the summer ozone season in Texas, and 40°F and 55°F represent two average daily temperatures common during the winter in Texas. Modeling of CO emissions only, on days that fall between 55°F and 80°F, could lead to small errors in total emissions estimates, however, relative changes (between a base scenario and a test scenario for example) are likely to be well represented. Final results (see Appendix D) indicate that temperature is not a big factor in emissions rates of other species. Figure 4.1 shows the form of diurnal profiles that MOBILE6 assumes. In each case, the daily temperature profile varied between the average plus or minus (±) 10°F. Assuming a non-constant daily temperature allows diurnal evaporative

emissions to be calculated and is more representative of real-world temperature fluctuations. For example, when compared to a run with a constant average 80°F, the running and evaporative VOC emissions and MSATs increased by approximately 5% in a run with a diurnal temperature pattern. However, sensitivity analyses conducted with MOBILE6 determined that the range of temperature was not a significant factor in the determination of total emissions rates (Giannelli, 2002).



Source: Giannelli (2002)

Figure 4.1: Temperature Profiles in MOBILE6

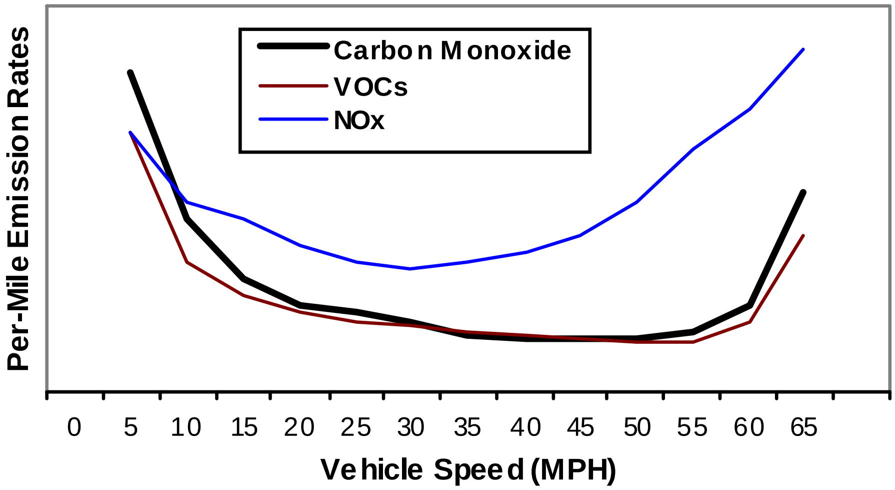
2. *Model Year*: The toolkit is designed for use from 2010 to 2025. Four model years were run: 2010, 2015, 2020, and 2025. MOBILE6.2 incorporates Corporate Average Fuel Economy (CAFÉ) standards and mobile emissions standards (Brzeznski, 2009), though MOBILE6 does not attempt to predict future policy decisions. The last new standard that was programmed into the model is the Tier II standards that were implemented in 2006 (Brzeznski, 2009). However, the TCEQ has developed future year-fuel economy estimates up to 2016 using predicted future year regulations (TCEQ, 2009).

3. *Vehicle Age:* Vehicle age impacts emissions in two ways: as vehicles age, components can deteriorate (for example, sensors monitoring the fuel to air ratio can malfunction affecting performance of the catalytic converter) causing higher emissions. Furthermore, the implementation of more stringent emissions standards means that newer model cars should have lower emissions (EPA, 2000).

4. *Facility:* As outlined in the MOBILE6 User's Guide (EPA, 2003), four facility types are available in MOBILE6.2: freeway, arterial, local, and ramp. While both local and ramp facility types imply a single average speed (12.9 mph and 34.6 mph respectively), freeway, and arterial facility types allow the user to define an average speed. However, MOBILE makes certain

assumptions based on facility type. Vehicles on freeways are assumed to maintain a relatively constant speed, while those on arterials are assumed to have a more stop-and-go traffic flow pattern. Above 30.5 mph, however, emissions rates on arterials and freeways are assumed to be the same (Brzeznski, 1999). "Ramp" facility types assume vehicle acceleration (though they do not model vehicle deceleration associated with off-ramps), while "local" facility types assume stop-and-go patterns (EPA, 2003).

5. *Average Speed*: Most vehicles get the best fuel economy around 55 mph (West, 1997). On the upper and lower ends of the speed curve, decreases in efficiency lead to a decrease in fuel economy and an increase in emissions per mile. As shown in Figure 4.2, older versions of MOBILE provide NOx emissions rates that increase above 55 mph (TRB, 1995). However, as vehicle technology has improved, passenger vehicles have become more efficient at higher speeds. As shown in Figure 4.3 the latest version of MOBILE (Version 6.2) shows minimal upward curvature with speeds above 55 mph for emissions species. David Brzeznski (one of the MOBILE6 developers within the U.S. EPA's Office of Transportation and Air Quality) argues that NOx emissions increase at speeds greater than 55 mph; however, there is not enough evidence to support this conclusion with the newer automobiles (Brzeznski, 2009). Idle emissions are assumed to be the same (in grams per hour) as emissions at 2.5 mph (Brzeznski, 1999).



Source: TRB, 1995

Figure 4.2: Emissions Rates versus Speed for MOBILE5.2 Output

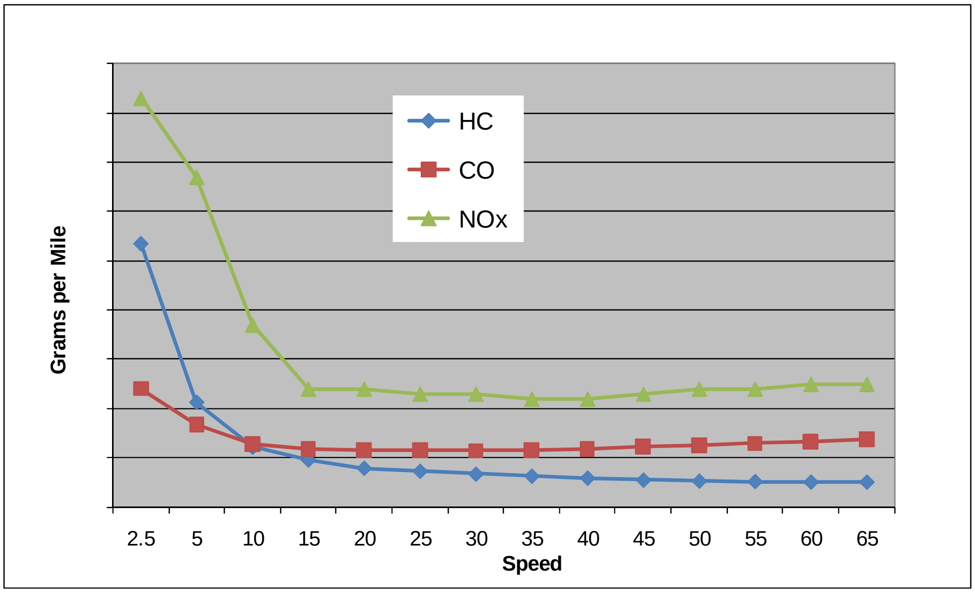


Figure 4.3: Representative Emissions Rates versus Speed for MOBILE6.2 Output (Note: These values are manipulated to best show curvature and are not to scale.)

6. *Vehicle Type*: Eight vehicle types are used to represent all possible vehicle types in the sketch planning tool (from among 28 possible). These are light duty gasoline vehicles (LDGV), light duty gasoline trucks (LDGT1, 2, 3, and 4), heavy-duty gasoline vehicles (HDGV2B), and heavy-duty diesel trucks (HDDV8a&b). The remaining 20 possible vehicle types (allowed in MOBILE) include motorcycles, city buses, and medium-duty trucks, among others; these make up only about 5% of the total VMT in Texas, according to Texas modelers (TCEQ, 2009). However, all vehicle types were run in MOBILE.

The following parameters were defined for the MOBILE6 runs:

1. *Relative Humidity*: The toolkit's emissions rates were developed with the relative humidity value set at the MOBILE default value of 75%. According to a sensitivity analysis done by EPA (2002), humidity has only a moderate impact on emissions and only on NO_x (Giannelli 2002). Moderate impact is defined as between a 5% and 20% change in emissions due to a 20% change in input variable (in this case humidity). More details on these results can be found in Appendix D of this document.

2. *Month*: MOBILE allows users to specify only either January or July, and two seasons were modeled. For the first two runs, average daily temperatures were 80°F and 95°F respectively, with modeling season defined as summer (ozone season) and the modeling month defined as July. For the second two runs, *average* daily temperatures were 40°F and 55°F, for the winter season, but the modeling month was also defined as July. This was done because MOBILE assumes that new model years of Heavy Duty Vehicles (HDVs) do not become available for sale until January 1. So a modeling run conducted on January 1 will not have any new HDVs, and thus no HDV emissions rates. In order to calculate emissions rates for new HDVs, the month was set to July to allow new models to be sold, but all other winter specific factors (temperature and season) were set to represent winter. Analysts can choose either time of year.

3. *Altitude*: The altitude was defined as 500 ft above sea level. MOBILE allows users to specify either 500 ft or 5,500 ft.

4. *Gasoline Sulfur Content*: Values were taken from TCEQ's data for Texas' on-road air toxics inventories (at ftp://ftp.tceq.state.tx.us/pub/OEPAA/TAD/Modeling/Mobile_EI/Toxics/), and are described below, in the Fuel Program details (below).

5. *Fuel Composition*: Fuel composition details (including gasoline sulfur content, as described above) were taken from TCEQ's data for the on-road air toxics inventories (at ftp://ftp.tceq.state.tx.us/pub/OEPAA/TAD/Modeling/Mobile_EI/Toxics/).

Note that gasoline and diesel sulfur content and compositions were taken from measurements in Dallas non-attainment counties in 2008. Measurements were made in both winter and summer seasons.

For each season, the entries shown below are specified as follows. The Fuel Program (below) describes the gasoline sulfur content. The first 16 values are average fuel sulfur content for each year from 2000 to 2015 (constant at 30 ppm). The next 16 values are maximum fuel sulfur content for the same time span (1000 ppm until 2003, 303ppm for 2004 and 2005, 87 ppm for 2006 and 2007, and then 80 ppm until 2015). All years after 2015 will be assigned the 2015 value. Fuel RVP is the Reid Vapor Pressure, a measure of volatility in units of psi. The gasoline aromatics, olefins, and benzene content are listed in percent by volume. E200 and E300 are the vapor percentage of gasoline at 200 and 300°F, respectively. For the "OXYGENATE" commands, the specific oxygenate compound is followed by the volume percent and then the market share. In both summer and winter months, ethanol is the only oxygenate used. The final entry is the diesel sulfur content in ppm. The compositions for the winter and summer runs follow.

The winter temperatures (30–50°F and 45–65°F) used fuel characteristics from a representative winter month in Dallas, as follows:

```
February, G10/H10 (gas/diesel source code for time period)
FUEL PROGRAM   : 4
30.0 30.0 30.0 30.0 30.0 30.0 30.0 30.0 30.0 30.0 30.0 30.0 30.0 30.0
30.0 30.0
1000.0 1000.0 1000.0 1000.0 303.0 303.0 87.0 87.0 80.0 80.0 80.0 80.0
80.0 80.0 80.0 80.0
FUEL RVP     : 12.08 psi
GAS AROMATIC%   : 18.31
GAS OLEFIN%    : 8.08
GAS BENZENE%   : 0.61
E200       : 60.74
E300       : 84.68
OXYGENATE     : ETOH 9.911 1.0
         : MTBE 0.000 0.0
         : ETBE 0.000 0.0
         : TAME 0.000 0.0
DIESEL SULFUR   : 6.1
```

The summer temperatures (70–90°F, 85–105°F) used fuel characteristics found in Dallas during the ozone season, as follows:

```
June through September, G10/H10 (gas/diesel source code for time
period)
```

```
FUEL PROGRAM   : 4
30.0 30.0 30.0 30.0 30.0 30.0 30.0 30.0 30.0 30.0 30.0 30.0 30.0 30.0
30.0 30.0
1000.0 1000.0 1000.0 1000.0 303.0 303.0 87.0 87.0 80.0 80.0 80.0 80.0
80.0 80.0 80.0 80.0
FUEL RVP     : 6.85
GAS AROMATIC%   : 18.46
GAS OLEFIN%    : 7.05
GAS BENZENE%   : 0.53
E200       : 49.00
E300       : 86.00
OXYGENATE     : ETOH 5.904 1.0
         : MTBE 0.000 0.0
         : ETBE 0.000 0.0
         : TAME 0.000 0.0
DIESEL SULFUR   : 6.1
```

Finally, the Inspection and Maintenance (I/M) Program variable was set to *Yes*. This selection reduces the fleet average emissions rates based on the assumption that the modeled regions I/M program will identify a portion of the highest emitters, these will be repaired, and their emissions reduced. The MOBILE runs conducted for this project were grouped by age, so each individual run represents only one age of vehicles. Newer vehicles are less likely to have maintenance problems; thus the I/M setting likely more often impacted older vehicles, with generally higher emission rates.

Dallas non-attainment area settings were chosen as the I/M program input settings. The Houston non-attainment area and Travis and Williamson counties in the Austin regions are two additional areas in Texas with existing I/M programs. TCEQ modeling of Houston and Dallas I/M programs differ only start date (TCEQ 2009). According to the TCEQ's Chris Kite, their modeling of Austin's I/M program assumes that Austin does not yet have the capability to do Acceleration Simulation Mode (ASM) testing. ASM testing is required in order to see NOx benefits from an I/M program on 1995 or earlier model year vehicles. In 1996, EPA began requiring vehicles to have on-board diagnostic capabilities. With these new capabilities, the two-speed idle test is the only I/M test needed to realize full benefits from an I/M program.

MOBILE6 also assumes that a small percentage of people will tamper with their vehicle's test results and "cheat" the system in the first few years of a new I/M program. Therefore, the model adjusts emissions rates to reflect this behavior (Kite, 2010). Houston I/M program's start date was in 1997, the Dallas program started in 1990, and the Austin program started in 2005 (TCEQ, 2009). Therefore, it is possible that modeling Austin's near-term emissions rates with Dallas I/M program inputs will under-estimate emissions rates due to start date differences. The same is possible for any other I/M program started after 1990. However, according to modelers at the TCEQ, this difference is very small (Kite, 2010).

4.1.2 Toolkit Inputs

The following parameters are inputs required of toolkit users:

1. *Summer and Winter Temperatures*: The toolkit assumes the temperature profile closest to 40, 55, 80, and 95ºF, though it should be noted that each of these values represent temperature ranges that were used when generating emissions rates.

2. *Number of Summer and Winter Months*: These are used to determine annual emissions quantities. In determining total expected emissions quantities, the emissions rates are assumed to be generated at the summer temperatures for the number of summer months and the winter temperature for the number of winter months.

3. *VMT*: VMT by link and vehicle type (and vehicle age), which come in a large part from the toolkits travel demand model.

4. *Vehicle Age Distribution and Fleet Makeup*: TCEQ's Texas statewide default values (at ftp://ftp.tceq.state.tx.us/pub/OEPAA/TAD/Modeling/) have been built into the tool. Users are encouraged to update these default values with project specific values.

4.1.3 Plug-In Hybrid Electric Vehicles (PHEVs) and Battery-Electric Vehicles (BEVs)

PHEVs run on a combination of electricity and gasoline, while BEVs use only electric power. Therefore, their emissions entail an understanding of electricity generation (and emissions) at power plants, sometimes very remote from population centers. Such fleet changes may affect emissions impacts of various projects. To get a sense of this (and to include such distinctions in a future version of the toolkit), a simple calculation of average NO_x, CO_2, and SO_2 emissions rates was conducted for power generating facilities within the Electric Reliability Council of Texas (ERCOT), using individual facility data available on EPA's eGRID (EPA, 2009a). A relative measure of how much electricity each plant contributes to the state's total was calculated by multiplying each plant's capacity factor by the nameplate capacity, summing the total over Texas, and then weighing each facility relative to the Texas total. In the weighting process, each facility was assigned a share of the Texas total. That share was multiplied by each facility's emissions rates, and those values were totaled to obtain an average Texas value (see Equation 4.1). The Texas emissions rates are shown in Table 4.1. These rates are within 10% of the national rates calculated by Kintner-Meyer (2007) of Pacific Northwest National Laboratory (PNNL). Because PHEV emissions originate from electricity generation regardless of the path of the individual vehicle, an average fuel economy across all speeds and driving conditions (while running on battery power) was estimated for PHEVs, via the following equation:

$$E_x = M \times 10^{-6} \times \sum\nolimits_n \left\{ \left[\frac{C_{f,n} \times C_{N,n}}{\sum_n \left(C_{f,n} \times C_{N,n} \right)} \right]_n \times ER_n^x \right\} \tag{4.1}$$

where:

E_x = Emission rate (gm/mile) of species x = NO_x, SO_x or CO_2
M = MOBILE6-adjusted AC electricity consumption (Wh/mile)
n = Power plants in ERCOT
$C_{f,n}$ = Capacity factor of plant n
$C_{N,n}$ = Nameplate capacity of plant n (i.e., maximum capacity, as designed)
ER_n^x = Annual emission rate (lb/MWh) of plant n for species x

All the above values were obtained from EPA's eGRID (EPA, 2009a). As Light Duty Vehicles (LDVs) become cleaner, the gap between NOx emissions associated with PHEVs and gasoline LDVs is closing. Only the cleanest sources of electricity are likely emit less NOx than the newest gasoline LDVs. SO_2 emissions are also likely higher in locations where many cars turn to electric power. Moving from HEVs to PHEVs and BEVs may not be a wise strategy for emissions reductions, because HEVs are already fuel efficient and avoid coal feedstocks altogether.

Table 4.1: Resulting PHEV Emissions Rates (Running off Battery Power) Based on Weighted Values for ERCOT Power Plants

Individual Vehicle Type	Gross Vehicle Weight (lb)	MOBILE6 Adjusted AC Electricity Consumption (Wh/mi)	Average ERCOT NOx Rate g/mile	Average ERCOT CO2 Rate g/mile	Average ERCOT SO2 Rate g/mile
Passenger Cars	-	318.2	0.14	196	0.43
Gas Truck	0-6000	394.2	0.18	242	0.54
Gas Truck	6001-8500	493.2	0.22	303	0.67

4.1.4 Hybrid Electric Vehicles (HEVs)

HEVs are not modeled by MOBILE6.2 (or in MOVES, where users have to input all rate assumptions for unusual or emerging vehicle types), and the EPA has not made a final decision on how they will handle HEVs in the MOVES model (Brzeznski, 2009). However, the HEV market share is growing and has the potential to be a significant fraction of the light duty vehicle fleet in the next 20 years (Christenson, 2007b). For this reason, it is important to include HEVs in a future version of the toolkit.

Many studies have evaluated the environmental impacts of HEVs by measuring fuel economy and emissions under different driving conditions (e.g., Huo, 2009; Fontaras, 2008; Christenson, 2007a, 2007b). The exhaust emissions rates of HEVs, like those of conventional vehicles, are highly correlated with air/fuel ratios, combustion temperature, catalyst temperature, and fuel economy (Christenson, 1997a, 1997b). HEV emissions rate patterns generally track those of conventional vehicles. For example, as the temperature of combustion increases, NOx emissions per mile increase; as the temperature of the catalyst increases, emissions per mile of CO, NOx, and VOCs all decrease; finally, as fuel economy decreases, emissions per mile increase. These correlations have been found to hold true for HEVs as well as conventional vehicles (Christenson, 2007b). Because of these emissions rate behavior similarities between HEVs and conventional vehicles, the toolkit uses the conventional vehicle emissions rates developed through MOBILE6.2, with a fuel economy scaling factor, to represent HEVs. Therefore, because studies have found that fuel economy increases by 50% in HEVs, when compared to similar conventional vehicles, HEV emissions rates are estimated at 67% of the emissions rate of conventional vehicles under the same driving conditions (Huo, 2009; Fontaras, 2008; Christenson, 2007b).

4.1.5 Additional Considerations

While developing the emissions rates-look up table, several important issues were encountered, as discussed below. These relate to soak time assumptions, weather effects, and evaporation.

Toolkit emissions rates were developed by running MOBILE6.2 with default distributions for vehicle soak times as presented in an EPA technical document (Glover and

Brzenski, 2001). For the purpose of modeling mobile emissions, a soak is defined as the duration of time preceding a vehicle start during which the vehicle's engine is not operating (EPA 2003). Soak determination is closely related to starts per day. Today's catalytic converters reduce exhaust emissions of HC, CO, air toxics, and NO_x by over 80%, but typically do not begin operating until they have heated to around 300°F (Weilenmann, 2008). Therefore, when an engine is started cold, emissions are higher than when an engine is started hot. Cold starts occur when an engine is restarted longer than 12 hours after being shut down. Any engine starts that occur less than 12 hours after last use fall into a distribution of hot start "soak times." The impact of soak determination is high for only the first couple minutes of a vehicle's trip, after which the engine is assumed to be running hot with full catalytic converter efficiency (Weilenmann, 2008).

MOBILE6 allows the user to define the soak distribution. When the model is run with 100% cold starts, MOBILE6 calculates both the cold start emissions that occur at the beginning of the trip, and the hot running emissions that occur once the engine is hot, and averages them together to get a weighted average (weighted by VMT under cold and hot catalytic converter status) of grams per mile over the entire trip. For shorter trips, emissions rates are larger. On longer trips, the emissions rates more closely reflect normal (hot engine) running conditions. MOBILE6 has a default soak distribution for each vehicle type based on default values for the number of starts per day per vehicle and for trip length distributions (with values presented and discussed in Glover and Brzezinski's (2001) technical report). For this reason, and because it would be difficult for the toolkit user to develop soak distributions for each scenario, MOBILE6's default soak distributions were used. If a toolkit scenario resulted in a large change in starts per day, then the existing emissions rates could over-estimate or under-estimate true emissions.

Several studies have found cold start emissions to be a significant component of total emissions. In Toronto, Hao et al. (2009) estimated emissions associated with starting a cold engine to lie between 15 and 20% of total daily mobile-source emissions. Jensen (1994) found that cars with catalytic converters have 10 to 20 times higher total emissions when the engine is cold than when it is hot. Existing literature cites studies on the effects of cold starts in temperatures ranging from -4°F to 75°F, which indicates that emissions of hydrocarbons and CO increase as temperature falls. However, the effect is most pronounced below freezing and therefore is not critical for a Texas toolkit or ozone concerns in warm rate-summer months. (Weilenmann, 2005, 2008).

With the exception of temperature and humidity, weather conditions (including cloud cover, rain, and wind) have minimal impact on emissions rates of mobile vehicles (Giannelli 2002). However, weather plays an important role in the formation of the secondary pollutant, ozone. Ozone is formed from complex reactions between NO_x and volatile organic compounds (VOCs) in the presence sunlight. Conditions such as cloud cover, rain, and/or high wind speeds all reduce ozone formation and potentially increase the removal of pollutants from the atmosphere by wet deposition (rain) or dry deposition (i.e., settling due to gravity).

All MOBILE6 emissions rates developed for the project toolkit are presented as grams per mile. Exhaustive emissions (besides CO_2) are the result of incomplete combustion of gasoline and thus occur when the vehicle is in use. In contrast, evaporative emissions (which are comprised entirely of VOCs) occur at all times, even when a vehicle is parked. While the most straightforward unit for evaporative emissions is grams per hour, MOBILE simplifies these by adding them over the course of the day (to provide a grams-per-day value for each vehicle type and age) and then calculating a grams-per-mile rate based on average VMT per day per vehicle type, by vehicle age (EPA, 2003). This method for calculating evaporative emissions rates can lead to error if a scenario creates a large change in assumed VMT for any vehicle type. For example, if a scenario causes a 50% decrease in VMT, it is probably increasing the amount of time vehicles are not in use (for example, in a parking lot). While the actual evaporative emissions will not change significantly, the calculated evaporative emissions will decrease because VMT has fallen and evaporative emissions rates (all in the form of VOCs) are provided in grams/mile. This is something to be aware of when using the tool.

Diurnal evaporative emissions occur as the ambient temperature changes throughout the day. For this reason, MOBILE6 was run with a variable diurnal temperature profile. This was accomplished by setting the minimum and maximum temperatures each day to different values. For example, one of the average daily temperatures run was 80°F. The MOBILE6 input files for those runs set the daily maximum temperature to 90°F and the daily minimum temperature to 70°F. MOBILE6 then ran a default distribution with the maximum temperature occurring at 3:00 p.m. and the minimum temperature at 6:00 a.m., thereby averaging 80°F.

For the final emissions lookup table in the toolkit, the exhaust and evaporative emissions were added together for ease of use.

4.1.6 Mobile Source Air Toxics

MOBILE6 provides emission rate estimates for six Mobile Source Air Toxics (MSATs): acetaldehyde, acrolein, benzene, 1,3 butadiene, diesel PM, and formaldehyde (EPA, 2003). With the exception of diesel PM, all MSAT species calculated by MOBILE are hydrocarbons, so any regulations reducing HC emission rates will also reduce MSAT emission rates. An EPA rule covering MSATs was published in 2001. This rule specifies an upper limit for non-methane hydrocarbons (NMHC) for both light-duty passenger vehicles below 6000 lbs (NMHC emissions must be below 0.3 grams per mile by 2013 with a four-year phase-in) and all passenger vehicles between 6,000 and 10,000 lbs (NMHC emissions must be below 0.5 grams per mile by 2015 with a four-year phase-in period) (EPA, 2007).

Benzene emissions are primarily a result of benzene in the gasoline. EPA has posted a rule specifying the volume percent of benzene in gasoline, which must be below 0.62% by 2011 (EPA, 2007). Figure 4.4 presents benzene emissions rates versus speed for MOBILE6.2, assuming a year-2010 vehicle fleet with six age groups as well as experimentally determined benzene emissions rates for a 1995 model year vehicle, as reported by Heeb et al. (1998). Heeb et al.’s emissions estimates from a new vehicle in 1995 closely match emissions estimates from a new vehicle in 2010 in the 40 to 65 mph range, the range when a vehicle is most fuel efficient. Below 40 mph, benzene emissions rates measured from the new 1995 model year vehicle match well with those rates produced by MOBILE6 for a 15-year-old (1995 model year) vehicle.

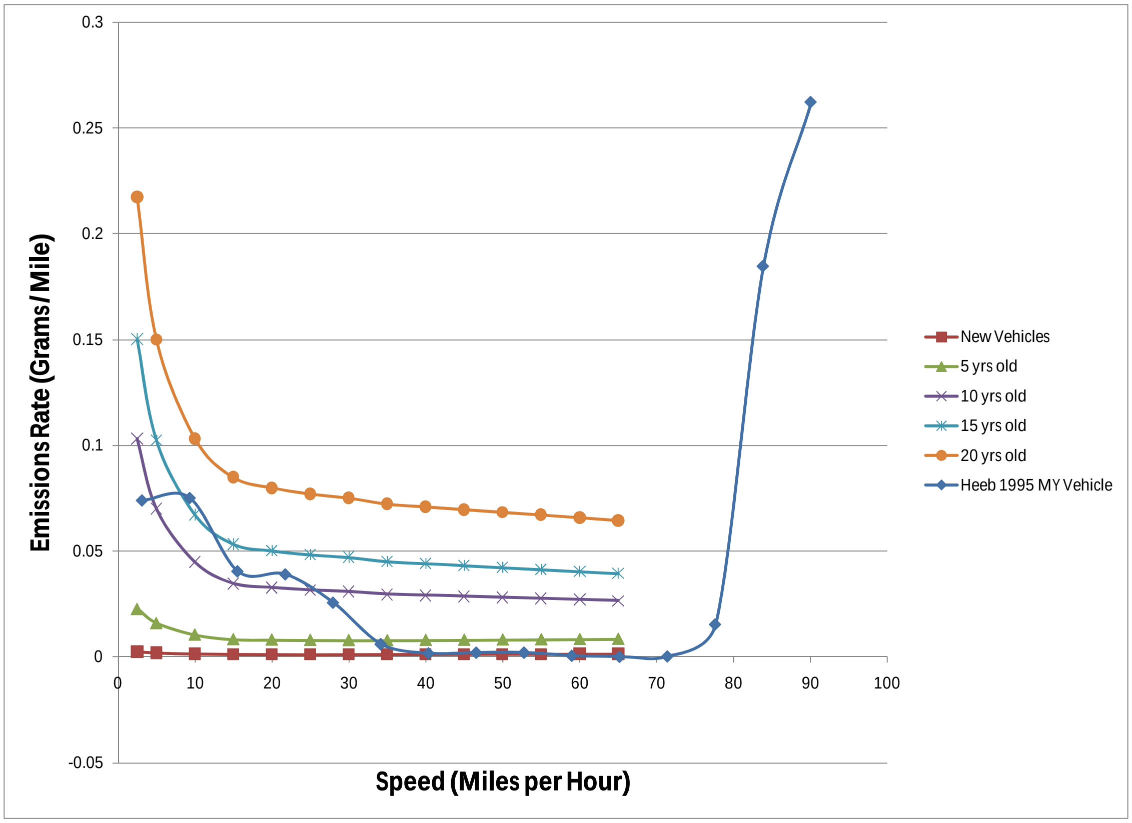
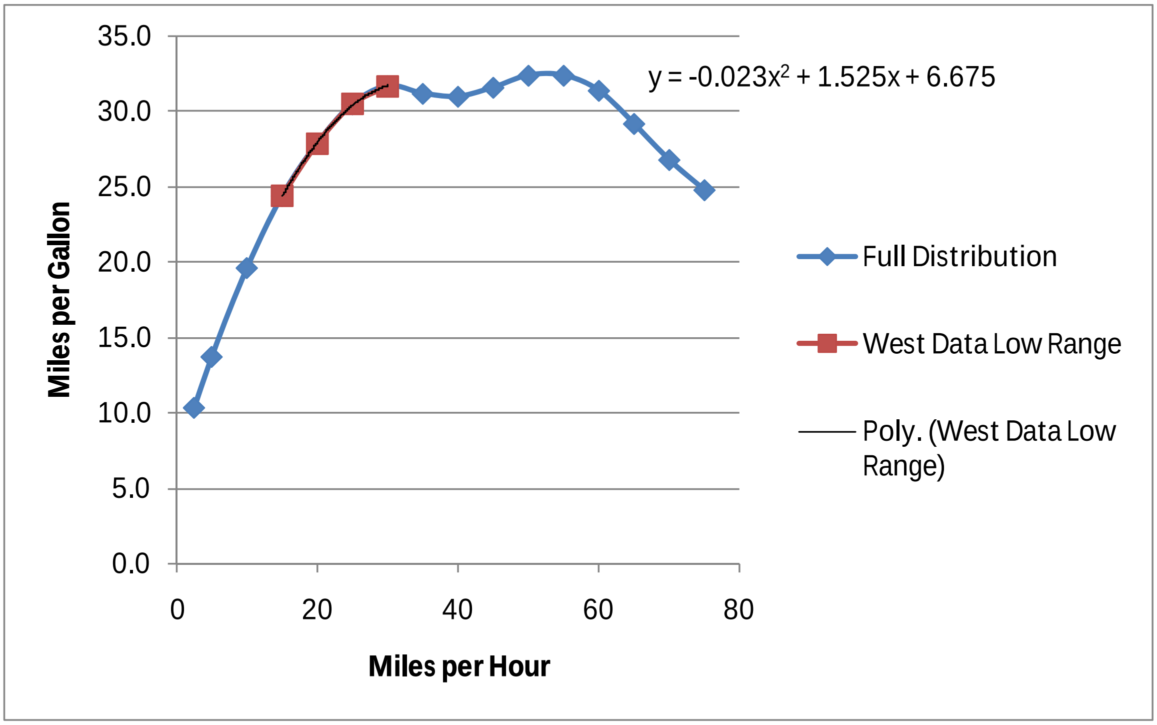


Figure 4.4: Benzene Emissions Rates Developed by MOBILE6.2 for Five Age Classes of Vehicles in the Year 2010 versus Experimental Emissions Rates Measured in a 1995 Model Year Vehicle Less Than Five Years Old

4.1.7 CO2 Emissions Rates

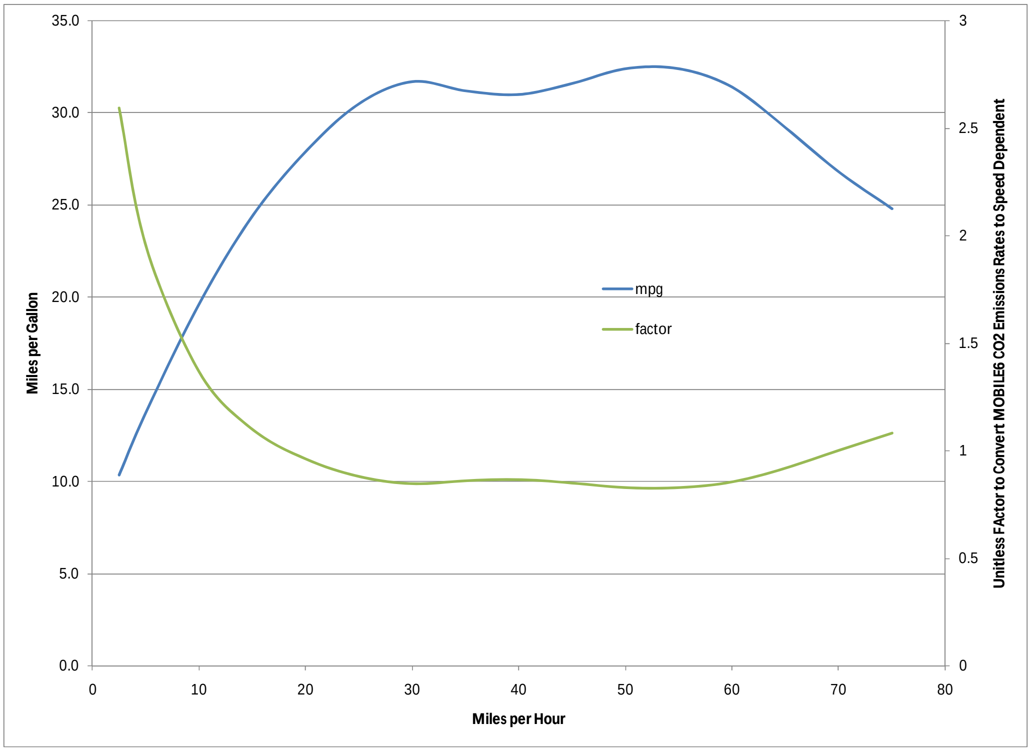
MOBILE6 naively/wrongly assumes constant fuel economy across all speeds. In reality, speed affects fuel economy, often quite dramatically (West 1997). The impact of speed on fuel economy becomes especially important when calculating CO_2 emissions rates (EPA 2005). Because of the direct link between grams of CO_2 per mile and fuel economy, a correction was made to MOBILE's CO_2 emissions rate estimates. Fuel economy distribution was obtained from West, et al. (1997). The minimum speed in the West dataset is 15 miles per hour and continues to 75 mph. The toolkit data minimum speed is 2.5 mph with MOBILE's maximum at 65 mph. In order to extend West et al.'s estimates to cover speeds, the data was plotted in Microsoft Excel and a polynomial trendline was fit to the West data points between 15 mph and 30 mph. The trend line was used to calculate mpg values for speeds between 2.5 mph and 10 mph, shown in Figure 4.5.

Once West et al.'s data were extended, a factor was calculated to convert MOBILE's single CO_2 emissions rate into a speed-based CO_2 emissions rate. CO_2 emissions and fuel economy are inversely proportional (in other words, gallons of fuel per mile is proportional to the inverse of CO_2 emissions per mile). Therefore, CO_2 emissions rates were divided by the ratio of the speed-adjusted fuel economy to the average fuel economy. A factor was created for each speed, and used to convert the CO_2 emissions rate in the emissions rate lookup table. Figure 4.6 shows a graph of each of the factors used for each of the 14 speeds represented in the toolkit lookup table. Figure 4.7 shows the CO_2 emissions rates after adjustments for fuel economy from a 2010 new car on a freeway, as well as the original constant rate. It should be noted that these are exhaust emissions rates, from "pump to wheel," rather than life-cycle well-to-wheel emissions rates (which tend to be about 25% higher, in practice). So the toolkit's CO_2 emissions estimates may be best inflated by 25%, to better reflect the true GHG and energy implications of highway travel with petroleum-based fuels.



Source: West et al. (1997)

Figure 4.5: Fuel Economy Distribution with Extended Low-Speed Range Calculated Using a Polynomial Trendline Fit to Data Points between 15 mph and 30 mph



Source: West et al. (1997)

Figure 4.6: Factors Calculated Using the Fuel Economy Distribution Data to Determine Speed Dependent CO_2 Emissions Rates

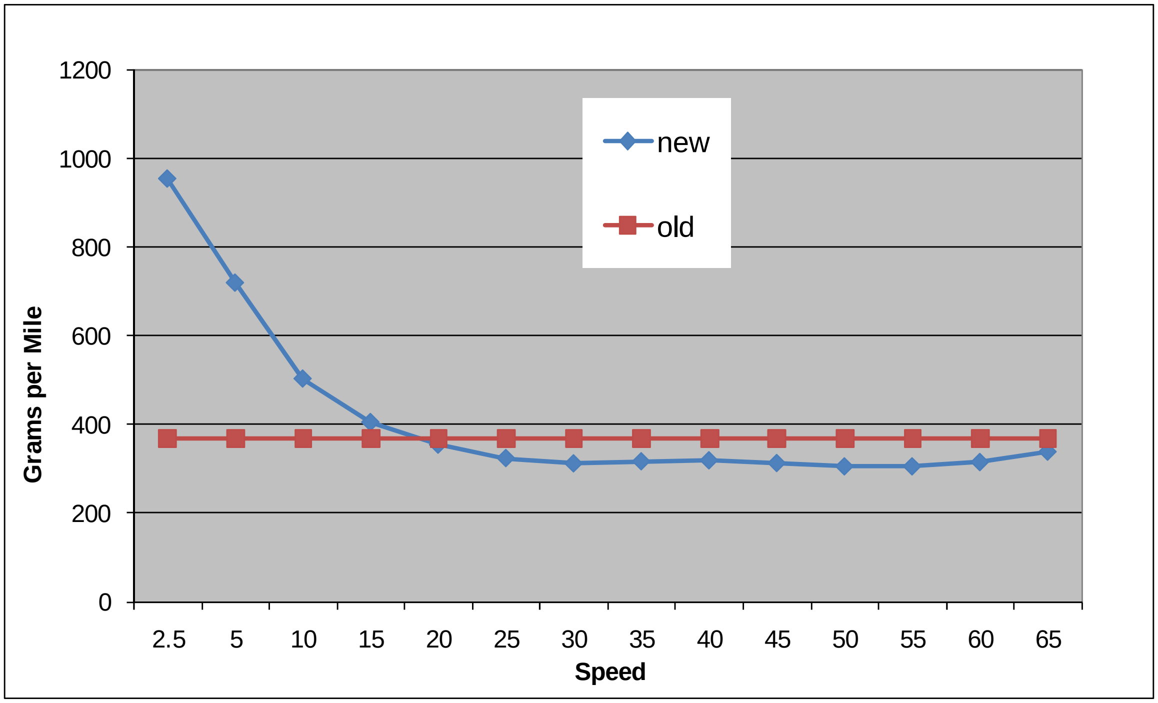


Figure 4.7: CO_2 Emissions Rates versus Speed after Adjustment for Fuel Economy (for a New Car on a Freeway in 2010)

4.1.8 Vehicle Registrations Data

Texas specific vehicle registration data have been built into the toolkit for ease of use. Default Texas-specific registration data are based on 2008 mid-year (July) registration data for the entire state of Texas. These provide the age distribution for each of 16 vehicle classes. This data was posted on the TCEQ's ftp site (ftp://ftp.tceq.state.tx.us/pub/OEPAA/TAD/Modeling/) for the Houston attainment demonstration and was accessed in December 2009 (TCEQ, 2009). Each vehicle class is distributed over 25 age groups starting with new vehicles (0 years old) and progressing to 24-year-old vehicles. The age categories for the toolkit emissions lookup table are in 5-year increments: 0, 5, 10, 15, 20, and 25 years and older. In order to match the toolkit, the TCEQ data were condensed. Table 4.2 shows the Texas-specific registration data and how these were applied to the age categories within the toolkit.

The top row of Table 4.2 shows the toolkit age categories. The second row shows the TCEQ age groups assigned to the toolkit's age categories. For example, for the 5-year-old LDV category, all registered LDVs between (and including) 3 years and 7 years of age were summed, totaling 37.6% of all Texas-registered LDVs. Note that both Bus categories, HDBS and HDBT, use MOBILE6 default values, as provided by the TCEQ.

Table 4.2: Texas Specific Vehicle Registration Distribution Data

Share of Vehicles	**0 Years Old**	**5 Years Old**	**10 Years Old**	**15 Years Old**	**20 Years Old**	**25 Years Old**
Vehicle Type	**0-2 Years**	**3-7 Years**	**8-12 Years**	**13-17 Years**	**18-22 Years**	**22+ Years**
LDV	0.220	0.355	0.256	0.114	0.034	0.021
LDT1	0.126	0.345	0.277	0.141	0.059	0.052
LDT2	0.126	0.345	0.277	0.141	0.059	0.052
LDT3	0.311	0.425	0.180	0.055	0.016	0.013
LDT4	0.311	0.425	0.180	0.055	0.016	0.013
HDV2b	0.407	0.411	0.126	0.032	0.012	0.012
HDV3	0.311	0.302	0.217	0.096	0.040	0.033
HDV4	0.275	0.283	0.278	0.083	0.044	0.037
HDV5	0.282	0.290	0.184	0.089	0.078	0.076
HDV6	0.218	0.253	0.267	0.128	0.065	0.069
HDV7	0.161	0.240	0.284	0.171	0.084	0.060
HDV8a	0.118	0.161	0.255	0.237	0.135	0.093
HDV8b	0.299	0.286	0.297	0.085	0.020	0.013
HDBS	0.181	0.281	0.200	0.142	0.101	0.112
HDBT	0.154	0.307	0.304	0.186	0.034	0.020
MC	0.342	0.376	0.144	0.049	0.027	0.062

4.1.9 Vehicle Emission Costs

Emissions costs can be broadly associated with the costs of damages caused by the pollutants (to human, plant, and animal health, as well as damage to buildings and ecosystems) and with control costs, to reduce such emissions (VPTI, 2009).

The research team investigated the potential costs associated with damages due to emissions. The calculated cost of emissions are a function of many variables (VTPI, 2009; Maibach, 2008), including pollutant species, location of emissions, exposure of humans, plants, animals, ecosystems, and buildings, as well as the values placed on human life and human health. The majority of studies attempting to calculate emissions costs have done so for the following species: NO_x, $PM_{2.5}$, PM_{10}, VOCs, and SO_2. The United States EPA has established National Ambient Air Quality Standards (NAAQS) for six criteria pollutants, thus limiting their concentrations in the atmosphere (EPA, 1990): ozone, $PM_{2.5}$ and PM_{10}, lead, NO_x, SO_2, CO. The costs associated with human health outcomes are dominated by PM (VTPI, 2009; Maibach, 2008; EC, 2005; Wang, 1994). NO_x and SO_2 form acid rain, which has been associated with ecosystem damage as well as degradation of the built environment (EPA, 2009b).

Ozone presents the most pervasive local and regional air quality challenge in the United States, based on the number of counties exceeding NAAQS (a number that will rise under new and future standards). However, ozone is a secondary pollutant, meaning that it is not released directly into the atmosphere but is formed from complex reactions of NO_x and VOCs during warm, sunny, calm conditions. Therefore, the costs associated with ozone damage must be attributed to NO_x and VOC emissions and require air quality modeling to simulate the reactions and formation of ozone. Ozone is a regional issue, meaning that it can react and form far from where the precursors were originally emitted. While ozone “hot spots” can and do form, they are not necessarily in areas of high population density (Thompson et al., 2008). Ozone exposure in humans is associated with breathing difficulty, asthma, airway and lung inflammation, and lung damage (EPA, 2008). Deposition of ozone to plants reduces the efficiency of photosynthesis and has contributed to 90% of air pollution-associated U.S. crop losses (Murphy, 1999).

A second variable affecting emission costs is their location, or more specifically, the potential for exposure of humans, plants, animals, and structures. Meteorological conditions as well as other factors (such as activity patterns) have a significant influence on the impact that the geographic location of emissions will have on human exposure and health outcomes. Air quality modeling is recommended, and in some cases, necessary in order to calculate the concentration of pollutants that result from mobile emissions due to atmospheric chemical transformations, meteorological factors (like wind speed and direction) temperature, sunlight, and physical removal processes (including dry and wet deposition).

In addition, two subjective variables impact emissions costs:

1. The value placed on human life and health. No universally accepted value has been determined, but many studies now include the economic costs of lost productivity (Maibach, 2008; VTPI, 2009).
2. The range of impacts to natural resources and the built environment included in the final cost value.

There has been much more research attempting to quantify such damage costs in Europe than in the U.S. (see, e.g., Maibach, 2008; EC, 2005; AEA, 2005). The Maibach and EC studies assign unique values to each country in Europe based on location, meteorological conditions, dose-response functions, and population density. Costs for each species vary by more than a factor of 20 between the highest and lowest costs for different European countries. Because of the high dependency of costs on both population density and specific meteorological conditions, the costs assigned to any one European country would be difficult to apply to Texas. Population density is much higher in Europe than it is in Texas, and weather patterns are unique to each area of the world. The most recent source for cost data specific to the United States comes from a study at Argonne National Laboratories in 1994, as described by VTPI (2009). Furthermore, Kazimi and Small (1995) developed values specific to the Los Angeles area, in units of dollars per vehicle-mile (and so are not applicable here).

4.1.10 Limitations of MOBILE6

Emission rates are highly variable, across vehicles and driving conditions. Many factors are at play, and MOBILE6 is ultimately just a means of estimating trendlines across diverse circumstances. Many limitations exist, though several have been addressed in EPA's new MOVES model. For example, MOBILE6 does not have an "idle" bin for HDVs, though these emissions can be significant. According to Miller et al. (2009) Toronto's idle emissions can account for 10 to 20% of total emissions in stop-and-go traffic situations. During normal driving, idle emissions were less than 5% of total emissions (Miller, 2009). According to MOBILE6, idle emissions are simply assumed to be the same (in grams per hour) as the emissions at 2.5 mph (Brzeznski, 1999).

Furthermore, with the exception of emissions on ramp facilities, MOBILE's rates assume flat grades, constant acceleration, and "normal" driving habits. Speeds above 65 mph are not included within the MOBILE model, which can lead to errors because highway speed limits can be 70 mph. MOBILE does account for aggressive driving in a limited capacity by using correction factors that include minimal aggressive driving behaviors (Brzeznski, 1999). In reality, aggressive driving can increase CO emissions by over 100%, and NO_x and HC emissions by 50% relative to "normal" driving (De Vlieger, 1997). Aggressive driving is defined as heavy breaking and heavy acceleration, and normal driving is defined as average breaking and acceleration (De Vlieger, 1997).

MOBILE does not account for PM_{10} deterioration, meaning that when emissions rates were originally calculated for the model, correlation between measured concentrations and vehicle emission assumed no deterioration. This is likely to lead to an under-prediction of PM_{10} emissions rates. California's EMFAC model does account for PM deterioration, so PM_{10} emissions rates are much higher in EMFAC than they are in MOBILE6 (Huo, 2009).

4.1.11 HDDVs

While there appears to be a tendency for MOBILE6 to overestimate NO_x emissions from older vehicles and underestimate NO_x emissions from newer vehicles, the variability between similar vehicles (in terms of weight and model year) tends to exceed the difference between MOBILE6 emissions rates and the emissions rates collected during engine testing on a chassis dynamometer (Clark, 2007; Pollack, 2004). Estimation of HDV emissions rates is complicated by the fact that truck bodies can have engines switched out with engines of different model years (Clark, 2007). The model year assigned to the truck is that of the body, not the engine.

4.2 Concluding Remarks

While MOBILE6 emissions rates for different vehicle types under different traffic, location, and weather scenarios are in reasonable agreement with the results from emissions studies (Pollack, 2004), MOBILE's accuracy is subject to the accuracy of input data. For the purposes of this study, inputs were carefully designed to best reflect the Texas-specific conditions in which the toolkit will be used. Using the results of previous studies, and information specific to the toolkit, a series of MOBILE6 inputs were designed to reflect the most important conditions for tool users. As described above, we note issues that could be important for users and, in some cases, where trade-offs were made to help simplify tool use. The toolkit's emissions rate look-up table was designed to be user-friendly while providing the most accurate and comprehensive emissions rates possible.

Appendix D of this document provides details of rates-speed-vehicle-temperature variations. Essentially, MOBILE6 estimates end at 65 mph, which is probably too low for most network applications (with speed limits of 70 and 75 mph not uncommon on high-design freeways). In addition, most emissions rate estimates fall for all LDVs, as speeds increase, when in reality fuel consumption is expected to rise past about 55 or 60 mph. Thus, a move to high-speed conditions is likely to increase most emissions rates, but MOBILE lookup tables in the toolkit will not reflect this phenomenon on many rates.

As noted earlier, the toolkit developers modified MOBILE's CO_2 rates to reflect fuel economy variations with speed variations and thus avoiding the obvious error of constant CO_2 rates that MOBILE entails. Thus, the toolkit's CO_2 rates do rise with lowered speeds (below about 30 mph) and also rise with higher speeds (though only slightly, as MOBILE does not allow for speeds above 65 mph). NOx also rises slightly, at speeds above roughly 30 mph, for several LDVs (and HDVs).

Emissions control technology deterioration after 5 and 10 years of age, for NOx and HC emissions, respectively, appears to play a big role in emissions rates. CO appears largely as a gasoline-fuel (and thus U.S. LDV) phenomenon (and much reduced at summertime temperatures). HDVs have significantly higher emissions rates for all other pollutant species, especially PM, which is associated with diesel fuel use. It is interesting to note that brake-and-tire-based PM exceeds exhaust PM by a wide margin, but NH3 forms of PM have the highest rates of all (with SO2-based PM rates approximating those from brake and tire use)[3]. Inappropriately, MOBILE assumes no changes in any PM emissions rates with speed changes. Toolkit developers expect that PM rates should likely track, on average, fuel consumption and thus CO2 rates (but at a different overall magnitude, in gm/mile). This may be the case with EPA's new MOVES model.

In general, emissions rates vary from vehicle to vehicle, of the same vintage and at the same speed, especially over time, as technologies on board each vehicle deteriorate differentially (and some are tampered with). MOBILE's rates are simply one estimate of averages, and EPA is continually improving estimates, through tools like MOVES and other activities.

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[3] For more information about diesel PM and health risk assessments of different PM emission components, one can examine the NATA link found at http://www.epa.gov/ttn/atw/index.html.

Chapter 5. Toolkit Design

The main product of this project is a spreadsheet-based sketch planning toolkit that can be used to efficiently assess emissions and other impacts associated with large-scale network improvements. The toolkit enables engineers, planners, and others to analyze and compare the travel and emissions impacts by link, traveler class, and time of day. The Microsoft Excel-based spreadsheet application offers users a familiar and powerful data manipulation interface, and allows users to take advantage of Excel's rich embedded functions to process and visualize various data sets. It also provides great flexibility for extending the tool's functionality using internal functions or external programs. Of course, proper/defensible simulation of travel patterns, and how these complex systems are impacted by network changes, requires significant computing. To achieve the most efficient computational performance, the core computational modules of the tool, including the sketch travel demand and vehicle emissions estimation methods, are coded in C++. The Excel spreadsheet interface and external C++ programs are seamlessly integrated by spreadsheet-embedded VBA (Visual Basic for Applications) scripts.

This chapter provides an overview of the toolkit's functional modules and conceptual design. The travel demand modules estimate the node-to-node trip table associated with the analyst-provided link flow estimates, by time of day, traveler type, and mode. The emissions, travel time, and other cost and benefit estimation modules are provided via VBA codes within Microsoft Excel. Many techniques to be used in the toolkit are relatively standard (e.g., logit models for mode choice and user-equilibrium model for route choice). The toolkit's project evaluation modules use traffic model outputs (including speeds and flows by vehicle type, time of day, and O-D pair) and generate multiple performance measures, including traveler welfare, travel time, travel time reliability, travelers' direct costs (e.g., road tolls), fuel consumption, emissions, and crash count estimates. These performance measures are further processed in combination with alternative scenario costs in order to develop economic summary measures, such as benefit-cost (B/C) ratios and net present value (NPV). The computational procedure through the toolkit is illustrated in Figure 5.1. For more information about using the toolkit, readers are referred to the accompanying CD, which contains the Toolkit User's Guide described in Appendix G.

5.1 Structure and Implementation of the Toolkit

To achieve maximum computational efficiency, all the functional modules were coded in C++ and compiled into stand-alone executable programs. Communication between the spreadsheet data interface and the C++ programs was achieved via spreadsheet-embedded VBA macros. Specifically, the VBA macros function as exchanging input and output data and parameters between the spreadsheet interface and the external programs and between the multiple external programs. This modular toolkit design toolkit conveniently enables future toolkit functionality extensions by modifying existing modules and adding new modules into the existing structure. The conceptual structure of the toolkit is shown in Figure 5.2.

This structure comprises the following software components:

- Excel spreadsheet: Data storage, manipulation, visualization environment
- C++ programs: Computational engines

- VBA macros: Data and parameter communication between the Excel spreadsheet and C++ programs

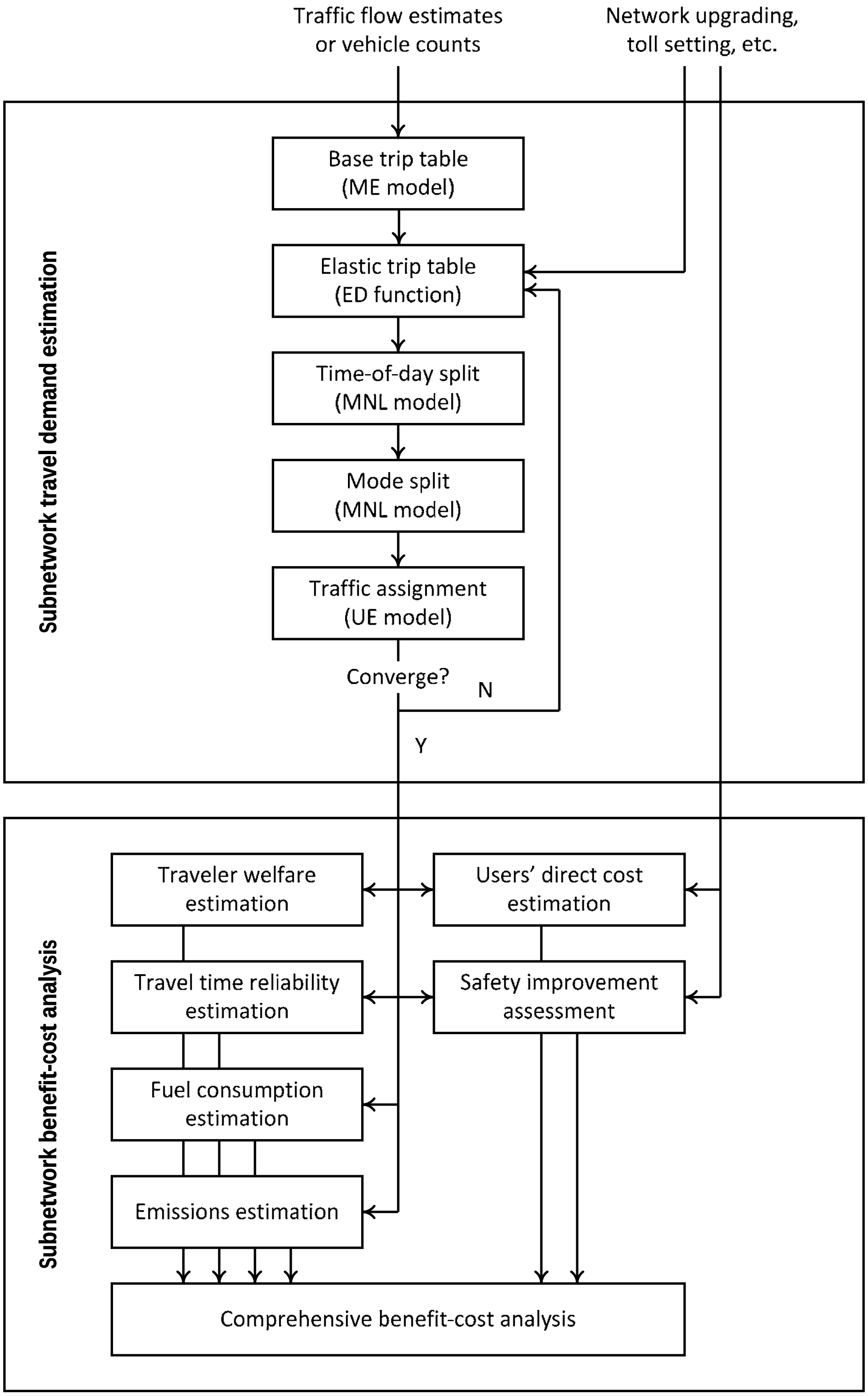
Traffic flow estimates or vehicle counts
Network upgrading, toll setting, etc.
Subnetwork travel demand estimation
Base trip table (ME model)
Elastic trip table (ED function)
Time-of-day split (MNL model)
Mode split (MNL model)
Traffic assignment (UE model)
Converge?
N
Y
Subnetwork benefit-cost analysis
Traveler welfare estimation
Users' direct cost estimation
Travel time reliability estimation
Safety improvement assessment
Fuel consumption estimation
Emissions estimation
Comprehensive benefit-cost analysis

Figure 5.1: Overall Model Perspective: Tying the Travel Demand Modules to Estimation and Valuation of Comprehensive Impacts

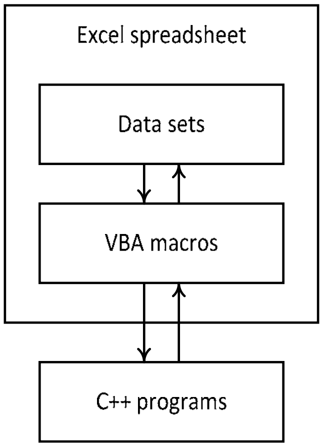

Figure 5.2: Conceptual Structure of the Toolkit

5.2 Performance Measures

The following performance measures are used in the toolkit for project evaluation and comparison.

5.2.1 Consumer Surplus

The demand model estimates traveler welfare benefits of each project scenario (vs. the no-build base case). These changes in traveler welfare are a function of travel times (and thus link speeds and traffic volumes) and direct user costs (including vehicle operating costs [fuel, maintenance, etc.] and tolls). Traveler welfare estimates are evaluated between each O-D pair, by necessity: when demand is elastic (i.e., travelers can choose different times of day, modes, and destinations), the economic value of complete trips cannot be captured at the link level. See Figure 5.3.

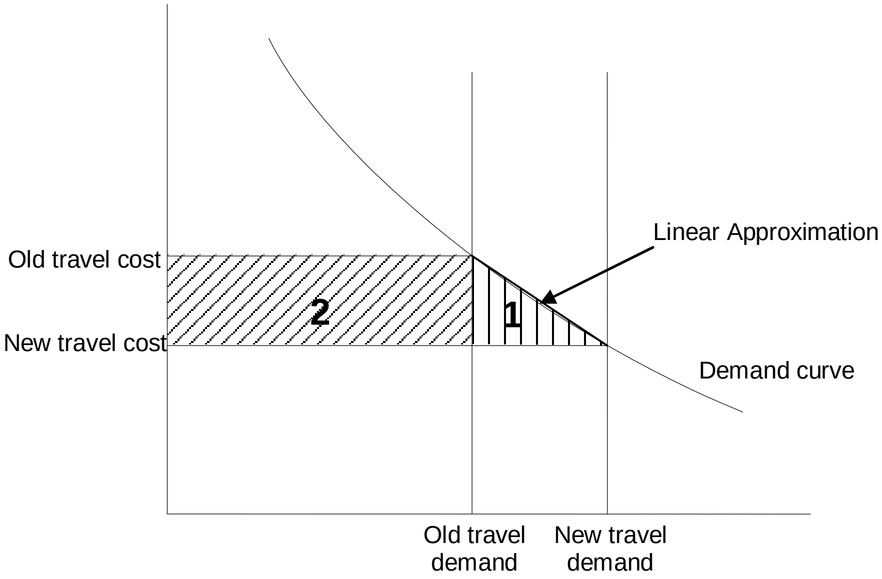

Figure 5.3: Changes in Consumer Surplus

The toolkit estimates traveler welfare using the Rule of Half (RoH), reflecting benefits to new travelers as well existing travelers between each O-D pair. As shown in Figure 5.3, the benefit to users equals the shaded areas. The RoH assumes a linear demand function applies estimation of Figure 5.3's area 1, for travel between each O-D pair. The toolkit also assumes multiple values of time, so each user group will experience different benefits (or costs) between each O-D pair. These impacts are summed over all O-D pairs, all traveler types, all modes, and all TODs, to properly reflect cost and benefit changes experienced by all system users.

The result of the variable travel demand model can be used to conduct network-wide benefit/cost analyses in terms of a variety of economic, environmental, and safety metrics. The performance measures the toolkit employs for project evaluation include traveler welfare or consumer surplus (CS) calculations, vehicle emissions, crash rates, construction cost, and reliability metrics. Because the toolkit uses an elastic demand model, it is more meaningful to use (estimates of) changes in traveler welfare than traditional total system travel time, which is used in the fixed-demand case. The following function may be used to calculate welfare changes under the specific modeling settings of the model's variable travel demand model.

Given the elastic demand function in (3.16)-(3.17) and the average occupancy rate in (3.24), the CS change ($\Delta CS_{ij,d}^{k}$) for travelers of class k from origin i to destination j during time-of-day period d can be approximately calculated by the rule-of-half method as, when the network change is not dramatic:

$$\mathit{\Delta} CS_{ij,d}^{k} \cong \frac{1}{2}\left(w_{ij}^{b,k} x_{ij,d}^{b,k} + w_{ij}^{k} x_{ij,d}^{k}\right)\left(g_{ij,d}^{b,k} - g_{ij,d}^{k}\right) \qquad \forall i, j, d, k \tag{5.1}$$

Then, the network-wide consumer surplus change is the sum of consumer surplus changes over all O-D pairs, and over all traveler classes and times of day:

$$\mathit{\Delta} CS = \sum_{d} \sum_{ij} \sum_{k} \mathit{\Delta} CS_{ij,d}^{k} \tag{5.2}$$

For more details about calculating and approximating CS changes, interested readers are referred to de Jong et al.'s review paper (2005), for example.

5.2.2 Reliability Estimates

The toolkit defines unreliability as the standard deviation in (link-level) travel times, so that reliability may be summed over all links, similar to travel times for route choices. Travel time deviations are estimated using a relationship calibrated between freeway volume-capacity ratios and travel time variances using traffic data provided by Cambridge Systematics, and obtained from two- to five-mile long freeway segments in Atlanta, Los Angeles, Seattle, and Minneapolis (Margiotta, 2009). The relationship is similar to a shifted version of the Bureau of Public Roads (BPR) link performance function, as follows:

$$r_{a,SD} = \sqrt{r_{a,VAR}^{0}\left(1 + \sigma\left(\gamma + \frac{v_a}{c_a}\right)^{\tau}\right)} \tag{5.3}$$

where $r_{a,VAR}^{0}$ is the free-flow travel time variance of link a, and σ, γ and τ are function parameters. Ordinary least squares regression resulted in the following parameter estimates: $r_{a,VAR}^{0}$=0.001, $\sigma = 2.3$, $\gamma = 0.7$, and $\tau = 8.4$.

The toolkit multiplies each link's travel time unreliability by each user's value of reliability[4] and sums over all links to determine the total system reliability costs.

5.2.3 Crash Estimates

Crashes are predicted using safety performance functions (SPFs) derived from Bonneson and Pratt's *Road Safety Design Workbook* (2009). These SPFs allow users to pivot off existing crash rates and crash counts to estimate future numbers of fatal, injurious (F+I), and property-damage-only crashes on each link in the system. Key factors are link functional classification, AADT, and number of lanes. Local land use type, median type, and intersection control also have important safety impacts along arterials, while entrance and exit ramp frequencies are important for freeways. Segment (link) crashes are estimated for all toolkit-coded roadway types, and intersection crashes are estimated for arterials and rural roads.

The toolkit default is to include the monetary impacts of motor vehicle crashes when assessing each project's Net Present Value (NPV), B/C ratio, Internal Rate of Return (IRR), and Payback Period (PP). Default crash costs were obtained from the National Highway Traffic Safety Administration's *Economic Impacts of Motor Vehicle Crashes 2000* (Blincoe et al., 2002), with a conversion to the USDOT's KABCO severity scale (and inflation to year 2010 costs). These values include market costs, such as lost productivity, medical services, travel delay, and property damage, but they do not include non-market factors, such as the value of life, pain and suffering, and values based on "willingness-to-pay" in order to avoid collisions.

5.2.4 Emission Estimates

The toolkit predicts emissions rates and totals using the U.S. Environmental Protection Agency's MOBILE 6.2 model's rates. The toolkit's extensive (1.37-million row) lookup tables provide grams per mile for 13 emissions species. These are the standard hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx), carbon dioxide (CO_2), particulate matter < 2.5μm ($PM_{2.5}$), particulate matter < 10μm (PM_{10}), and sulfur dioxide (SO_2), along with the following mobile-source air toxics (MSATs): ammonia (NH_3), benzene (BENZ), butadiene (BUTA), formaldehyde (FORM), acetaldehyde (ACET), and acrolein (ACRO). While many MSATS are not yet regulated, they are carcinogenic and thus of interest to the public and its policy makers (Health Effects Institute, 2007).

Emissions rates depend on facility type (freeway, arterial, local road, or ramp), vehicle speed (14 speed categories—from 2.5 mph and slower to 65 mph and faster), temperature range (four temperature ranges, with 30 degrees at the low end and 105 at the high end), year of analysis (based on analysis year closest to 2010, 2015, 2020, or 2025, and impacting vehicle ages [and thus rates]), vehicle type (28 types), and vehicle age (6 age categories in 5-year increments). The toolkit estimates the number of light and heavy duty vehicles on each link and their respective speeds. Sub-categories of light and heavy vehicles are then extrapolated from overall vehicle fleet distribution tables. Emissions rate estimates are provided for normal, exhaust generation of all emissions types. Evaporative emissions are also estimated for HC and BENZ, as are $PM_{2.5}$ and PM_{10} from brake wear and tear.

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[4] Brownstone and Small (2005) estimated the value of reliability (VOR), as measured in $/hr of travel time standard deviation, to be roughly 95 to 145% of the corresponding VOTT along freeways SR-95 and I-15 in the Los Angeles area. For this reason, the toolkit default is to assume that each user class's VOR equals its VOTT.

MOBILE6.2 assumes fixed CO_2 emissions rates (and essentially constant PM emissions rates) with speed, which is generally found to be unrealistic. Fuel use and CO_2 values across different speeds were modified based on fuel economies developed under work by West et al. (1997), as presented in Davis and Diegel (2007). Lower speeds thus significantly impact CO_2 and most other species, though not PM or NH_3 (which remains unintuitive). Various emissions rates begin to rise slightly for certain species above 40 mph but MOBILE6.2 rates terminate at 65 mph. Figure 5.4 illustrates per-mile emission rates with respect to vehicle speed on a freeway facility with 10% heavy vehicles at 80°F for HC, CO, and NOx.

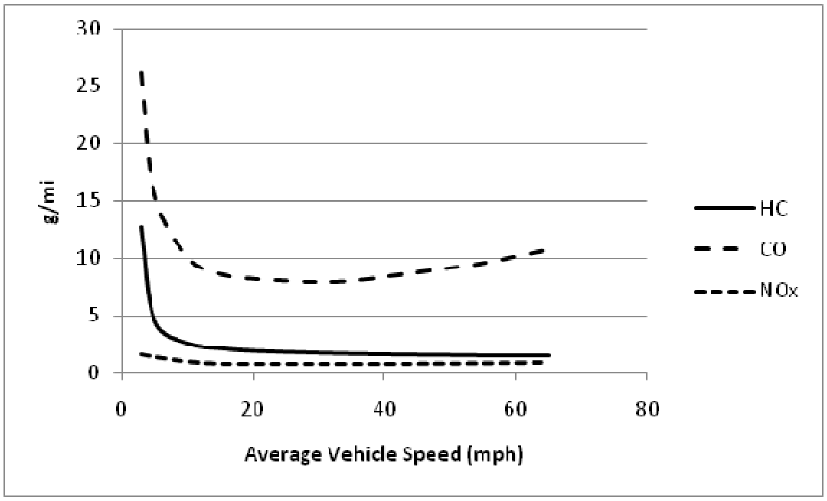


Figure 5.4: Freeway Emission Rates (2010, 10% HDV, 80°F)

Toolkit defaults do not monetize emissions, though McCubbin and Delucchi (1996) provide U.S. estimates and Maibach et al. (2008) present European estimates of emission costs for certain species based on health impacts. These range from \$2,900-\$5,800 per ton of HC, \$70–\$140 per ton of CO, \$620–\$7,600 per ton of NOx, \$620-\$18,000 per ton of SO_2 and \$4,500–\$830,000 per ton of $PM_{2.5}$ (all 2010 \$US), depending on area density, country and study.

5.2.5 Summary

The toolkit produces four summary measures (NPV, B/C, PP, and IRR, as noted earlier) for each project scenario, over the project lifetime. All measures require a base-case (typically no-build) point of reference to determine project impacts in terms of *changes* in traveler welfare and other benefits having monetary equivalents. NPV is determined with project costs as absolute values (not in relation to the base-case scenario), while other summary measure costs are in relation to the base-case scenario.

NPV is the project's worth over the entire design life (e.g., 20 to 30 years) in present dollars (measured from the initial build year). The B/C ratio is the sum of discounted (initial-year) benefits (relative to the base-case/no-build scenario) divided by the sum of discounted project costs over the entire project life. All project impacts are assumed to be benefits, and all changes to agency budgets are assumed to be costs. The PP is the point in time at which of the NPV of annual benefits first equals the NPV of all project costs, relative to the base-case scenario. The project's IRR determines the discount rate at which the sum of discounted costs equals the sum of discounted benefits (at their present-year worth) (Newnan and Lavelle, 1998).

If the B/C ratio is negative (i.e., greater disbenefits than benefits), the toolkit reports that the scenario's IRR is negative (but gives no specifics).

Traveler welfare (emphasizing travel time and operating costs) is always included in these summary measures. Travel time reliability, motor vehicle crash costs, and air pollutant costs may be monetized and included in the summary economic measures at the discretion of the analyst. The toolkit default monetizes *market* or economic components of crash costs only (including property damage, medical costs and lost productivity). The default does not monetize emissions costs, simply because these vary with exposure to population and remain rather uncertain and undocumented by the U.S. EPA. However, the toolkit's documentation provides ranges of potential valuations users can input if they elect to monetize these. Fuel consumption is not included in the summary measures because it is already accounted for in the operating costs component of traveler welfare valuations. Toll revenues are also not included because their direct impact should be neutralized by the transfer of traveler monies to tolling agencies. In other words, this cost to travelers is an equal dollar benefit to road authorities, excluding maintenance and overhead. However, the user-friendly spreadsheets of the toolkit (which serve as the graphical user interface) provide all these values.

5.3 Interface and Outputs of the Toolkit

The spreadsheet-based toolkit provides a variety of performance measures for economic, environmental, and safety evaluations. Total network travel time has long been used as a performance measure for evaluating network-wide improvements and traffic congestion levels. It is conveniently calculated based on the estimated traffic flow pattern using the links' cost functions. However, its meaningfulness is seriously compromised when accounting for elastic demand (including that coming from outside a sub-network). Essentially, this is because total travel time will often rise in expanded networks (as travelers opt for longer trips to more attractive destinations, at better [often peak] times of day, and may shift routes and modes [toward the automobile, in the case of highway improvements]). Instead, traveler welfare is often evaluated as a change in consumer surplus, reflecting changes in generalized travel costs and demand levels (by OD pair, time of day, user class, and mode). The toolkit has the capability to utilize rule-of-half estimates to quantify consumer surplus changes following network improvements.

Travel time reliability is best assessed in complicated dynamic networks, where travel time variability can be properly specified and quantified. In a deterministic network (as in the case of the sketch planning pursued here), travel time reliability (or unreliability) is best estimated using an empirical relationship between travel time variability and link volume-to-capacity (V/C) ratio (by different road types). The toolkit estimates this relationship on the link/route level based on the traffic data provided by Cambridge Systematics (Margiotta, 2009), as described in Chapter 6 and in Appendix A.

Direct, out-of-pocket costs, such as tolls, can be important factors affecting traveler choices and, hence, a network's traffic flow patterns. Fuel and emissions costs also relate to network outputs (including speeds and distances by vehicle and link type). These are quickly assembled from the network assignment results. In our models, tolls are charged on the link level and operating costs are assumed proportional to the link length.

Safety evaluation resorts to a relative complex procedure. Changes in flows, capacity, and highway design features can influence crash rates and outcomes. Crash prediction models (also referred to as safety prediction models) and accident modification factors (AMFs) are used to anticipate expected changes in crash frequency, then converted to monetary values for purposes of overall inter-project evaluations. Based on demand modeling results, the toolkit's project evaluation modules conduct comprehensive comparisons of expected travel, safety and emissions impacts to proposed project costs (both start-up and annual/longer term), using a variety of summary performance measures. These include net present values, cost-benefit ratios, internal rate of return, and payback periods, with the latter three summary measures as relative to the no-build case. All are described in detail in the toolkit's documentation, found on the accompanying CD.

The project toolkit has three levels of output detail that analysts can review. These reflect results for all project scenarios examined (in summary and versus the base case/no-build scenario) and include the following:

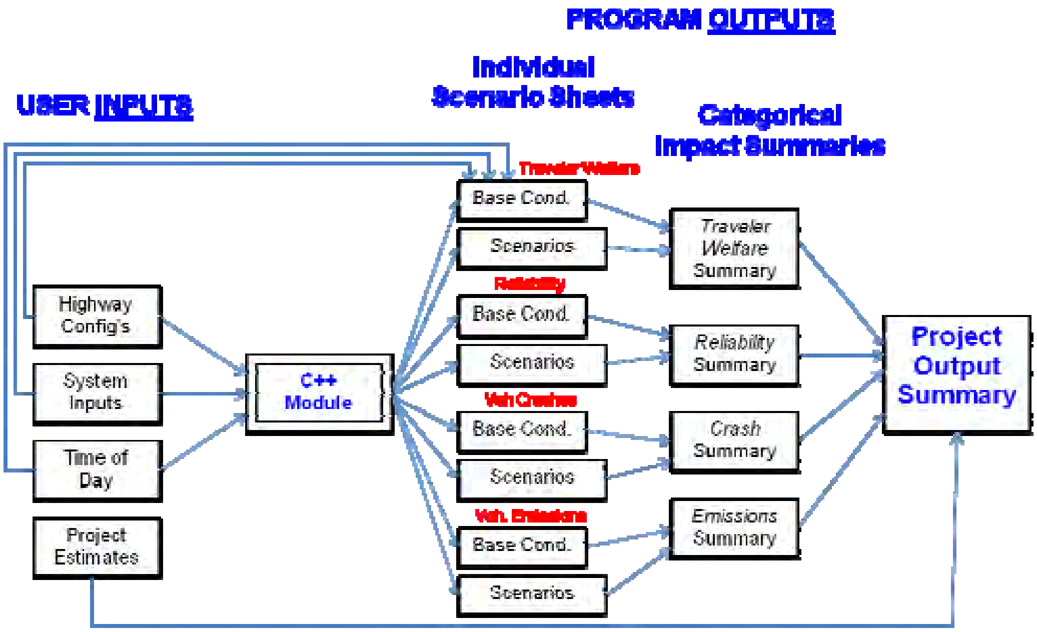
- The overall Project Output Summary,
- Impact Category Summaries, and
- Individual Scenario Sheets for each impact category.

Impact categories include:

- Traveler Welfare/User Surplus,
- Travel Time Reliability,
- Motor Vehicle Crashes, and
- Vehicle Emissions.

Each Individual Scenario Sheet assesses impacts for a single impact category and single scenario, for either the base year (construction year) or the future design year. Impact Category Summaries use that information to assess and compare the impacts across scenarios over the project design lives. The Project Output Summary uses the information determined by the Impact Category Summaries, along with other project costs (as input by the user), to develop an economic evaluation for each scenario.

Figure 5.5 details the toolkit's data flow diagram from the spreadsheet component's reference point.


PROGRAM OUTPUTS
USER INPUTS
Individual Scenario Sheets
Categorical Impact Summaries
Traveler Welfare
Base Cond.
Scenarios
Reliability
Base Cond.
Scenarios
Veh Crashes
Base Cond.
Scenarios
Veh. Emissions
Base Cond.
Scenarios
Highway Config's
System Inputs
Time of Day
Project Estimates
C++ Module
Traveler Welfare Summary
Reliability Summary
Crash Summary
Emissions Summary
Project Output Summary

Note: Hwy Configurations, System Inputs and Time of Day all directly influence all Individual Scenarios for Base Conditions and Scenarios, across all Impact Categories. Data link lines not shown to each Individual Scenario for diagram clarity.

Figure 5.5: The Toolkit's Data Flow Diagram

5.3.1 Project Output Summary

The Project Output Summary contains one column for each proposed project scenario alternative (up to three) plus an extra column for a 'no build' scenario. Total up-front design, right-of-way, and construction costs are listed for each scenario as well as annual changes in maintenance and operations, and interim project costs and year (if applicable). Also included for each scenario are the monetary impacts expected in the initial year and design year, as compared to the base-case scenario. These impacts are assessed and listed for traveler welfare, though annual monetized values may also be included for changes in reliability, vehicle crash, and emission costs, at the discretion of the toolkit user. Finally, an end-of-life salvage value is available for use by the user, for each scenario.

The toolkit uses the values listed above to perform financial analyses. For each scenario, net present values, internal rates of return, benefit-cost ratios, and payback periods are determined and listed in the Project Output Summary. The discount rate and the project design life may be specified by the user (by overwriting easily accessible default values).

The following equations illustrate how the program calculates net present values, internal rates of return, benefit-cost ratios, and payback periods:

Net Present Value (NPV) is calculated as follows:

$$\begin{aligned} NPV = -C_i + SV\left(\frac{1}{1+DR}\right)^{proj\ life} - IPC\left(\frac{1}{1+DR}\right)^{year} \\ + \sum_{y=1}^{proj\ life} (B_y - C_y)\left(\frac{1}{1+DR}\right)^{y} \end{aligned} \tag{5.4}$$

where C_i is the initial project cost, SV is the salvage value, IPC is the interim project costs, DR is the discount rate, B_y is the benefits realized in a given year, and C_y is the costs realized in a given year.

The Benefit-Cost (B/C) Ratio is calculated as:

$$B/C\ Ratio = \frac{\sum_{y=1}^{proj\ life}\left(B_y\right)\left(\frac{1}{1+DR}\right)^{y}}{C_i + \sum_{y=1}^{proj\ life}\left(C_y\right)\left(\frac{1}{1+DR}\right)^{y} - SV\left(\frac{1}{1+DR}\right)^{proj\ life} + IPC\left(\frac{1}{1+DR}\right)^{year}} \tag{5.5}$$

The Payback Period (PP) is the point at which the sum of the annual benefits subtracted from the annual costs equal the initial project costs. This is calculated using Excel's embedded financial calculator to solve the following equation:

$$C_i = \sum_{y=1}^{PP}\left(B_y - C_y\right)\left(\frac{1}{1+DR}\right)^{y} \tag{5.6}$$

The project's Internal Rate of Return (IRR) determines the discount rate at which the sum of discounted costs equals the sum of discounted benefits (i.e., at their present-year worth). This is calculated using Excel's embedded financial calculator, to solve the following equation:

$$C_i + \sum_{y=1}^{proj\ life}\left(C_y\right)\left(\frac{1}{1+IRR}\right)^{y} - SV\left(\frac{1}{1+IRR}\right)^{proj\ life} + IPC\left(\frac{1}{1+DR}\right)^{year} = \sum_{y=1}^{proj\ life}\left(B_y\right)\left(\frac{1}{1+IRR}\right)^{y} \tag{5.7}$$

Also shown in the Project Output Summary are total changes in motor vehicle crashes, listed by severity, and total changes in emissions, listed by emissions type. This is particularly useful for project assessment if the analyst chooses not to include monetized annual crash and emissions values.

Figure 5.6 illustrates a Project Output Summary screen for a set of example projects. Navigation aids will be present on this sheet to linking to Project Cost Estimates and Categorical Impact Summaries (not shown here yet), and all sheets with have lower tabs automatically titled with relevant info.

5.3.2 Impact Category Summary

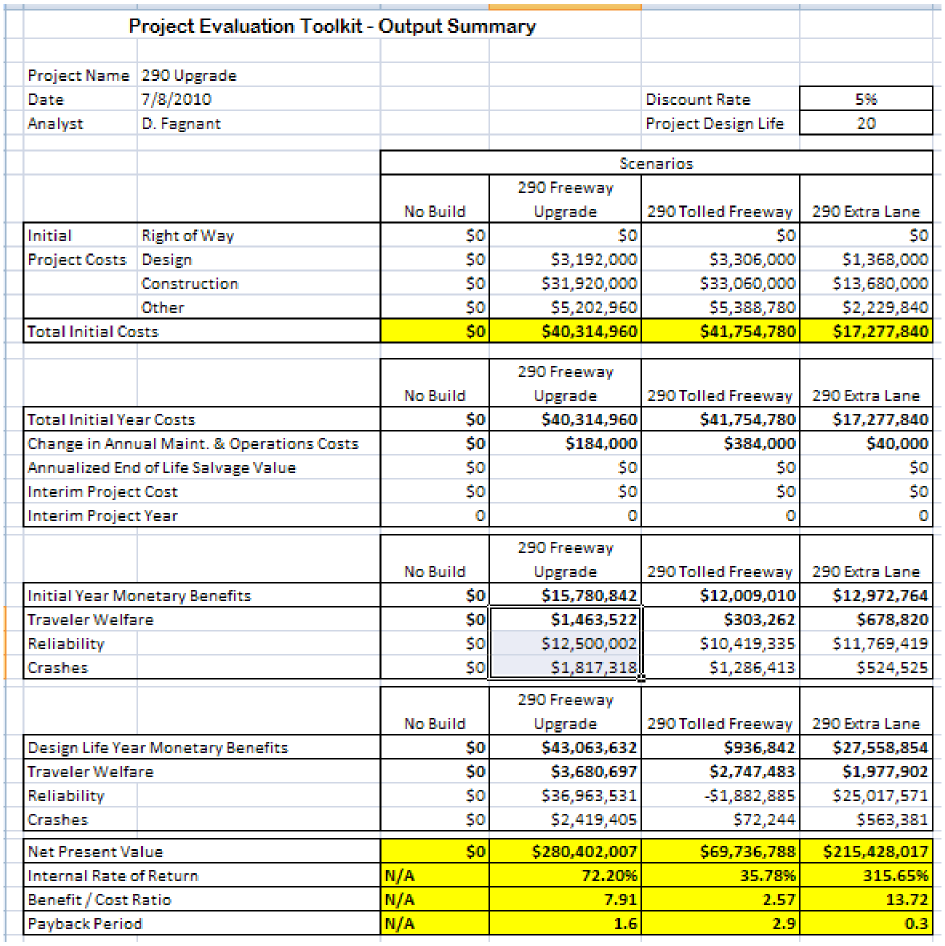
Impact Category Summaries are provided for traveler welfare, reliability, crash, and emissions impacts. Each summary sheet takes cost information for each scenario's base and design year (Figure 5.7). Either linear or exponential growth (as selected by the analyst) is applied to all costs for years between the base year and design life year. Average annual costs, growth rates, and cost changes (versus the base-case scenario) are assessed for each scenario.

5.3.3 Individual Scenario Sheets

Individual Scenario Sheets detail what is occurring at the link level for each time of day for a given impact category. Table 5.1 shows impacts identified at the link level for individual scenarios:

Table 5.1: Link-Level Performance Measures

Impact Category	Measured Link Level Impacts
Traveler Welfare[5]	Link Speed and Traffic Volumes, Listed by User Type
Reliability	Travel Time Variance
Motor Vehicle Crashes	Number and Cost of Crashes, Listed by Severity
Vehicle Emissions	Quantity and Cost of Emissions, Listed by Type and Fuel Use



Project Evaluation Toolkit - Output Summary

Project Name	290 Upgrade		
Date	7/8/2010	Discount Rate	5%
Analyst	D. Fagnant	Project Design Life	20

		Scenarios			
		No Build	290 Freeway Upgrade	290 Tolled Freeway	290 Extra Lane
Initial Project Costs	Right of Way	$0	$0	$0	$0
	Design	$0	$3,192,000	$3,306,000	$1,368,000
	Construction	$0	$31,920,000	$33,060,000	$13,680,000
	Other	$0	$5,202,960	$5,388,780	$2,229,840
Total Initial Costs		$0	$40,314,960	$41,754,780	$17,277,840

	No Build	290 Freeway Upgrade	290 Tolled Freeway	290 Extra Lane
Total Initial Year Costs	$0	$40,314,960	$41,754,780	$17,277,840
Change in Annual Maint. & Operations Costs	$0	$184,000	$384,000	$40,000
Annualized End of Life Salvage Value	$0	$0	$0	$0
Interim Project Cost	$0	$0	$0	$0
Interim Project Year	0	0	0	0

	No Build	290 Freeway Upgrade	290 Tolled Freeway	290 Extra Lane
Initial Year Monetary Benefits	$0	$15,780,842	$12,009,010	$12,972,764
Traveler Welfare	$0	$1,463,522	$303,262	$678,820
Reliability	$0	$12,500,002	$10,419,335	$11,769,419
Crashes	$0	$1,817,318	$1,286,413	$524,525

	No Build	290 Freeway Upgrade	290 Tolled Freeway	290 Extra Lane
Design Life Year Monetary Benefits	$0	$43,063,632	$936,842	$27,558,854
Traveler Welfare	$0	$3,680,697	$2,747,483	$1,977,902
Reliability	$0	$36,963,531	-$1,882,885	$25,017,571
Crashes	$0	$2,419,405	$72,244	$563,381

Net Present Value	$0	$280,402,007	$69,736,788	$215,428,017
Internal Rate of Return	N/A	72.20%	35.78%	315.65%
Benefit / Cost Ratio	N/A	7.91	2.57	13.72
Payback Period	N/A	1.6	2.9	0.3

(a) Economic Summary Measures

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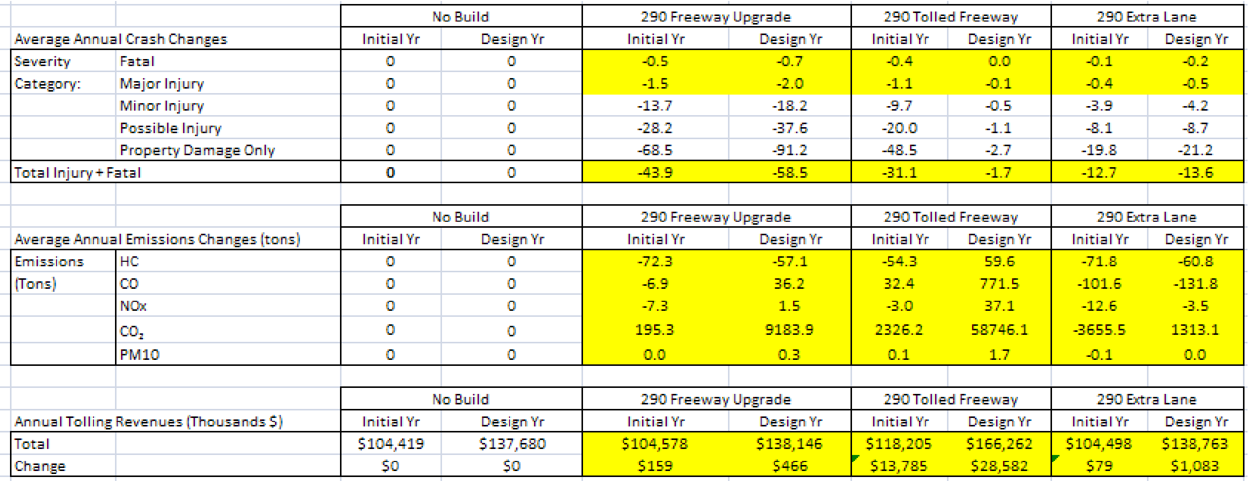
[5] Changes in traveler welfare are a function of travel times (and thus link speeds and traffic volumes), direct user costs (fuel, tolls, fares, vehicle maintenance, etc.) and the base attractiveness of various choices (time of day, destination, and mode). Thus, while vehicle speeds and volumes are relevant to traveler welfare, they are not the sole influences. When demand is elastic (e.g., travelers can choose different times of day, modes, and destinations) the economic value of complete trips is impossible to capture at the link level, so user surplus is not included at the link level in the traveler welfare Individual Scenario Sheet.



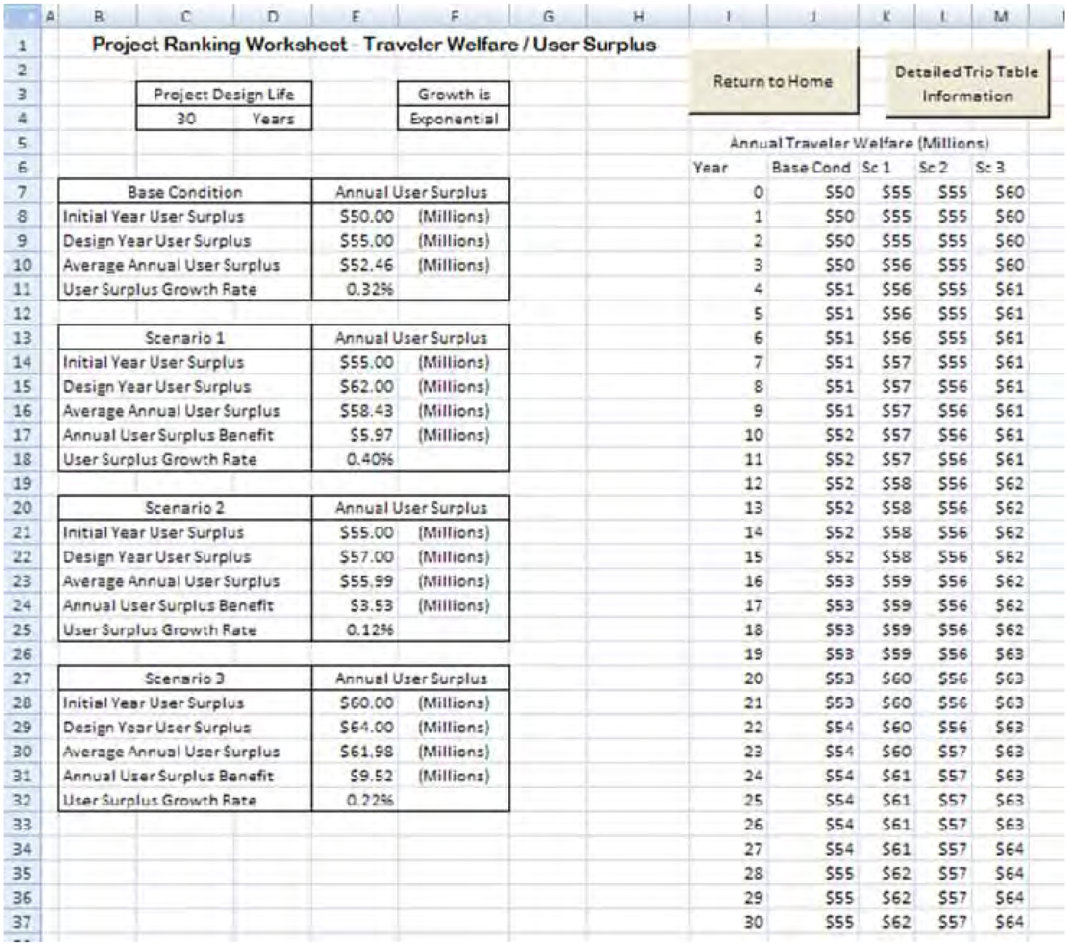
		No Build		290 Freeway Upgrade		290 Tolled Freeway		290 Extra Lane	
Average Annual Crash Changes		Initial Yr	Design Yr	Initial Yr	Design Yr	Initial Yr	Design Yr	Initial Yr	Design Yr
Severity	Fatal	0	0	-0.5	-0.7	-0.4	0.0	-0.1	-0.2
Category:	Major Injury	0	0	-1.5	-2.0	-1.1	-0.1	-0.4	-0.5
	Minor Injury	0	0	-13.7	-18.2	-9.7	-0.5	-3.9	-4.2
	Possible Injury	0	0	-28.2	-37.6	-20.0	-1.1	-8.1	-8.7
	Property Damage Only	0	0	-68.5	-91.2	-48.5	-2.7	-19.8	-21.2
Total Injury + Fatal		0	0	-43.9	-58.5	-31.1	-1.7	-12.7	-13.6

		No Build		290 Freeway Upgrade		290 Tolled Freeway		290 Extra Lane	
Average Annual Emissions Changes (tons)		Initial Yr	Design Yr	Initial Yr	Design Yr	Initial Yr	Design Yr	Initial Yr	Design Yr
Emissions	HC	0	0	-72.3	-57.1	-54.3	59.6	-71.8	-60.8
(Tons)	CO	0	0	-6.9	36.2	32.4	771.5	-101.6	-131.8
	NOx	0	0	-7.3	1.5	-3.0	37.1	-12.6	-3.5
	CO_2	0	0	195.3	9183.9	2326.2	58746.1	-3655.5	1313.1
	PM10	0	0	0.0	0.3	0.1	1.7	-0.1	0.0

		No Build		290 Freeway Upgrade		290 Tolled Freeway		290 Extra Lane	
Annual Tolling Revenues (Thousands $)		Initial Yr	Design Yr	Initial Yr	Design Yr	Initial Yr	Design Yr	Initial Yr	Design Yr
Total		$104,419	$137,680	$104,578	$138,146	$118,205	$166,262	$104,498	$138,763
Change		$0	$0	$159	$466	$13,785	$28,582	$79	$1,083

(b) Additional Project Impacts

Figure 5.6: Sample Project Output Summary



Project Ranking Worksheet - Traveler Welfare / User Surplus

Project Design Life	
30	Years

Growth is
Exponential

Base Condition	Annual User Surplus	
Initial Year User Surplus	$50.00	(Millions)
Design Year User Surplus	$55.00	(Millions)
Average Annual User Surplus	$52.46	(Millions)
User Surplus Growth Rate	0.32%	

Scenario 1	Annual User Surplus	
Initial Year User Surplus	$55.00	(Millions)
Design Year User Surplus	$62.00	(Millions)
Average Annual User Surplus	$58.43	(Millions)
Annual User Surplus Benefit	$5.97	(Millions)
User Surplus Growth Rate	0.40%	

Scenario 2	Annual User Surplus	
Initial Year User Surplus	$55.00	(Millions)
Design Year User Surplus	$57.00	(Millions)
Average Annual User Surplus	$55.99	(Millions)
Annual User Surplus Benefit	$3.53	(Millions)
User Surplus Growth Rate	0.12%	

Scenario 3	Annual User Surplus	
Initial Year User Surplus	$60.00	(Millions)
Design Year User Surplus	$64.00	(Millions)
Average Annual User Surplus	$61.98	(Millions)
Annual User Surplus Benefit	$9.52	(Millions)
User Surplus Growth Rate	0.22%	

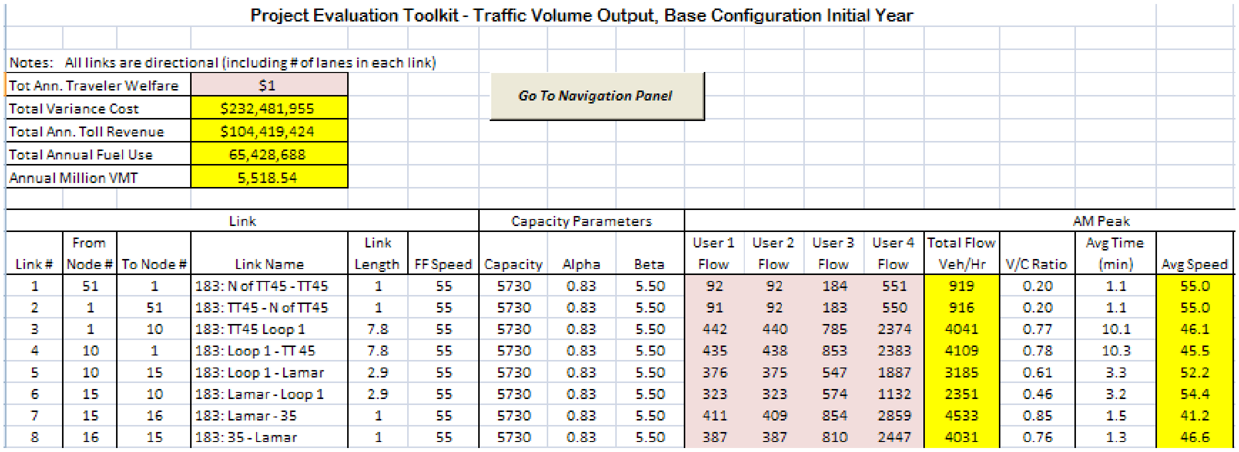
Annual Traveler Welfare (Millions)

Year	Base Cond	Sc 1	Sc 2	Sc 3
0	$50	$55	$55	$60
1	$50	$55	$55	$60
2	$50	$55	$55	$60
3	$50	$56	$55	$60
4	$51	$56	$55	$61
5	$51	$56	$55	$61
6	$51	$56	$55	$61
7	$51	$57	$55	$61
8	$51	$57	$56	$61
9	$51	$57	$56	$61
10	$52	$57	$56	$61
11	$52	$57	$56	$61
12	$52	$58	$56	$62
13	$52	$58	$56	$62
14	$52	$58	$56	$62
15	$52	$58	$56	$62
16	$53	$59	$56	$62
17	$53	$59	$56	$62
18	$53	$59	$56	$62
19	$53	$59	$56	$63
20	$53	$60	$56	$63
21	$53	$60	$56	$63
22	$54	$60	$56	$63
23	$54	$60	$57	$63
24	$54	$61	$57	$63
25	$54	$61	$57	$63
26	$54	$61	$57	$63
27	$54	$61	$57	$64
28	$55	$62	$57	$64
29	$55	$62	$57	$64
30	$55	$62	$57	$64

Figure 5.7: Sample Project Impact Category Summary for Traveler Welfare/User Surplus

Also shown on the Individual Scenario Sheets is other relevant travel data that influences traveler welfare, crashes, and/or emissions. For each Impact Category Summary there are eight Individual Scenario Sheets, one for the base case and each alternative scenario for both the initial year and the design year. The exception is the 16 vehicle crash Individual Scenario Sheets, which show estimates of intersection crashes separately from roadway segment crashes.

The following text describes how outputs are derived for each Individual Scenario Sheet, including traveler welfare (user surplus), travel time reliability, motor vehicle crashes, and vehicle emissions. For example, the Individual Scenario Sheets for traveler welfare (user surplus) detail the user types, speeds, and numbers of vehicles. User surplus is displayed on the sheet at the total system level, but not for individual links. This is because user surplus is estimated at the origin-destination level and does not translate to the link level. User surplus is calculated using logit models that determine (expected) maximum utility for the average system user in each category (e.g., each origin-destination pair and each value of travel time category). Figure 5.8 illustrates an Individual Scenario Sheet of traveler welfare for an example project.



Project Evaluation Toolkit - Traffic Volume Output, Base Configuration Initial Year

Notes: All links are directional (including # of lanes in each link)

Tot Ann. Traveler Welfare	$1
Total Variance Cost	$232,481,955
Total Ann. Toll Revenue	$104,419,424
Total Annual Fuel Use	65,428,688
Annual Million VMT	5,518.54

Link						Capacity Parameters			AM Peak							
Link #	From Node #	To Node #	Link Name	Link Length	FF Speed	Capacity	Alpha	Beta	User 1 Flow	User 2 Flow	User 3 Flow	User 4 Flow	Total Flow Veh/Hr	V/C Ratio	Avg Time (min)	Avg Speed
1	51	1	183: N of TT45 - TT45	1	55	5730	0.83	5.50	92	92	184	551	919	0.20	1.1	55.0
2	1	51	183: TT45 - N of TT45	1	55	5730	0.83	5.50	91	92	183	550	916	0.20	1.1	55.0
3	1	10	183: TT45 Loop 1	7.8	55	5730	0.83	5.50	442	440	785	2374	4041	0.77	10.1	46.1
4	10	1	183: Loop 1 - TT 45	7.8	55	5730	0.83	5.50	435	438	853	2383	4109	0.78	10.3	45.5
5	10	15	183: Loop 1 - Lamar	2.9	55	5730	0.83	5.50	376	375	547	1887	3185	0.61	3.3	52.2
6	15	10	183: Lamar - Loop 1	2.9	55	5730	0.83	5.50	323	323	574	1132	2351	0.46	3.2	54.4
7	15	16	183: Lamar - 35	1	55	5730	0.83	5.50	411	409	854	2859	4533	0.85	1.5	41.2
8	16	15	183: 35 - Lamar	1	55	5730	0.83	5.50	387	387	810	2447	4031	0.76	1.3	46.6

Figure 5.8: Sample Project Individual Scenario Sheet of Traveler Welfare

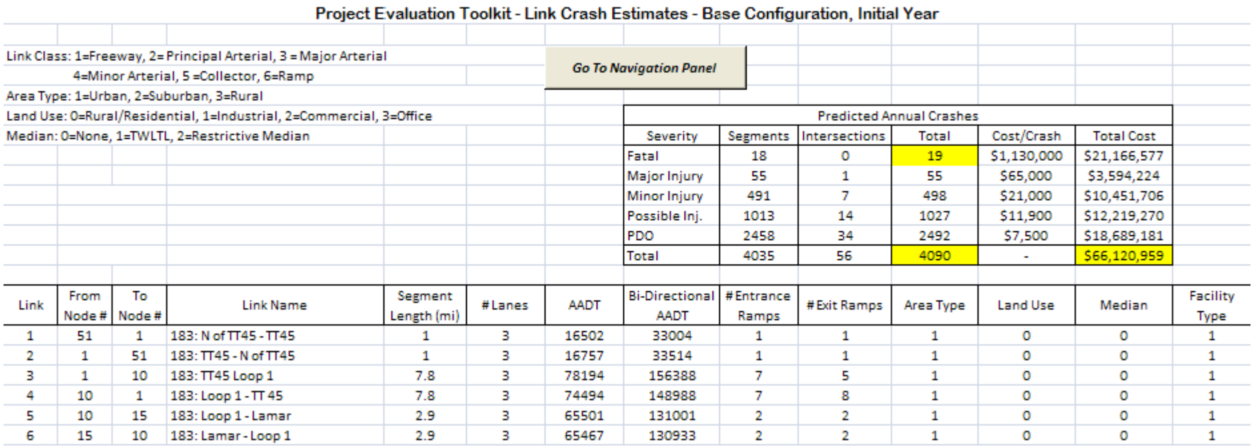
Fuel usage and reliability are also reported in the traffic volume output Individual Scenario Sheets, though fuel is not monetized. The economic effects of fuel are accounted for in the user surplus estimations. And total fuel consumption estimates is reported in the summary sheets (to give users a sense of energy impacts across project scenarios). Estimates of total change in the economic value of reliability is calculated if the user elects to include monetized reliability. Reliability data from Cambridge Systematics are being used to ascertain travel time uncertainty directly as a function of the V/C ratio, allowing for route choices to be made on the basis of unreliability costs (along with average travel time, fuel, tolls, and other costs). Coupled with values of reliability estimated in the literature (see, e.g., Small and Verhoef, 2007), impact costs can be ascertained. Users can turn this toolkit feature off by assigning a value of $0 to reliability for each type of user.

The Individual Scenario Sheets for motor vehicle crashes estimate the expected numbers of crashes to occur over each link each year. The estimates are generated using a base crash rate (per VMT) for each facility type, with accident modification factors (AMFs). Crash rates are calculated as:

$$Crash\ Rate = Crash\ Rate_{Facility\ Type\ Avg} \times AMF_1 \times \ldots \times AMF_N \tag{5.8}$$

The toolkit automatically calculates AMFs for congestion levels (V/C ratio) and number of lanes. The user can also input additional AMFs in the highway configuration input sheets that he/she expects will affect crash rates (e.g., widened shoulders, installing lighting). These may be obtained from Bonneson and Pratt's *Road Safety Design Workbook* (2009) or the recently released Highway Safety Manual, though some formulas that may be more commonly used will be provided in an AMF reference tab in the project toolkit.

Total crash cost estimates are also calculated in the Individual Scenario Sheet, if the user elects to include monetized crash values. Figure 5.9 illustrates a motor vehicle crash Individual Scenario Sheet for an example project.



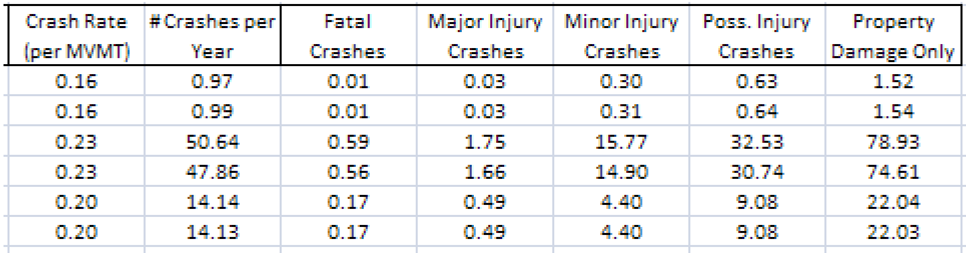
Project Evaluation Toolkit - Link Crash Estimates - Base Configuration, Initial Year

Link Class: 1=Freeway, 2= Principal Arterial, 3 = Major Arterial
4=Minor Arterial, 5 =Collector, 6=Ramp
Area Type: 1=Urban, 2=Suburban, 3=Rural
Land Use: 0=Rural/Residential, 1=Industrial, 2=Commercial, 3=Office
Median: 0=None, 1=TWLTL, 2=Restrictive Median

Predicted Annual Crashes					
Severity	Segments	Intersections	Total	Cost/Crash	Total Cost
Fatal	18	0	19	$1,130,000	$21,166,577
Major Injury	55	1	55	$65,000	$3,594,224
Minor Injury	491	7	498	$21,000	$10,451,706
Possible Inj.	1013	14	1027	$11,900	$12,219,270
PDO	2458	34	2492	$7,500	$18,689,181
Total	4035	56	4090	-	$66,120,959

Link	From Node #	To Node #	Link Name	Segment Length (mi)	# Lanes	AADT	Bi-Directional AADT	# Entrance Ramps	# Exit Ramps	Area Type	Land Use	Median	Facility Type
1	51	1	183: N of TT45 - TT45	1	3	16502	33004	1	1	1	0	0	1
2	1	51	183: TT45 - N of TT45	1	3	16757	33514	1	1	1	0	0	1
3	1	10	183: TT45 Loop 1	7.8	3	78194	156388	7	5	1	0	0	1
4	10	1	183: Loop 1 - TT 45	7.8	3	74494	148988	7	8	1	0	0	1
5	10	15	183: Loop 1 - Lamar	2.9	3	65501	131001	2	2	1	0	0	1
6	15	10	183: Lamar - Loop 1	2.9	3	65467	130933	2	2	1	0	0	1

(a) Input



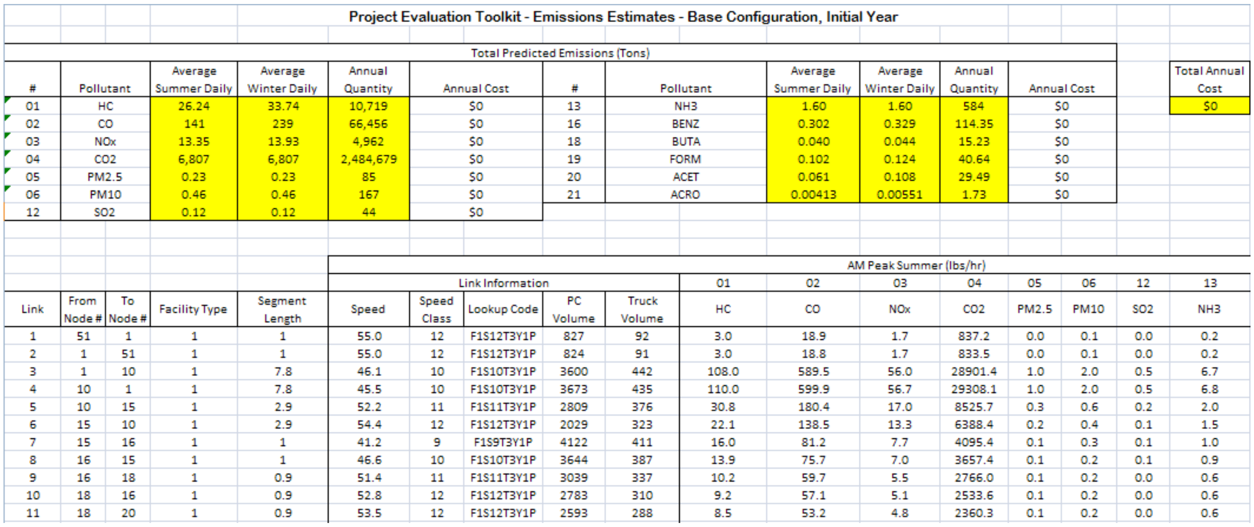
Crash Rate (per MVMT)	# Crashes per Year	Fatal Crashes	Major Injury Crashes	Minor Injury Crashes	Poss. Injury Crashes	Property Damage Only
0.16	0.97	0.01	0.03	0.30	0.63	1.52
0.16	0.99	0.01	0.03	0.31	0.64	1.54
0.23	50.64	0.59	1.75	15.77	32.53	78.93
0.23	47.86	0.56	1.66	14.90	30.74	74.61
0.20	14.14	0.17	0.49	4.40	9.08	22.04
0.20	14.13	0.17	0.49	4.40	9.08	22.03

(b) Output

Figure 5.9: Sample Project Individual Scenario Sheet for Vehicle Crashes

The Individual Scenario Sheets for vehicle emissions provide estimates of tons of emissions per link per year, as generated using lookup tables based on EPA's MOBILE 6.2 software. The project toolkit uses traffic volumes, speeds, temperatures, vehicle fleet makeup, and facility type to estimate emissions volumes in a given hour. These are summed up over all hours of the day, days of the year, and links in the system to estimate total emissions by scenario and year. They include VOC, NOx, CO, PM_{10}, $PM_{2.5}$, CO_2, and mobile source air toxins (MSATS).

Estimates of total emissions costs are also provided in the Individual Scenario Sheet, if the user elects to include monetized values. (The default is to not monetize these, though users can modify monetary assumptions, based on guidance provided in the toolkit documentation or any other information the user elects to use.) Figure 5.10 illustrates an emissions Scenario Sheet for an example project.



Project Evaluation Toolkit - Emissions Estimates - Base Configuration, Initial Year

Total Predicted Emissions (Tons)

#	Pollutant	Average Summer Daily	Average Winter Daily	Annual Quantity	Annual Cost	#	Pollutant	Average Summer Daily	Average Winter Daily	Annual Quantity	Annual Cost
01	HC	26.24	33.74	10,719	$0	13	NH3	1.60	1.60	584	$0
02	CO	141	239	66,456	$0	16	BENZ	0.302	0.329	114.35	$0
03	NOx	13.35	13.93	4,962	$0	18	BUTA	0.040	0.044	15.23	$0
04	CO2	6,807	6,807	2,484,679	$0	19	FORM	0.102	0.124	40.64	$0
05	PM2.5	0.23	0.23	85	$0	20	ACET	0.061	0.108	29.49	$0
06	PM10	0.46	0.46	167	$0	21	ACRO	0.00413	0.00551	1.73	$0
12	SO2	0.12	0.12	44	$0						

Total Annual Cost
$0

					Link Information					AM Peak Summer (lbs/hr)							
										01	02	03	04	05	06	12	13
Link	From Node #	To Node #	Facility Type	Segment Length	Speed	Speed Class	Lookup Code	PC Volume	Truck Volume	HC	CO	NOx	CO2	PM2.5	PM10	SO2	NH3
1	51	1	1	1	55.0	12	F1S12T3Y1P	827	92	3.0	18.9	1.7	837.2	0.0	0.1	0.0	0.2
2	1	51	1	1	55.0	12	F1S12T3Y1P	824	91	3.0	18.8	1.7	833.5	0.0	0.1	0.0	0.2
3	1	10	1	7.8	46.1	10	F1S10T3Y1P	3600	442	108.0	589.5	56.0	28901.4	1.0	2.0	0.5	6.7
4	10	1	1	7.8	45.5	10	F1S10T3Y1P	3673	435	110.0	599.9	56.7	29308.1	1.0	2.0	0.5	6.8
5	10	15	1	2.9	52.2	11	F1S11T3Y1P	2809	376	30.8	180.4	17.0	8525.7	0.3	0.6	0.2	2.0
6	15	10	1	2.9	54.4	12	F1S12T3Y1P	2029	323	22.1	138.5	13.3	6388.4	0.2	0.4	0.1	1.5
7	15	16	1	1	41.2	9	F1S9T3Y1P	4122	411	16.0	81.2	7.7	4095.4	0.1	0.3	0.1	1.0
8	16	15	1	1	46.6	10	F1S10T3Y1P	3644	387	13.9	75.7	7.0	3657.4	0.1	0.2	0.1	0.9
9	16	18	1	0.9	51.4	11	F1S11T3Y1P	3039	337	10.2	59.7	5.5	2766.0	0.1	0.2	0.0	0.6
10	18	16	1	0.9	52.8	12	F1S12T3Y1P	2783	310	9.2	57.1	5.1	2533.6	0.1	0.2	0.0	0.6
11	18	20	1	0.9	53.5	12	F1S12T3Y1P	2593	288	8.5	53.2	4.8	2360.3	0.1	0.2	0.0	0.6

Figure 5.10: Sample Project Individual Scenario Output Sheet for Emissions Costs

5.4 Summary

Transportation planners and analysts using this project's toolkit should be able to quickly identify the major impacts, benefit-cost ratios, and other key points of comparison for all user-defined projects. The toolkit's output structure enables users to quickly perform and review a range of key project impacts, including comprehensive economic analyses. Users can choose to observe the broad impacts of individual projects and how they affect traveler welfare, reliability, crash counts (by severity), and mobile-source emissions. Moreover, users can drill down to the individual link level for each scenario in base and future years to appreciate estimates affecting one or more impact categories. In this way, program outputs provide both clear and broad summaries as well as detailed link level information, to meet individual users' needs.

Chapter 6. Results of Case Studies

Two case studies that use the developed toolkit to evaluate highway upgrade projects are presented in this chapter. The upgrade options used in these two case studies include capacity expansion and setting tolls. The purpose of the case studies was to demonstrate the effectiveness and capability of the developed toolkit in assessing changes in travel patterns, traveler welfare, travel time reliability, vehicle crashes, emissions, fuel use, and tolling revenues across multiple project scenarios. The toolkit provides a quick-response, cost-effective approach for agency staff and decision makers to rigorously compare each alternative scenario and pursue projects that are likely to provide the best outcomes per dollar invested.

6.1 Case Studies

Two major case studies were conducted in Austin to test the toolkit's capabilities. The first focuses on a 5.2-mile stretch of US Route 290 between US Route 183 and State Highway 130. US Route 290 is a major east-west corridor on the edge of Austin in a developing area of the city, about 7 miles northeast of Austin's downtown and capitol building. Travel demand currently matches or exceeds roadway capacity along this four-lane arterial during the mid-day and PM peak periods. Three alternative scenarios were investigated, including a grade-separated freeway upgrade (keeping the same number of lanes), a grade-separated tollway (keeping the same number of lanes and tolled at $1 or just under $0.20 per mile), and an added lane in each direction.

The second major case study focuses on strategies to limit travel demand on an eight-lane 4.9-mile stretch of Interstate Highway 35 between US Route 183 and 15th Street. IH 35 is a major U.S. trade corridor and the backbone of Austin's congested network, running north-south through the eastern edge of Austin's downtown, with over 100,000 AADT in each direction along the modified segments. Three alternative scenarios were examined in this case study; the first two attempt to limit travel demand by introducing either a $1 or a $2 toll (just under $0.20 and $0.40 per mile, respectively), and the third attempts to limit capacity by removing a travel lane in either direction (to match the six-lane sections that lie just outside the 4.9-mile stretch).

To model both contexts, an abstracted roadway network for the region was created as shown in Figure 6.1. It includes 194 freeway and arterial links and 62 nodes, capturing approximately 70% of all Austin area VMT. Link capacities were obtained from the Capital Area Metropolitan Planning Organization's (CAMPO's) regional travel demand model, and traffic link volumes were obtained from the Texas Department of Transportation's (TxDOT's) most recent 2008 traffic counts (CAMPO, 2009). An annually compounded 1% growth rate in travel demand between all O-D pairs was assumed, along with a 5% annual discount rate. This latter value is lower than the 7% required by the Office of Management and Budget (OMB) for federal projects, but is on the high end of the 3 to 5% discount rates typically used for state transportation projects, as reported by the FHWA (2007). Summer temperatures were assumed to average 80 degrees and winter temperatures 50 degrees Fahrenheit (impacting emissions rates). Fatal and injury (F+I) crashes as a share of total crashes was assumed to mirror Texas' statewide statistics for urban areas (TxDOT, 2009) (so 1.2% of all F+I crashes were assumed to be fatalities.

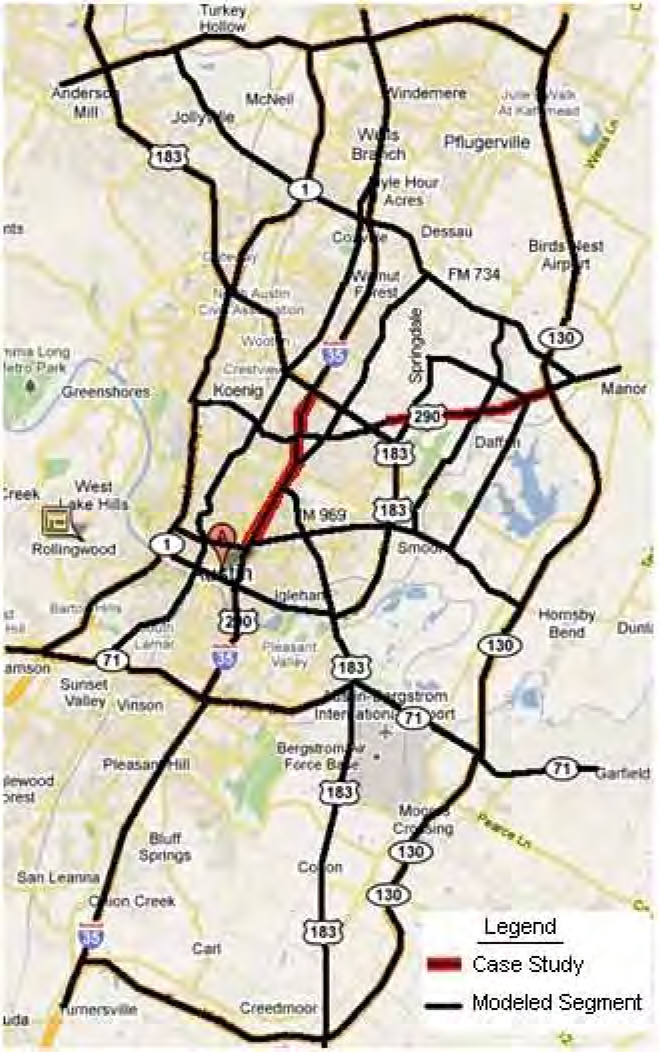

Legend
Case Study
Modeled Segment
Turkey Hollow
McNeil
Windemere
Pflugerville
Dessau
FM 734
Manor
Koenig
Springdale
290
183
130
71
1
35
Rollingwood
West Lake Hills
Greenshores
Hornsby Bend
Sunset Valley
Vinson
Pleasant Hill
Bluff Springs
San Leanna
Creedmoor
Garfield
FM 969
Bergstrom Air Force Base

Figure 6.1: Case Study Locations

Four user classes were assumed, with AADT input shares in the base-case initial year as follows: 10% of total traffic on each link as commercial trucks with a $50 per hour VOTT, 10% work-related travelers with a $30 per hour VOTT, 20% at $10 per hour VOTT, and 60% at $5 per hour VOTT. Those seeking further details can refer to Kockelman et al.'s (2010) report. All case studies represent hypothetical uses for the toolkit, and do not reflect actual planned projects.

6.1.1 Capacity Expansion (Case Study 1)

The US Route 290 case study enjoys an existing/base-case corridor capacity that varies between 1,360 vehicles per hour (vph) and 1,720 vph. This was expanded to a uniform capacity of 3,820 vph in the tolled and non-tolled grade-separation alternatives and to a uniform capacity of 2,040 vph in the lane-add scenario. Project costs were estimated at $71.8 million for Alternative 1 (non-tolled grade-separated freeway), $72.9 million for Alternative 2 (grade-separated tollway), and $25.8 million for Alternative 3 (arterial with lane additions). Each scenario was assumed to require increased annual funding for facility maintenance and operations, at $184 thousand per year for the Alternative 1, $384 thousand per year for

Alternative 2 (not accounting for toll collection offsets), and $40 thousand per year for Alternative 3. A year-10 (mid-life) $30 million pavement reconstruction project was also required for Alternative 3 (as the main facility remained, and would need rehabilitation before 20 years passed) and for the base-case scenario. Project construction, road maintenance, and reconstruction cost estimates were obtained from the Victoria Transport Policy Institute (2009).

Alternative 3 appears as the preferred alternative based on B/C, IRR, and PP measures, while Alternative 1 is preferred from a NPV perspective, as shown in Table 6.1. This sort of shift in rankings is common in practice, as “bigger” projects generally enjoy higher NPVs (Alternative 1) but potentially lower B/C ratios and IRRs. Here, all IRRs and B/C ratios are high (while the Do-Nothing base case is costly), suggesting all alternatives make sense, even though reliability and emissions benefits are not yet included (though the former are sizable), and crash benefits are only monetary in nature (but remain slight when non-monetary benefits are added).

Table 6.1: Economic Summary Measures of Case Study 1’s Project Alternatives

	Base-Case: No Build	**Alternative 1: Grade Sep. Freeway**	**Alternative 2: Grade Sep. Tollway**	**Alternative 3: Extra Lanes (Arterial)**
Net Present Value	-$18 M	$134 M	$109	$117
Internal Rate of Return	N/A	26%	22%	70%
Benefit / Cost Ratio	N/A	3.86	3.24	6.38
Payback Period (yrs)	N/A	4.9	6.0	1.6

Traveler welfare and system reliability benefits are striking in terms of impact magnitudes. Annual traveler welfare benefits of Alternative 1 range from $10 (initial year) to $14 million (design year)—similar to other alternatives—while travel time reliability benefits varied from $18 to $281 million, crashes from $0.4 to $4 million ($0.9 to $9 million when using willingness to pay measures, as reported by NSC [2010]), and HC, CO, NOx, $SO_{2,}$ and $PM_{2.5}$ from $0.5 to $2 million (total) when using McCubbin and Delucchi’s (1996) pollutant cost estimates, inflated to 2010 dollars.

Over the entire 20-year evaluation period, the toolkit also estimates that the Alternative 1 results in the fewest fatal and injury crashes. This scenario resulted in 1,481 F+I fewer crashes than the base-case scenario over 20 years. This compares to the 39.4 thousand total system crashes in the base case scenario and thus amounts to a 3.76% reduction in total predicted crashes. Similar reductions are estimated for Alternative 2, and about one-third of these benefits under Alternative 3.

The toolkit estimates that total system VMT fell just 0.11%, 0.05%, and 0.01% in the initial year (from 5.57 billion annual VMT) and by 0.66%, 0.62%, and 0.61% in the design year (from 6.85 billion) for Alternatives 1, 2, and 3, respectively. This VMT decrease, along with other changes, such as increased speeds, resulted in very slight emission reductions across almost all species in all scenarios. Traffic volumes and (flow-weighted) average speeds along the altered corridor increased from 20,900 AADT at 28 mph in the base-case initial year to 23,300 AADT at 54 mph, 21,500 AADT at 54 mph, and 21,800 AADT at just 35 mph under Alternatives 1, 2, and 3, respectively. In the design year traffic volumes and speeds along the corridor increased from an average of 25,600 AADT at 20 mph (base case conditions) to an average of 29,900 AADT at 52 mph, 27,600 AADT at 52 mph, and 27,800 AADT at 26 mph in Alternatives 1, 2, and 3, respectively.

6.1.2 Travel Demand Management (Case Study 2)

The second case study sought to reduce IH 35 traffic levels by imposing tolls or reducing capacity. Alternative 1 imposed a $1 toll (just over $0.20 per mile), Alternative 2 imposed a $2 toll (just over $0.40 per mile), and Alternative 3 removed a travel lane in each direction (reducing capacity from 9,200 vph to 6,900 vph in each direction). It should be noted that the abstracted network (of 194 links) did not model IH 35's frontage roads, and a more complete analysis that included these links may produce different results. See Tables 6.2 and 6.3.

Table 6.2: Toolkit-Estimated VMT Changes (as a Percentage of the Base-Case Scenario)

	Initial Year			**Design Year**		
	Alt 1	**Alt 2**	**Alt 3**	**Alt 1**	**Alt 2**	**Alt 3**
System VMT	0.23%	1.40%	-0.01%	-0.37%	0.53%	-0.46%
IH 35	-9.0%	-23.4%	-1.3%	-7.2%	-19.1%	-4.7%
Surrounding Links	6.8%	21.9%	0.5%	4.6%	15.6%	1.9%

Table 6.3: Toolkit-Estimated VMT Changes vs. Base-Case Scenario (Annual Million VMT)

	Initial Year			**Design Year**		
	Alt 1	**Alt 2**	**Alt 3**	**Alt 1**	**Alt 2**	**Alt 3**
System VMT	12.8	78	-0.72	-25.2	36.4	-31.6
IH 35	-41	-106.6	-6	-40.1	-106.9	-26.1
Surrounding Links	51	163.8	3.8	42.7	144.7	17.2

Though all scenarios attempted to reduce network VMT, results were mixed: slight VMT increases were estimated under both initial-year tolling alternatives and under Alternative 2's design year. While all alternative scenarios predicted travel reduction along IH 35, the toolkit's travel demand model predicted that many travelers would shift their routes rather than forego travel altogether. This is despite the model's accounting for the possibility of fewer total travelers through use of travel demand elasticities (which vary between -0.5 and -0.85, depending on time of day[6]. Table 6.2 shows the toolkit's estimated changes in the coded-network's VMT. The 'Surrounding Links' row listed in Table 6.2 reflects VMT changes along the 24 links closest to the impacted IH 35 project area. These links represent the most likely alternative routes that travelers could take instead of IH 35, while still reaching the same destination.

The most striking impacts are shown along one bypass route east of IH 35. In Alternative 1's design year, Cameron Road's traffic volumes (between IH 35 and US 183) rose by 54%, accounting for an additional 16,000 vehicles on each of the four impacted links. Similarly, 20,000 additional vehicles were added to the US 183 links between 35th Street and Cameron, increasing traffic on those links by 33%. Additional changes in VMT could be attributed to longer distance trips. The cost increases on IH 35 (either time or money) could cause some vehicles to take longer routes around it (thus increasing VMT) and other vehicles to forgo the trip altogether (thus decreasing VMT). Furthermore, a more complete analysis could be run, modeling IH 35's frontage roads and other nearby alternative local routes. This may mitigate some of the system VMT increases that were shown in Alternate 3.

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[6] Period-dependent elasticity values were estimated using millions of predicted changes in flow rates between Austin's 1,074 zones from a few network upgrade scenarios (Lemp and Kockelman, 2009).

Crashes were predicted to increase in all scenarios, with Alternative 2 showing crash cost increases of up to over $13 million in the initial and design years (crash costs rose by less than $3 million per year in other scenarios). Reliability improved in Alternative 1 ($8 million, initial year and $68 million, design year), was mixed in Alternative 2 (-$10 million, initial year and $39 million, design year), and worsened in Alternative 3 (-$24.5 million, initial and design years). All alternatives showed reductions in some pollutants and increases in others. For example, Alternative 1 results suggest a 2.2% reduction in HC in the initial year, but a 3.2% increase in CO. Overall, however, Alternative 1 resulted in the most significant air quality benefits (an average of 0% in the initial year and -1.1% in the design year), while Alternative 2 resulted in the worst air quality changes (increases of 1.5% in the initial year and 0.3% in the design year). Emissions and crash increases were attributable in part to changes in total VMT but also to shifting freeway traffic to arterials (where crash and emission rates are higher due to more stop-and-go behavior and conflicts, caused by signalized intersections and driveways).

6.2 Concluding Remarks

The toolkit developed here seeks to provide transportation engineers, planners, and policy makers with the ability to quickly predict and compare project impacts among a variety of alternative scenarios. The case study findings show that, when monetized, the toolkit values reliability over all other measures. However, when reliability is excluded, as per the toolkit's default, traveler welfare becomes the most important summary measure impact (excluding project costs). If monetized, crashes and emissions can still play a significant factor in overall project impacts, as they may account for up to a combined 44% of benefits, as was found in one scenario's design year impacts (using higher willingness to pay measures to avoid crashes). Furthermore, case study results show that attempts to reduce travel demand through congestion pricing or limiting capacity can have unintended results, such as shifting traffic to alternative routes that may be far less suited to handling the added traffic.

While existing project evaluation tools provide transportation officials with a number of methods for project evaluation, the toolkit described in this report offers new outputs and applications not available in other tools. Transportation agencies adopting toolkits such as this will ideally help bring about a new era of project budgeting for optimal investment of public funds. Of course, expert evaluations of the toolkit are also valuable, and these were sought early on, in order to address potential limitations in the toolkit's development. The results of such outreach also helped the team anticipate the toolkit's usefulness, for users within Texas and elsewhere, as described in the next chapter.

Chapter 7. Expert Review, Conclusions, and Recommendations for Future Work

7.1 Expert's Review

For an external review of the developed toolkit, the project team contacted ten individuals identified as experts or key users, from government agencies, consulting firms, and universities across the U.S. These individuals have extensive backgrounds in transportation modeling and/or the development of sketch planning toolkits.

Requests for review were submitted to the expert panel during two phases of the toolkit development process:

- *Phase 1*: The development of the toolkit framework as described in Technical Memorandum IV, submitted for review in November 2009; and
- *Phase 2*: The case study application as described in Technical Memorandum VI, submitted for review in March 2010. A preliminary version of the project toolkit's Excel component was also submitted to the expert panel for review during the second phase.

Three of the ten experts responded to the request for review for phase 1. These are Chris Williges (consultant to Caltrans), Dan Beagan (Cambridge Systematics), and Patrick DeCorla-Souza (FHWA). These reviewers raised questions regarding project objectives, toolkit design, and data requirements. For phase 2, four of the experts, including Dan Beagan (Cambridge Systematics), Ken Cervenka (Federal Transit Authority, and formerly head modeler at NCTCOG), Dr. Alan Horowitz (University of Wisconsin-Milwaukee), and Madhusudhan Venugopal (NCTCOG) provided valuable responses to the Austin case study results and toolkit components.

The expert reviewers provided the project team with valuable suggestions and outside perspectives regarding the project toolkit's capabilities and assumptions. The reviewers posed many meaningful questions about how the toolkit and its underlying models operate. The project team responded promptly to all reviewers and was able to quickly address most of their comments. Some issues posed by expert reviewers still need to be resolved (many by the larger transportation community, rather than toolkit-specific issues), and the review process helped the project team identify key issues and plan strategies to address them. Finally, the expert review process helped the project team identify areas for clarification in the toolkit's documentation (which is still under development). The questions posed by reviewers illuminate sections of the existing documentation that can best be expanded. In this way, the model's operations, strengths, and limitations should become more transparent to toolkit users.

Appendix F summarizes the comments from the experts and the responses given by the project team.

7.2 Workshop Feedback

The project team delivered a technical workshop titled "Comprehensive Evaluation of Competing Projects: A Toolkit for Sketch Planning" at the 2010 Transportation Planning Conference in Bastrop, Texas, hosted by the Transportation Planning and Programming Division of TxDOT, on June 30, 2010. The workshop covered both theoretical and practical issues of developing and using the toolkit, with a focus on the technical functions, performance measures, input/output information of the toolkit, and a case study for toolkit implementation, as well as some demonstration examples. Most of attendees in the workshop were transportation planners and engineers from TxDOT and Texas MPOs, though representatives from private firms were also present. The attendees showed strong interest in the potential use of the toolkit for various project evaluation tasks and provided the project team useful responses on the functionality and data compatibility of the toolkit.

7.3 Conclusions and Recommendations for Future Work

The research project resulted in a very powerful yet user-friendly toolkit, whose application complexity falls between a regional travel demand model and a stand-alone corridor analysis, while providing a host of new and increasingly critical outputs and costs. In this way, toolkit users obtain a preliminary estimate of system-wide project impacts, often before conducting a more detailed analysis of demand patterns using a full-network demand model.

The toolkit estimates changes in traveler welfare (accounting for changes in travel times and operating costs) as well as travel time reliability, crashes, emissions, fuel use, and tolling revenues. It summarizes individual component impacts while providing economic summary measures. This allows users to comprehensively evaluate and compare scenario alternatives in a robust and consistent framework as outlined in the case studies described within this document. Such estimates can prove highly cost-effective for agency budgeting and project-targeting decisions.

The preliminary version of the toolkit provides a set of basic functions and procedures to estimate travel demand changes, assess environmental impacts from vehicle emissions, evaluate safety improvements, and conduct a comprehensive economic analysis over the design period of a variety of transportation projects on the sketch planning level. The modularization design and open architecture of the toolkit make its functionalities to readily be expanded and enhanced.

The travel demand modeling module of this toolkit can estimate travel demand pattern changes by origin and destination, time-of-day, mode, and route over networks. The capacity, cost, and other attributes are all associated links of node-link networks, while nodes only provide the network connectivity. Any supply change reflected by link attribute change can be evaluated by the current version of the toolkit. Some more detailed modeling requirements, such as lane-based toll policy (e.g., HOV/HOT lanes) or an explicit evaluation of intersection delays, need the network modeling as well as the travel demand modeling procedure on a finer level. Moreover, network changes accommodated by the current version have to be time-varying. To model a time-dependent travel demand management policy (e.g., a time-varying tolling system), the network supply model will need to incorporate the time dimension into its data structure. This and several other meaningful improvements are envisioned for the near future, as the research team pursues related work via a TxDOT-funded implementation project and a highly related TxDOT research project, #0-6487 (which seeks to similarly evaluate operational strategies, like speed harmonization and ramp metering). Thus, the toolkit will be enhanced with more capabilities and it will be applied to a variety of Texas regions, demonstrating its applicability for a variety of contexts. It is hoped that it will one day rise to national prominence, as transport budgets tighten everywhere, and project scrutiny and modeling sophistication (and expectations) rise.

References

AAA. 2009. Your Driving Costs. American Automobile Association. Available online at www.ouraaa.com/news/library/drivingcost/driving.html.

American Association of State Highway and Transportation Officials. 2010. Highway Safety Manual. AASHTO, Washington, D.C. (Forthcoming)

Barnes, G. and Langworthy, P. 2003. Per Mile Costs of Operating Automobiles and Trucks. Humphrey Institute of Public Affairs, University of Minnesota. Available online at www.hhh.umn.edu.

Bazaraa, M.S., Jarvis, J.J. and Sherali, H.D. 1990. *Linear Programming and Network Flows*. Wiley, New York, NY.

Beardsley, M., Warila, J., Dolce, G., Koupal, J. 2009. Air Pollution Emissions from Highway Vehicles: What MOVES Tells Us. The 18th Annual International Emission Inventory Conference, Baltimore, MD.

Beckmann, M.J., C.B. McGuire, and C.B. Winsten. 1956. *Studies in the Economics of Transportation*. Yale University Press, New Haven, CT.

Ben-Akiva, M. and S. Lerman. 1985. *Discrete Choice Analysis: Theory and Application to Travel Demand*. MIT Press, Cambridge, MA.

Bhat, C. 2004. Austin Commuter Survey: Findings and Recommendations. Center for Transportation Research, The University of Texas at Austin, Austin, TX. Available online at http://www.utexas.edu/research/ctr/about/news_items/Austin_commuter_report.pdf.

Blincoe, L., Seay, A., Zaloshnja, E., Miller, T., Romano, E., Luchter, S. and Spicer, R. 2002. The Economic Impact of Motor Vehicle Crashes 2000. National Highway Traffic Safety Administration. Available Online at http://www.nhtsa.dot.gov/staticfiles/DOT/NHTSA/Communication%20&%20Consumer%20Information/Articles/Associated%20Files/EconomicImpact2000.pdf.

Bonneson, J.A. and Pratt, M.P. 2009. Road Safety Design Workbook. Texas Transportation Institute. Prepared for the Texas Department of Transportation. College Station, TX. Available Online at http://tti.tamu.edu/documents/0-4703-P2.pdf.

Brownstone, D. and Small K.A. 2005. Valuing Time and Reliability: Assessing the Evidence from Road Pricing Demonstrations. *Transportation Research* 39A (4): 279-293.

Brzeznski, D., Enns, P., Hart, C.J. 1999. Facility-Specific Speed Correction Factors. Report M6.SPD.002. Assessment and Modeling Division. EPA.

Brzeznski, D. 2009. MOBILE6 co-developer, at the U.S. EPA. Phone interview. October 28.

Bureau of Labor Statistics. 2010. Consumer Price Index—All Urban Consumers. Available Online at http://data.bls.gov/PDQ/servlet/SurveyOutputServlet.

Bureau of Labor Statistics. 2010. Median Weekly Earnings of Full-Time Wage and Salary Workers by Selected Characteristics. Available online at ftp://ftp.bls.gov/pub/special.requests/lf/aat37.txt.

California Department of Transportation. 2010. Life Cycle Benefit Cost Analysis Model (Cal B-C). Available online at http://www.dot.ca.gov/hq/tpp/offices/ote/benefit.html.

Cambridge Systematics, Inc., Dowling Associates, Inc., System Metrics Group, Texas Transportation Institute. 2008. Cost Effective Performance Measures for Travel Time Delay, Variation, and Reliability. NCHRP Report 618, Washington D.C.

Carey, M., and R. Revelli. 1986. Constrained Estimation of Direct Demand Functions snd Trip Matrices. *Transportation Science*, Vol. 20, No. 3, pp. 143-152.

Chan, Y. 1976. A Method to Simplify Network Representation in Transportation Planning. *Transportation Research*, Vol. 10, No. 3, pp. 179-191.

Chan, Y., T.S. Shen, and N.M. Mahaba. 1989. Transportation Network Design Problem: Application of a Hierarchical Search Algorithm. *Transportation Research Record*, No. 1251, pp. 24-34.

Christenson, M., Karman, D., Graham, L.A. 2007a. The effect of driving conditions and ambient temperature on light duty gasoline-electric hybrid vehicles (1): Particulate Matter emission rates and size distributions. SAE International.

Christenson, M., Loiselle, A., Karman, D., Graham, L.A. 2007b. The effect of driving conditions and ambient temperature on light duty gasoline-electric hybrid vehicles (2): Fuel consumption and gaseous pollutant emission rates. SAE International.

Clark, N, Gautam, M, Scott Wayne, W, Lyons, W, Thompson, G. 2007. Heavy-Duty Vehicle Chassis Dynamometer Testing for Emissions Inventory, Air Quality Modeling, Source Apportionment and Air Toxics Emissions Inventory. CRC Report No E55/59.

Dafermos, S.C. 1972. The Traffic Assignment Problem for Multiclass-User Transportation Networks. *Transportation Science*, Vol. 6, No. 1, pp. 73-87.

Dantzig, G.B. 1963. *Linear Programming and Extensions*. Princeton University Press, Princeton, NJ.

Dial, R.B. 1996. Bicriterion Traffic Assignment: Basic Theory and Elementary Algorithms. *Transportation Science*, Vol. 30, No. 2, pp. 93-111.

Dial, R.B. 1997. Bicriterion Traffic Assignment: Efficient Algorithms plus Examples. *Transportation Research* Part B, Vol. 31, No. 5, 357-379.

de Jong, G., Pieters, M., Daly, A., Graafland, I., Kroes, E. and Koopmans, C. 2005. Using Logsum as an Evaluation Measure. Working Paper WR-275-AVV, RAND Europe, Leiden, The Netherlands.

de Vlieger, I. 1997. On-Board Emission and Fuel Consumption Measurement Campaign on Petrol-Drive Passenger Cars. *Atmospheric Environment*, Vol. 31, No. 22, 3753-3761.

Dowling, R.G., and A.D. May. 1985. Comparison of Small-Area O-D Estimation Techniques. *Transportation Research Record,* No. 1045, pp. 9-15.

Eash, R.W., K.S. Chon, Y.J. Lee, and D.E. Boyce. 1983. Equilibrium Traffic Assignment on an Aggregated Highway Network for Sketch Planning. *Transportation Research Record*, No. 944, pp. 30-37.

EC. 2005. ExternE: Externalities of Energy - Methodology 2005 Update, Directorate-General for Research Sustainable Energy Systems, European Commission, at www.externe.info/brussels/methup05a.pdf.

Glover, E.L., Brzezinski, D.J. Soak Length Activity Factors for Start Emissions. M6.FLT.003 Office of Air and Radiation. EPA. April 2001. http://www.epa.gov/OMS/models/mobile6/r01011.pdf

Elefteriadou, L., Chrysikopoulos, G. and Lombard, M. 2010. Travel Time Reliability Modeling for Florida. Final Report of FDOT Contract BDK 77-977-02, Florida Department of Transportation, Tallahassee, FL.

EPA. 1990. National Ambient Air Quality Standards (NAAQS) Office of Air and Radiation. Clean Air Act 1990. http://www.epa.gov/air/criteria.html.

EPA. 2000. Mobile Source Emissions—Past, Present and Future. Office of Transportation and Air Quality. Updated July, 2007. Accessed Jan, 2010. http://www.epa.gov/otaq/invntory/overview/pollutants/index.htm.

EPA. 2002. Development of Heavy-Duty NOx OFF-CYCLE Emission Effects for MOBILE6. Office of Air and Radiation. US Environmental Protection Agency Report M6.HDE.003. January 2002. http://www.epa.gov/otaq/models/mobile6/r02004.pdf.

EPA. 2003. Users Guide to MOBILE6.1 and MOBILE6.2: Mobile Source Emissions Factor Model. US Environmental Protection Agency Office of Air and Radiation. August 2003.

EPA. 2005. Emission Facts: Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel. US Environmental Protection Agency Office of Transportation and Air Quality.

February 2005. Webpage accessed on December 3, 2009. http://www.epa.gov/oms/climate/420f05001.htm.

EPA. 2007. Control of Hazardous Air Pollutants from Mobile Sources: Final Rule to Reduce Mobile Source Air Toxics. US Environmental Protection Agency Office of Transportation and Air Quality. August 10. Website accessed Jan. 2010. http://www.epa.gov/otaq/regs/toxics/420f07017.htm#info

EPA. 2008. Health and Environment: Ground-Level Ozone. US Environmental Protection Agency Office of Air and Radiation. http://www.epa.gov/air/ozonepollution/health.html.

EPA. 2009a. eGRID website. US Environmental Protection Agency. http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html.

EPA. 2009b. Six Common Air Pollutants. US Environmental Protection Agency Office of Air and Radiation. http://www.epa.gov/air/urbanair/.

FHWA. 2005. Travel Time Reliability: Making It There on Time, All the Time. U.S. Federal Highway Administration. www.ops.fhwa.dot.gov/publications/tt_reliability/TTR_Report.htm. Accessed September 11, 2009.

FHWA. 2007. Asset Management—Evaluation and Economic Investment. U.S. Federal Highway Administration. Available online at http://www.fhwa.dot.gov/infrastructure/asstmgmt/primer03.cfm.

FHWA. 2008. Highway Performance Monitoring System. U.S. Federal Highway Administration. http://www.fhwa.dot.gov/policy/ohpi/hpms/. Accessed on January 15, 2010.

Fisk, C.S. 1988. On Combining Maximum Entropy Trip Matrix Estimation with User Optimal Assignment. *Transportation Research*, Vol. 22B, No. 1, pp. 69-79.

Fontaras, G., Pistikopoulos, P., Samaras, Z. 2008. Experimental evaluation of hybrid vehicle fuel economy and pollutant emissions over real-world simulation driving cycles. *Atmospheric Environment* 42: 4023-4035.

Frank, M. and Wolfe, P. 1956. An algorithm for quadratic programming. *Naval Research Logistics Quarterly* 3(1-2): 95-110.

Giannelli, R.A., Gilmore, J.H., Landman, L., Srivastava, S., Beardsley, M., Brzezinski, D., Dolce, G., Koupal, J., Pedelty, J., Shyu, G. 2002. Sensitivity Analysis of MOBILE6.0. EPA420-R-02-035, Assessment and Standards Division of the US EPA, Office of Transportation and Air Quality, December 2002.

Glover, E.L., Brzezinski, D.J. 2001. Trip Length Activity Factors for Running Loss and Exhaust Running Emissions. EPA Report: M6-FLT005, April 2001.

Gulipalli, P., and Kockelman, K.M. 2008. Credit-Based Congestion Pricing: A Dallas-Fort Worth Application. *Transport Policy* 15 (1): 23-32.

Haghani, A.E., and M.S. Daskin. 1984. Network Design Application of an Extraction Algorithm for Network Aggregation. *Transportation Research Record,* No. 944: 37-46.

Haghani, A.E., and M.S. Daskin. 1986. Aggregation Effects on the Network Design Problem. *Journal of Advanced Transportation*, Vol. 20, No. 3: 239-258.

Hao, Y., J, Hatzopoulou, M, Miller, E.J. 2010. An Integrated Microsimulation Framework for Modeling Traffic Emissions in the Greater Toronto Area. Under review.

Hearn, D.W. 1984. Practical and Theoretical Aspects of Aggregation Problems in Transportation Planning Methods. In *Transportation Planning Models*, M. Florian, Ed., North-Holland, Amsterdam, pp. 257-287.

Heeb, N, Forss, A-M, Bach, C, Mattrel, P. 2000. Velocity-dependent emission factors of benzene, toluene and C2-benzenes of a passenger car equipped with and without a regulated 3-way catalyst. *Atmospheric Environment* 34: 1123-1137.

Horowitz, A. 2010. University of Wisconsin-Milwaukee. Private communication by e-mail exchange. March 16, 2010.

Huo, H, Wu, Y, Wang, M. 2009. Total versus urban: Well-to-wheels assessment of criteria pollutant emissions from various vehicle/fuel systems. *Atmospheric Environment* 43: 1796-1804.

Ingle, A. 2004. Development of Passenger Car Equivalents for Basic Freeway Segments. Virginia Polytechnic and State University. Available online at: http://scholar.lib.vt.edu/theses/available/etd-07102004-112810/unrestricted/passenger_car_equivalents_ingle.pdf.

Jeihani, M., Law, S. and Connolly, J.P. 2006. Improving Traffic Assignment Model Using Intersection Delay Function. The 47th Annual Transportation Research Forum. Available online at http://www.trforum.org/forum/downloads/2006_8B_IntersectionDelay_paper.pdf?PHPSESSID=4221c9bf9d10e47b3ba965dc1ce7743f.

Jensen, S.S. 1995. Driving patterns and emissions from different types of roads. *The Science of the Total Environment* 169: 123-128.

Kaplan, M.P., Y.J. Gur, and A.D. Vyas. 1984. Sketch Planning Model for Urban Transportation Policy Analysis. *Transportation Research Record,* No. 952: 32-39.

Kintner-Meyer M, Schneider K and Pratt R. 2007. Impact Assessment of Plug-in Hybrid Vehicles on Electric Utilities and Regional US Power Grids. Part I: Technical Analysis. http://www.pnl.gov/energy/eed/etd/pdfs/phev_feasibility_analysis_combined.pdf.

Kite, C. 2010. Lead Mobile Source Modelers for the Texas Commission on Environmental Quality. Phone interview. February 2, 2010.

Kockelman, K.M. and Lemp, J. 2009. The Financing of New Highways: Opportunities for Welfare Analysis and Credit-Based Congestion Pricing. Proceedings of the 88th Meeting of the Transportation Research Board.

Kockelman, K., Bottom, J. Kweon, Y.J. Ma, J. and Wang, X. 2006. Safety Impacts and Other Implications of Raised Speed Limits on High-Speed Roads. (NCHRP) Report 17-23. Available online at http://www.ce.utexas.edu/prof/kockelman/public_html/NCHRPSpeedLimits17-23.pdf.

Lemp, J.D. 2007. Travel Demand Forecasting Models: Development, Application, and Comparison of Aggregate and Activity-Based Approaches for the Austin, Texas Region. Master's Thesis, Department of Civil, Architectural and Environmental Engineering, The University of Texas, Austin, TX.

Lemp, J. and K. Kockelman. 2009. Anticipating welfare impacts via travel demand forecasting models: Comparison of aggregate and activity-based approaches for the Austin, Texas region. *Transportation Research Record*, 2133: 11-22.

Levinson, D. and Smalkoski, B. 2003. Value of Time for Commercial Vehicle Operators in Minnesota. TRB International Symposium on Road Pricing, 2003. University of Minnesota. Available online at http://nexus.umn.edu/Papers/TruckValueOfTime.pdf.

Litman, T. 2009. Air Pollution Costs Spreadsheet. Victoria Transport Policy Institute. Accessed Jan. 20, 2010. www.vtpi.org/airpollution.xls.

Litman, T. 2009. Transportation Cost and Benefit Analysis Second Edition. Victoria Transport Policy Institute. Available online at http://www.vtpi.org/tca/.

Lopez, C. 2008. Highway Safety Improvement Program Manual. Prepared for the Texas Department of Transportation. Available online at http://onlinemanuals.txdot.gov/txdotmanuals/hsi/using_the_safety_improvement_index.htm.

Maibach, M. et al. 2008. Handbook on Estimation of External Cost in the Transport Sector. CE Delft, Accessed at http://ec.europa.eu/transport/sustainable/doc/2008_costs_handbook.pdf.

Margiotta, J. 2009. Private communication by e-mail exchange. October 7, 2009.

Martin, W.A. and N.A. McGuckin. 1998. Travel Estimation Techniques for Urban Planning. NCHRP Report 365, National Cooperative Highway Research Program, Transportation Research Record, National Research Council, Washington, DC.

McCubbin, D. and Delucchi, M. 2003. The Health Effects of Motor Vehicle-Related Air Pollution. Working Paper UCD-ITS-RP-04-06, Institute for Transportation Studies, University of California, Davis, CA.

McFadden, D. 1981. Econometric Models of Probabilistic Choice. In C.F. Manski and D. McFadden (eds.), *Structural Analysis of Discrete Data with Econometric Applications*, 198-272, MIT Press, Cambridge, MA.

Murphy, J.J., Delucchi, M.A., McCubbin, D.R., Kim, H.J. 1999. The cost of crop damage caused by ozone air pollution from motor vehicles. *Journal of Environmental Management* 55: 273-289.

Nagurney, A. 2000. A Multiclass, Multicriteria Traffic Network Equilibrium Model. *Mathematical and Computer Modeling*, Vol. 32, No. 3-4: 393-411.

National Safety Council. 2010. Estimating the Costs of Unintentional Injuries. Available at http://www.nsc.org/news_resources/injury_and_death_statistics/Pages/EstimatingtheCostsofUnintentionalInjuries.aspx.

Oppenheim, N. 1995. *Urban Travel Demand Modeling: From Individual Choices to General Equilibrium*. John Wiley & Sons, New York, NY.

Oregon Department of Transportation. 2006. The Value of Travel Time: Estimates of the Hourly Value of Time for Vehicles in Oregon 2005. Available online at http://www.oregon.gov/ODOT/TD/TP/docs/publications/ValueTravelTime2005.pdf.

Parsons Brinkerhoff. 2009. High Occupancy Vehicle Lanes I: Achieving Current Policy Objectives? Available online at http://www.docstoc.com/docs/25073526/HIGH-OCCUPANCY-VEHICLE-(HOV)-LANES-I--ACHIEVING-CURRENT-POLICY.

Pollack, AK, Lindhjem, C, Stoeckenius, TE, Tran, C, Mansell, G, Jimenez, M, Wilson, G, Coulter-Burke, S. 2004. Evaluation of the US EPA MOBILE6 Highway Vehicle Emissions Factor Model. CRC Project E-64. Environ Corp.

Polzin, S., Chu, X. and Raman, V.S. 2008. Exploration of a Shift in Household Transportation Spending from Vehicles to Public Transportation, Center for Urban Transportation Research. Available online at at www.nctr.usf.edu/pdf/77722.pdf.

Rogus, M.J. 1996. Building Sketch Networks: The Development of Sketch Zones Boundaries and Aggregation Process of Detailed Highway Networks. Working Paper No. 96-11, Chicago Area Transportation Study, Chicago, IL.

Schrank, D.and Lomax, T. 2009. 2009 Urban Mobility Report. Texas Transportation Institute. Available online at http://tti.tamu.edu/documents/mobility_report_2009_wappx.pdf.

Sheffi, Y. 1985. *Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods*. Prentice Hall, Englewood Cliffs, NJ.

Small, K., and Verhoef, E. 2007. *The Economics of Urban Transportation*. Routledge, NY.

Small, Kenneth and Yan, J. 2001. The Value of “Value Pricing” Roads: Second-Best Pricing and Product Differentiation. *Journal of Urban Economics*, 49(2), 310-336.

Taylor, M.A.P., W. Young, and P.W. Newton. 1988. PC-Based Sketch Planning Methods for Transport and Urban Applications. *Transportation*, Vol. 14, No. 4: 361-375.

TCEQ. 2009. Air Quality Modeling Files ftp Site. Accessed December 2009. ftp://ftp.tceq.state.tx.us/pub/OEPAA/TAD/Modeling/.

Texas Department of Transportation. 2009a. Age Counts by County Using Gross Weight. Software Package: AGEPERKD. Run Date: 7/31/09.

Texas Department of Transportation. 2009b. Rural and Urban Crashes and Injuries by Severity 2008. Available Online at ftp://ftp.dot.state.tx.us/pub/txdot-info/trf/crash_statistics/2008/2008_9.pdf.

Thompson, T. Webber, M., Allen, D.T. 2008 Air Quality Impacts of Using Overnight Electricity Generation to Charge PHEVs for Daytime Use. *Environmental Research Letters* 4(1): 1-12.

TRB. 1995. Expanding Metropolitan Highways: Implications for Air Quality and Energy Use, TRB Special Report #345, National Academy Press. www.nap.edu/openbook.php?record_id=9676.

TRB. 2000. *Highway Capacity Manual*. Transportation Research Board, Washington, D.C.

Van Zuylen, H.J., and L.G. Willumsen. 1980. The Most Likely Trip Matrix Estimated from Traffic Counts. *Transportation Research*, Vol. 14B, No. 3: 281-293.

Verhoef, E.and Kenneth, S. 1999. Product Differentiation on Roads: Second-Best Congestion Pricing with Heterogeneity under Public and Private Ownership. Free University Amsterdam. Available online at: http://www.tinbergen.nl/discussionpapers/99066.pdf.

VTPI. 2009. Transportation Cost and Benefits Analysis: 5.10 Air Pollution Costs. Victoria Transport Policy Institution. http://www.vtpi.org/tca/.

Wang, J. 2010. United States Department of Transportation. Private communication by e-mail exchange. April 14, 2010.

Weilenmann, Martin, Soltic, P., Saxer, C., Forss, A-M., Heeb, N. 2005. Regulated and nonregulated diesel and gasoline cold start emissions at different temperatures. *Atmospheric Environment* 39: 2433-2441.

Weilenmann, Martin, Favez, J-Y, Alvarez, R. 2009. Cold-start emissions of modern passenger cars at different low ambient temperatures and their evolution over vehicle legislation categories. *Atmospheric Environment* 43: 2419-2429.

West, B.H., R.N. McGill, J.W. Hodgson, S.S. Sluder, and D.E. Smith. 1997. Development and Verification of Light-Duty Modal Emissions and Fuel Consumption Values for Traffic Models , FHWA Report, Washington, DC, April 1997, and additional project data, April 1998.

Willumsen, L.G. 1981. Simplified Transport Models Based on Traffic Counts. *Transportation*, Vol. 10, No. 3: 257-278.

Xie, C., Kockelman, K.M. and Waller, S.T. 2010. Maximum entropy method for sub-network origin-destination trip matrix estimation. *Transportation Research Record*. (In press)

Zamparini, L. and Reggiani, A. 2007. Meta Analysis of the Value of Travel Time Savings: A Transatlantic Perspective in Passenger Transport. Springer Science & Business Media, *Networks and Spatial Economics*, 7(4), 377-396.

Zhou, X., S. Erdogan, and H.S. Mahmassani. 2006. Dynamic Origin-Destination Trip Demand Estimation for Subarea Analysis. *Transportation Research Record*, No. 1964: 176-184.

Appendix A: Estimation of the Parameters of the Travel Time Variance Function

The data used to evaluate travel time reliability was collected over a set of highway segments of 2 to 5 miles long, in Atlanta, Los Angeles, Seattle, and Minneapolis, by Rich Margiotta (2009) of Cambridge Systematics. The original travel time reliability data were recorded as *buffer indices*. These represent the share of extra time needed (relative to the mean travel time) to finish a trip with a certain probability. In other words, buffer index (BI) is the percentage of mean travel time that the buffer represents, in order to finish a trip within a certain probability (P_{BI}). $P_{BI} = 95\%$ is a common choice, as recently used to evaluate freeway travel times' reliability in Florida (Elefteriadou et al., 2010).

Without loss of generality, we assumed that individual travel times in a road network follow a normal distribution (from one day to the next [at the same time of day, between the same O-D pair], or from one minute to the next). By using the cumulative distribution function of the normal distribution, one can establish the relationship of travel time variance (r) and BI as follows:

$$P_{BI} = 1 - \int_{-\infty}^{t(1+2BI)} \frac{1}{\sqrt{2\pi r}} \exp\left[-\frac{\left(x - t(1+BI)\right)^2}{2r}\right] dx \tag{A.1}$$

$$= \frac{1}{2}\left(1 - \operatorname{erf}\left[\frac{t \cdot BI}{\sqrt{2r}}\right]\right) \tag{A.2}$$

where t and r are travel time mean and variance. This formula was used to calculate the travel time variances from the sample data. Then, a regression relationship between travel time variances and corresponding V/C ratios was estimated, as follows:

$$r = r^0\left(1 + \sigma\left(\gamma + \frac{v}{c}\right)^{\tau}\right) \tag{A.3}$$

where r^0 is the free-flow travel time variance, v and c are traffic flow rate and roadway capacity, and σ, γ, and τ are regression parameters. The estimated result is: $\sigma = 2.3$, $\gamma = 0.7$, and $\tau = 8.4$, from the following regression analysis (see Figure A.1).

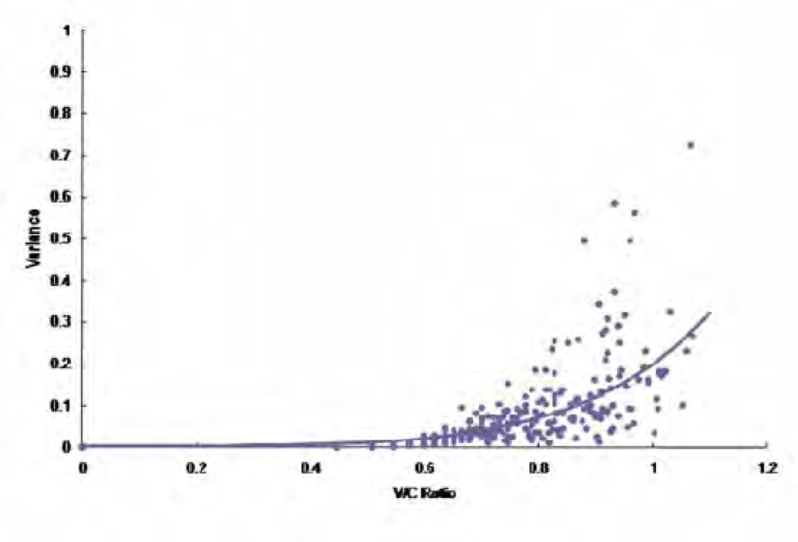


Figure A.1: Travel Time Variance versus V/C Ratio (Data from Margiotta [2009])

Appendix B: Solution Algorithm for the Base Trip Matrix Estimation Model

As identified earlier, within the sub-network demand modeling process, the key and most challenging task is trip table estimation. This appendix presents a solution method for the ME model proposed in Chapter 3, in order to tackle the trip table estimation problem.

The Frank-Wolfe algorithm (Frank and Wolfe, 1956) can be adapted for solving the ME model defined here, as briefly depicted below.

Step 0 **(Initialization):** Find an initial feasible O-D trip table. One possible initial trip table can be obtained by setting $x_{rs} = \hat{v}_a$, if nodes r and s are the head and tail nodes of some link a, i.e., $a = (r, s)$, and $x_{rs} = 0$, for all other O-D pairs.

Step 1 **(Direction finding):** Find an auxiliary trip table y_{rs}, $\forall r \in R$, $s \in S$, by solving the following linearized problem:

$$\min \quad \sum_{rs} y_{rs} \ln x_{rs}^{n} \tag{B.1}$$

$$\text{subject to} \quad \sum_{rs} \sum_{k} f_k^{rs} \delta_{a,k}^{rs} = \hat{v}_a \qquad \forall a \in A \tag{B.2}$$

$$f_k^{rs} \geq 0 \qquad \forall k \in K_{rs}, r \in R, s \in S \tag{B.3}$$

where trip rate y_{rs} is defined as

$$y_{rs} = \sum_{k} f_k^{rs} \qquad \forall k \in K_{rs} \tag{B.4}$$

Step 2 **(Line search):** Find an optimal α value for $0 \leq \alpha \leq 1$ by solving the following line search problem:

$$\min \quad \sum_{rs} [x_{rs}^{n} + \alpha(y_{rs} - x_{rs}^{n})] \ln[x_{rs}^{n} + \alpha(y_{rs} - x_{rs}^{n})] - [x_{rs}^{n} + \alpha(y_{rs} - x_{rs}^{n})] \tag{B.5}$$

$$\text{subject to} \quad 0 \leq \alpha \leq 1 \tag{B.6}$$

Step 3 **(Solution update):** Set $x_{rs}^{n+1} = x_{rs}^{n} + \alpha(y_{rs} - x_{rs}^{n})$.

Step 4 **(Convergence test):** If a convergence criterion is met (for example, $\sum_{rs} \frac{|x_{rs}^{n+1} - x_{rs}^{n}|}{x_{rs}^{n+1}} < \varepsilon$), stop; otherwise, go to step 1.

It should be noted that the computational bottleneck of the Frank-Wolfe algorithm in solving the ME problem is the linearized ME subproblem formed in step 1. The standard linear programming (LP) solution method—the simplex method—may not be directly applied to this linear problem, because an explicit statement and processing of such an LP problem requires enumeration of all possible path flows between each O-D pair, which is computationally prohibitive for problems of realistic network size. For this reason, an efficient approach that avoids path enumeration is required; otherwise, the application of the Frank-Wolfe algorithm for the ME problem may be limited to sub-networks of small size only.

To relax the computational difficulty, this work resorts to the column generation approach, which generates path flows only as and when needed within the solution framework of the revised simplex method (see, e.g., Dantzig, 1963; Bazaraa et al., 1990). Given that the linearized problem is in the form of path flows, we label the path set of the network as $P = \bigcup_{r\in R, s\in S} K_{rs}$. Because the optimal solution of this linearized problem is a basic feasible solution, it is readily known that there are at most $|A|$ paths with positive flow rate in the optimal solution.

For convenience, one can first rewrite the linearized ME problem into the following path-based matrix form:

$$\min \quad \mathbf{c}^T \cdot \mathbf{f} \tag{B.7}$$

where $\mathbf{c}$ is the negative of the path entropy impedance vector, $\mathbf{c} = [c_{rs}^n]_{|P|\times 1} = [\ln x_{rs}^n]_{|P|\times 1}$, and $\mathbf{f}$ is the path flow vector, $\mathbf{f} = [f_k^{rs}]_{|P|\times 1}$,

$$\text{subject to} \quad \Delta \cdot \mathbf{f} = \hat{\mathbf{v}} \tag{B.8}$$

$$\mathbf{f} \geq \mathbf{0} \tag{B.9}$$

where Δ is the link-path incidence matrix, $\Delta = \left[\delta_{a,k}^{rs}\right]_{|A|\times|P|}$, and $\hat{\mathbf{v}}$ is the estimated link flow vector, $\hat{\mathbf{v}} = [\hat{v}_a]_{|A|\times 1}$.

Suppose that we are at some iteration of the simplex procedure, where the current basic feasible solution contains $|A|$ basic paths of positive flow. The sets of basic paths and nonbasic paths are labeled P_B and $P_{\bar{B}}$, respectively. Suppose that the corresponding basis matrix and cost vector are $\mathbf{B}$ and $\mathbf{c_B}$, where $\mathbf{B} = \left[\delta_{a,k}^{rs}\right]_{|A|\times|A|}$ and $\mathbf{c}_B = [\ln x_{rs}^n]_{|A|\times 1}$. Given the simplex multiplier vector $\mathbf{w} = \mathbf{c}_B\mathbf{B}^{-1}$, one knows that the reduced cost for a nonbasic path flow variable f_k^{rs} is $c_k^{rs} - z_k^{rs} = \ln x_{rs}^n - \mathbf{c}_B\mathbf{B}^{-1}\Delta_k^{rs}$, where Δ_k^{rs} is the corresponding column of Δ to the nonbasic path k. It is readily known that if all reduced costs $c_k^{rs} - z_k^{rs} \geq 0$, $\forall k \in P_{\bar{B}}$, the current basic feasible solution is optimal; otherwise, one may increase the path flow rate of a nonbasic path with $c_k^{rs} - z_k^{rs} < 0$, $k \in P_{\bar{B}}$ from 0 to some positive level so that the objective function value is decreased while the problem feasibility is maintained. In the latter case, a nonbasic path with the lowest reduced cost value may be chosen for this purpose, according to Dantzig's rule. Without enumerating all the nonbasic paths in the set $P_{\bar{B}}$, Dantzig's rule can be implemented by solving the following minimization problem:

$$\min_{k\in P}\{c_k^{rs} - z_k^{rs}\} \tag{B.10}$$

which can be further decomposed into a set of minimization problems by O-D pairs:

$$\min_{r\in R, s\in S}\left\{\cdots, \min_{k\in K_{rs}}\{c_k^{rs} - z_k^{rs}\}, \cdots\right\} \tag{B.11}$$

Note that the minimization problem for each O-D pair r-s is essentially a shortest path problem, as follows, given that $c_k^{rs} = \ln x_{rs}^n$ is fixed for all paths between O-D pair r-s:

$$\min \quad -z_k^{rs} = -\mathbf{c}_B\mathbf{B}^{-1}\Delta_k^{rs} \tag{B.12}$$

$$\text{subject to} \quad k \in K_{rs} \tag{B.13}$$

where Δ_k^{rs} is the link-path incidence vector of path k between O-D pair r-s, which exists in Δ as a column. It is obvious that for this shortest path problem, the negative of the simplex multiplier vector $-\mathbf{w} = -\mathbf{c}_B\mathbf{B}^{-1}$ specifies the link costs over the network. It should be noted that an arbitrary element in $\mathbf{w}$ (or $-\mathbf{w}$) (i.e., the cost of an arbitrary link) may be positive or negative, so a shortest path algorithm that prevents negative cost loops is needed.

After executing the shortest path search for each O-D pair, one can then obtain the entering path flow variable (to the basis matrix) with the lowest $c_k^{rs} - z_k^{rs}$ value over all O-D pairs, which generates a new column for the basis matrix, Δ_l^{od}. The remaining algorithmic issue is to determine the value of the entering path flow variable and accordingly identify a leaving path flow variable (from the basis matrix). Suppose that the entering path is l between O-D pair o-d and its flow rate and the link-path incidence vector are f_l^{od} and Δ_l^{od}, respectively. Then the leaving path flow variable is the one that maximizes the f_l^{od} value while maintaining the problem feasibility (i.e., all the basic feasible path flow variables must be greater than or equal to 0):

$$\max\left\{f_l^{od}\colon \mathbf{f}_B = \mathbf{B}^{-1}\hat{\mathbf{v}} - \left(\mathbf{B}^{-1}\Delta_l^{od}\right)f_l^{od} \geq \mathbf{0}\right\} \tag{B.14}$$

where $\mathbf{f}_B$ is the vector of path flow variables corresponding to the current basis matrix and $\hat{\mathbf{v}}$ is the link flow vector. Because $\mathbf{B} \geq \mathbf{0}$ (where each element $\delta_{a,k}^{rs}$ in $\mathbf{B}$ is equal to 1 or 0), the inequality in (B.14) is reduced to $\mathbf{v} - \Delta_l^{od}f_l^{od} \geq \mathbf{0}$, which in turn results in:

$$\left(f_l^{od}\right)_{\max} = \min\left\{\hat{v}_a/\delta_{a,l}^{od} : \delta_{a,l}^{od} = 1, \forall a\right\} \tag{B.15}$$

This result implies that $\left(f_l^{od}\right)_{\max}$ should be set to equal the minimum link flow along path l. Accordingly, the path flow variables in the current basis matrix should be updated by $\mathbf{f}_B = \mathbf{B}^{-1}\mathbf{v} - \left(\mathbf{B}^{-1}\Delta_l^{od}\right)\left(f_l^{od}\right)_{\max}$, in which the path flow variable whose value is decreased to 0 is the leaving variable.

The algorithmic steps of the column generation approach described above can be summarized as follows, which synthetically serve as step 1 of the Frank-Wolfe solution framework:

***Step 1.1* (Initialization):** Find an initial, feasible O-D trip table for the linearized problem. Such an initial trip table can be obtained by setting $f_k^{rs} = \hat{v}_a$ for such a path k between such an O-D pair r-s that nodes r and s are the head and tail nodes of some link a (i.e., $a = (r, s)$) and path k contains link a only (i.e., $\delta_{a,k}^{rs} = 1$) and $\delta_{b,k}^{rs} = 0$, $\forall b \neq a$, and by setting $f_l^{rs} = 0$, $\forall l \neq k$ between O-D pair r-s. The values of all other path flow variables are set to be 0.

***Step 1.2* (Entering path determination):** Solve a shortest path problem defined in (B.12)-(B.13) for each O-D pair and identify entering path flow variable f_k^{rs} with the minimum $c_k^{rs} - z_k^{rs}$ value over all O-D pairs. If the minimum $c_k^{rs} - z_k^{rs}$ value is greater than or equal to 0, the current basic feasible solution is optimal; otherwise, go to step 1.3.

***Step 1.3* (Leaving path determination):** Compute the value of the entering path flow variable by $\left(f_l^{od}\right)_{\max} = \min\left\{v_a/\delta_{a,l}^{od} : \delta_{a,l}^{od} = 1\right\}$ and identify the leaving path flow variable whose value is decreased to 0.

***Step 1.4* (Basis matrix updating):** Update the basic feasible path flow variables by $\mathbf{f}_B = \mathbf{B}^{-1}\mathbf{v} - \left(\mathbf{B}^{-1}\Delta_l^{od}\right)f_l^{od}$ and update the basis matrix by inserting the entering path's link-path incidence vector and removing the leaving path's link-path incidence vector.

Appendix C: Estimation of O-D Demand Elasticities

A set of O-D demand elasticity values for different time-of-day periods are estimated by using the travel demand data from the Austin regional network. Table C.1 and Figures C.1–C.6 show some typical results from a couple of example network-upgrading scenarios. While it is recognized that demand elasticity on the O-D level is subject to a variety of socio-economic and demographic factors and scenario settings, the estimation result shows that a more congested network state (due to a higher travel demand level) typically implies a lower elasticity value. For example, in the Austin network, we found that the lowest demand elasticity value appears in the AM period, then a higher value in the PM period, and the highest value in other periods, where the average generalized O-D travel cost approximately indicates the network congestion level.

Table C.1: Estimated Sample Demand Elasticity Values

Scenario	Time-of-Day	Average Travel Cost	Estimated Elasticity Value	R^2 Value
Capacity-Increasing Scenario	AM Period	\$3.45	-0.299	0.2265
	MID Period	\$2.18	-0.574	0.2436
	PM Period	\$2.55	-0.431	0.1779
Toll Road Scenario	AM Period	\$3.45	-0.708	0.1365
	MID Period	\$2.18	-1.245	0.1415
	PM Period	\$2.55	-0.834	0.2136

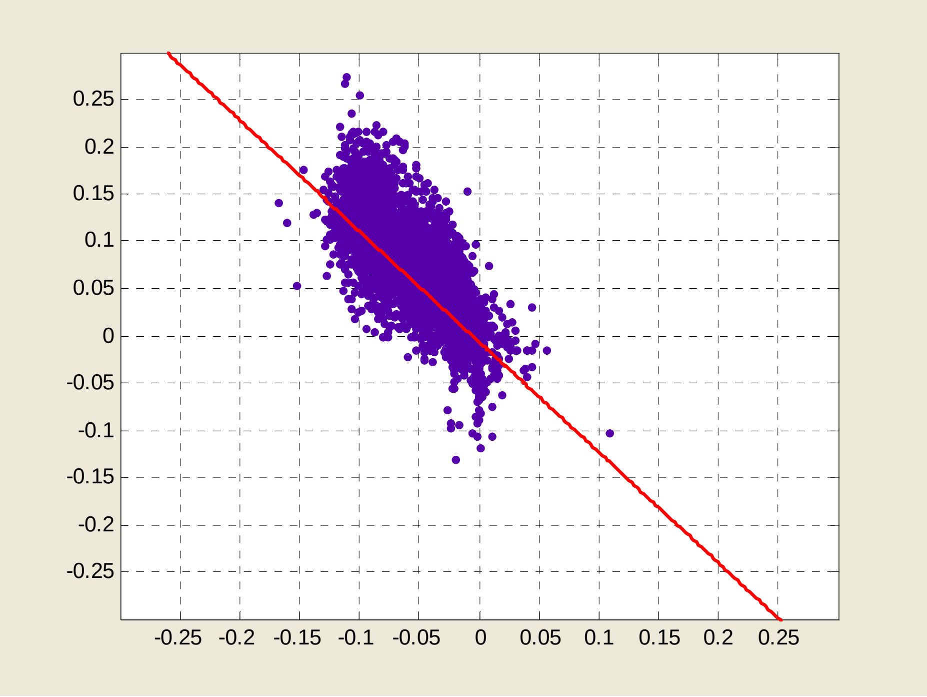


Figure C.1: Demand Elasticity Estimation for the Capacity-Increasing Scenario in the Morning Peak Period

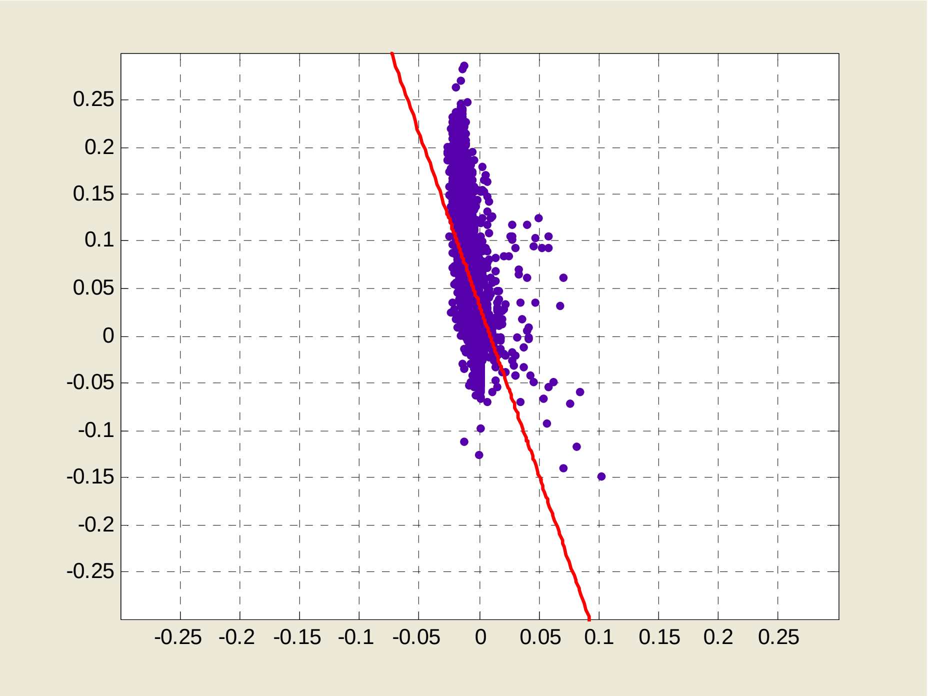


Figure C.2: Demand Elasticity Estimation for the Capacity-Increasing Scenario in the Midday Period

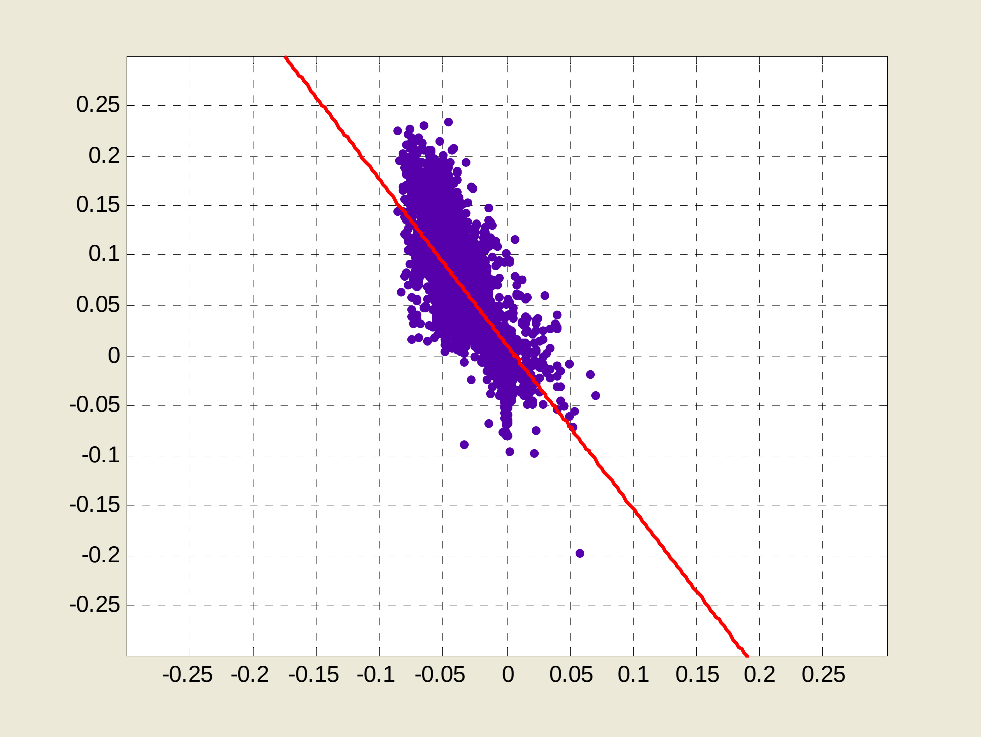


Figure C.3: Demand Elasticity Estimation for the Capacity-Increasing Scenario in the Afternoon Peak Period

Appendix D: Emissions Rates Used in the Toolkit's Vehicle Emissions Database

The following series of emissions rate charts were developed using the data from the emissions rate lookup table developed for the Toolkit. The purpose behind presenting these charts is to clearly show the variations in emissions rates over the possible Toolkit input variables as well as to identify and highlight any issues that may arise.

D.1 Carbon Dioxide (CO_2)

MOBILE assumes constant fuel economy across speeds, resulting in constant emissions rates estimates (once vehicle type and model year are specified). Once adjustments were made to account for the changing fuel economy versus speed (as described below), CO_2 emissions rates versus speed provided the expected pattern. CO_2 emissions rates do not change with temperature or facility, but they do change by vehicle type and model year, as shown below.

All fuel economy rules up to and including the rules that would improve fuel economy from 2012 to 2016 (maximum value is 38 mpg for LDV and 28.3 for LDT in 2016 and all years beyond) are included in this toolkit (TCEQ 2009). See Figure D.1.

D.2 Oxides of Nitrogen (NOx)

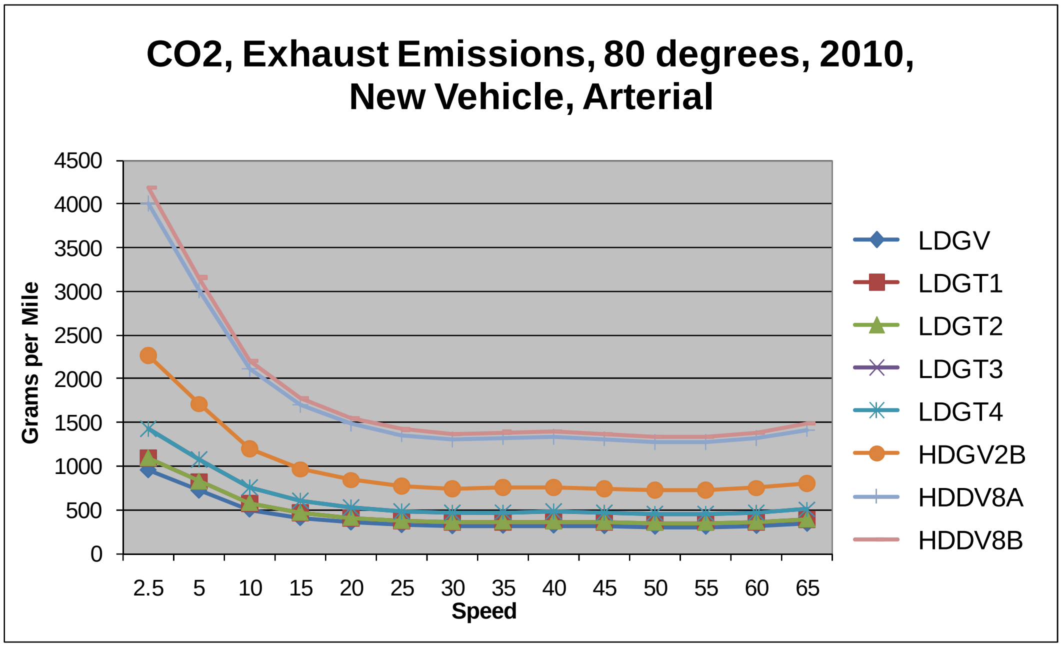
The concave pattern expected of NOx emission rates versus speed is apparent in all but heavy duty gasoline trucks. It is likely that this is due to lack of data regarding those vehicles. Additionally, one can see the impact facility has on emissions in Figure D.2, namely the stop-and-go traffic patterns found on arterials cause higher emissions rates than more steady-speed traffic found on freeways up to 30mph. NOx emissions rates change only slightly due to temperature, with higher temperatures leading to more NOx.

D.3 Carbon Monoxide (CO)

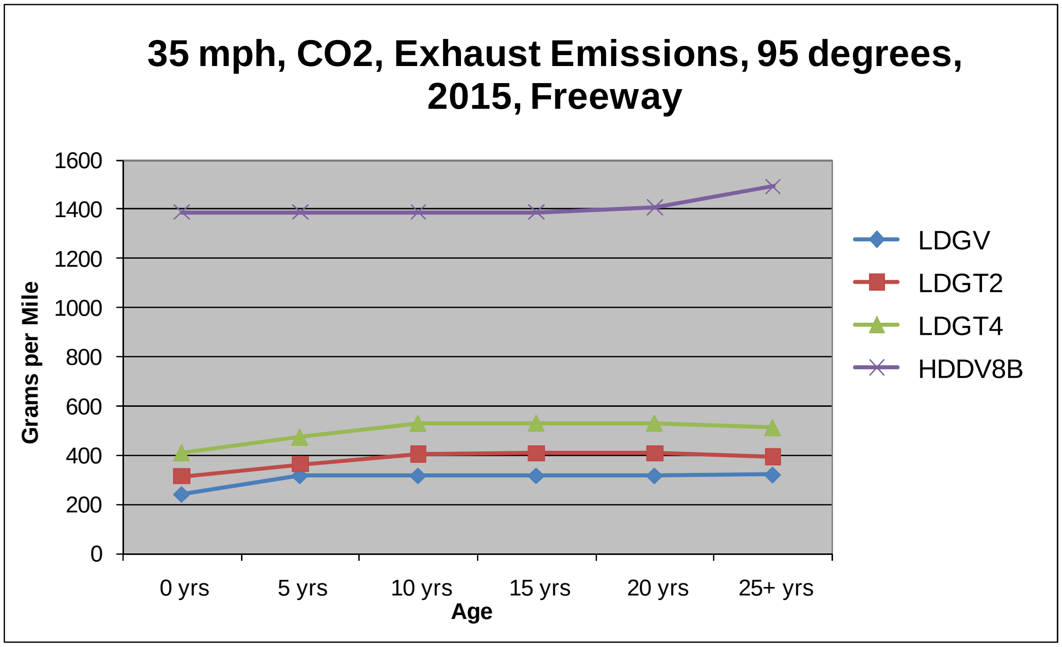
CO emissions rates increase as temperature decreases. Diesel engines emit less carbon monoxide than gasoline engines. CO emissions rates show the expected concave pattern with higher values at low and high speeds. See Figure D.3.

D.4 Hydrocarbons (HC)

One surprising result from the following MOBILE-generated HC charts is the fact that HC emissions are not significantly lower in the cold winter settings (as shown in Figure D.4) than in the summer temperature settings. One would expect that higher temperatures would result in higher evaporative HC emissions; however, that is not the case. This is due to the gasoline composition and the reduction of RVP that occurs during summer months. Additionally, because of diesel fuel properties, diesel vehicles have very low evaporative emissions. Similar to NOx, one expects HC emissions rates to show a concave pattern, with higher rates at low and high speeds (when more fuel is consumed). However, MOBILE results do not show this effect.

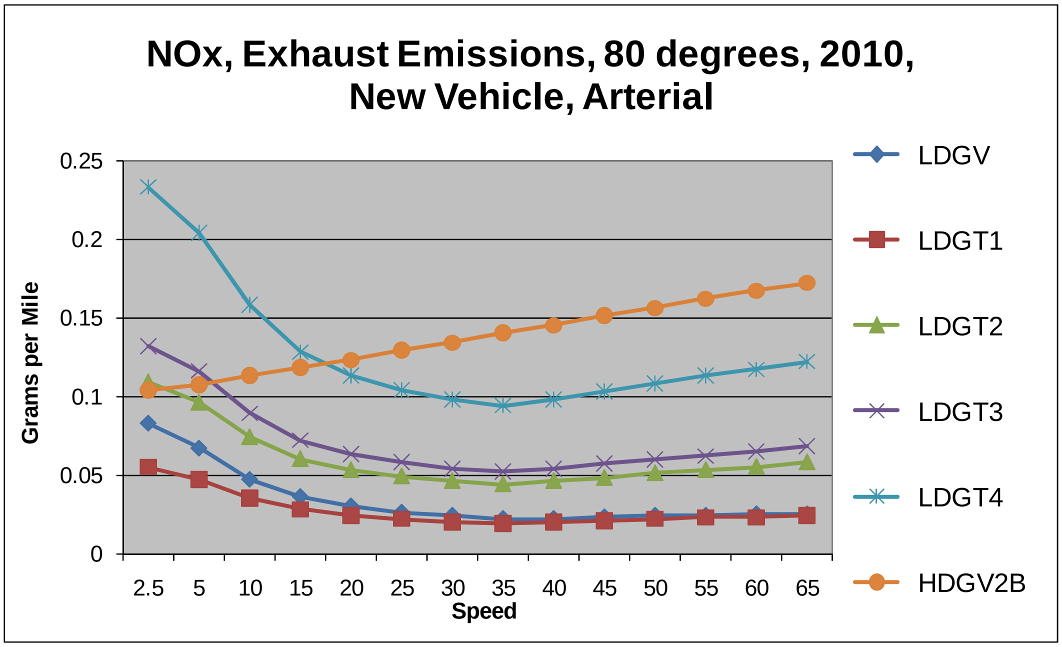


(a)

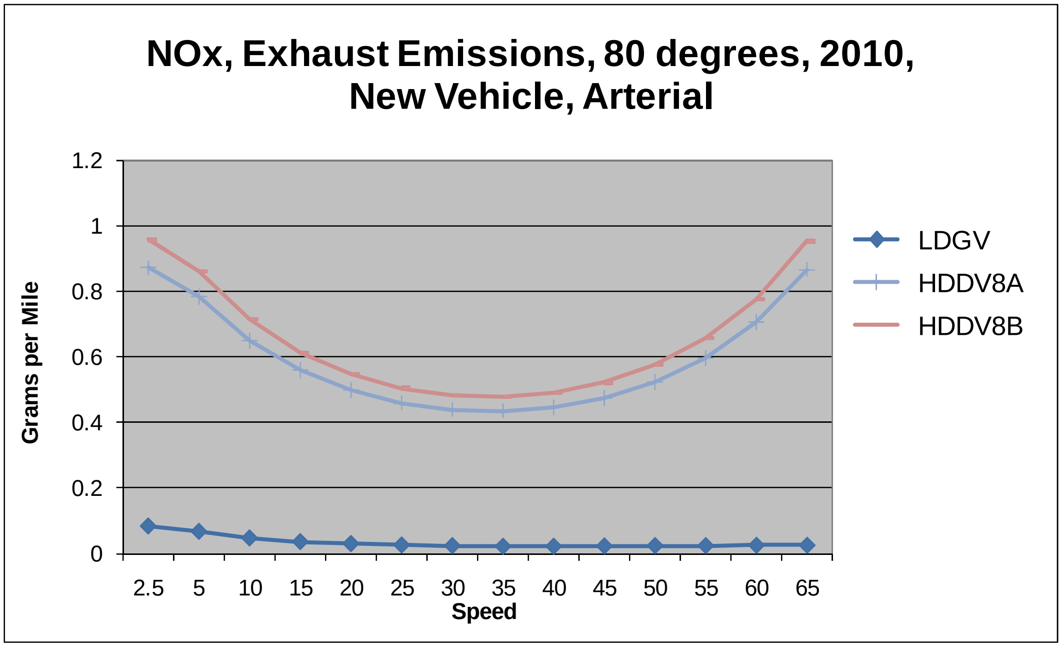


(b)

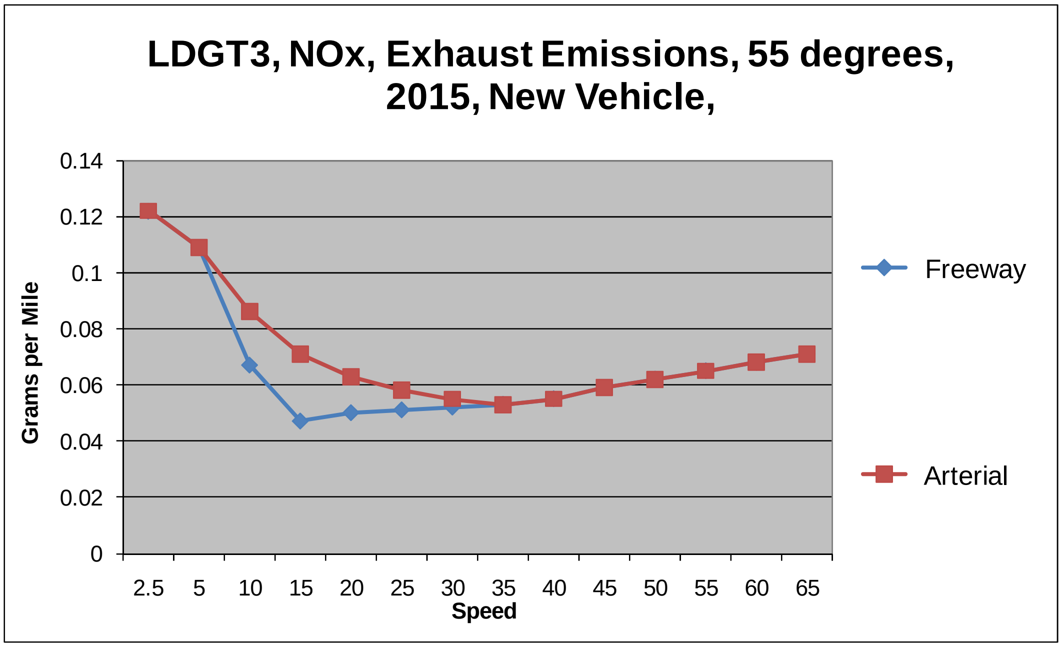
Figure D.1: CO_2 Exhaust Emissions


NOx, Exhaust Emissions, 80 degrees, 2010, New Vehicle, Arterial
Grams per Mile
0.25
0.2
0.15
0.1
0.05
0
2.5
5
10
15
20
25
30
35
40
45
50
55
60
65
Speed
LDGV
LDGT1
LDGT2
LDGT3
LDGT4
HDGV2B

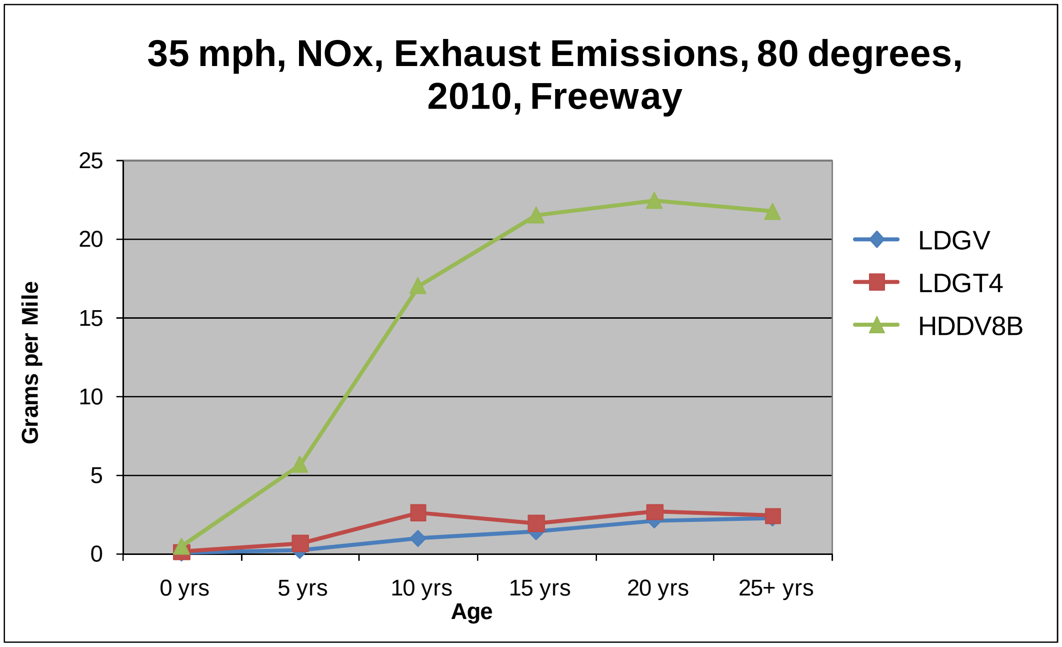
(a)


NOx, Exhaust Emissions, 80 degrees, 2010, New Vehicle, Arterial
Grams per Mile
1.2
1
0.8
0.6
0.4
0.2
0
2.5
5
10
15
20
25
30
35
40
45
50
55
60
65
Speed
LDGV
HDDV8A
HDDV8B

(b)

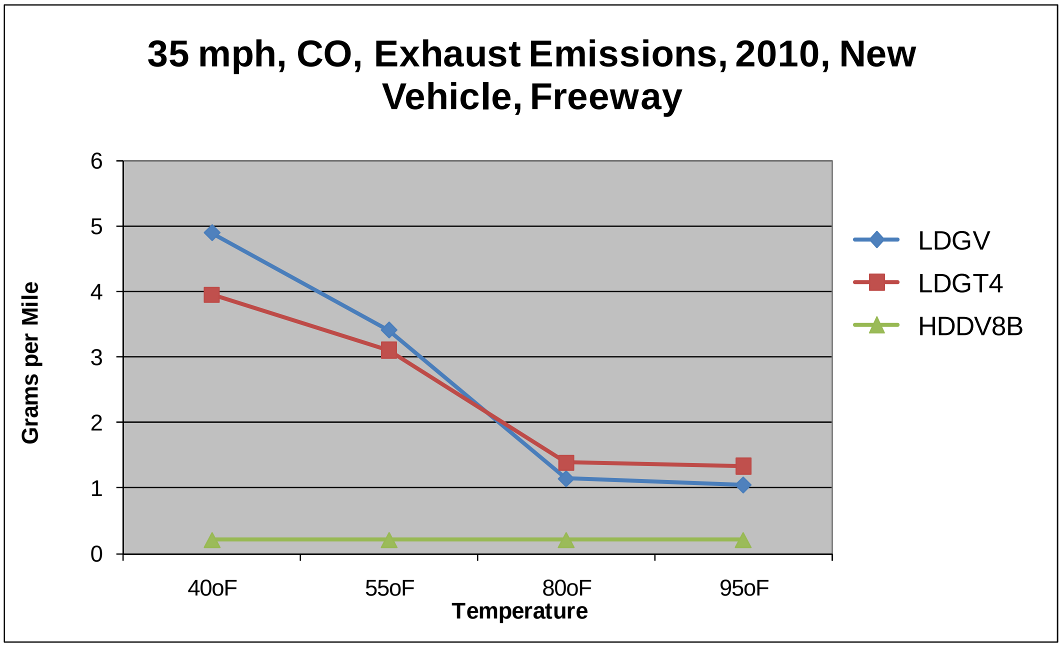


(c)

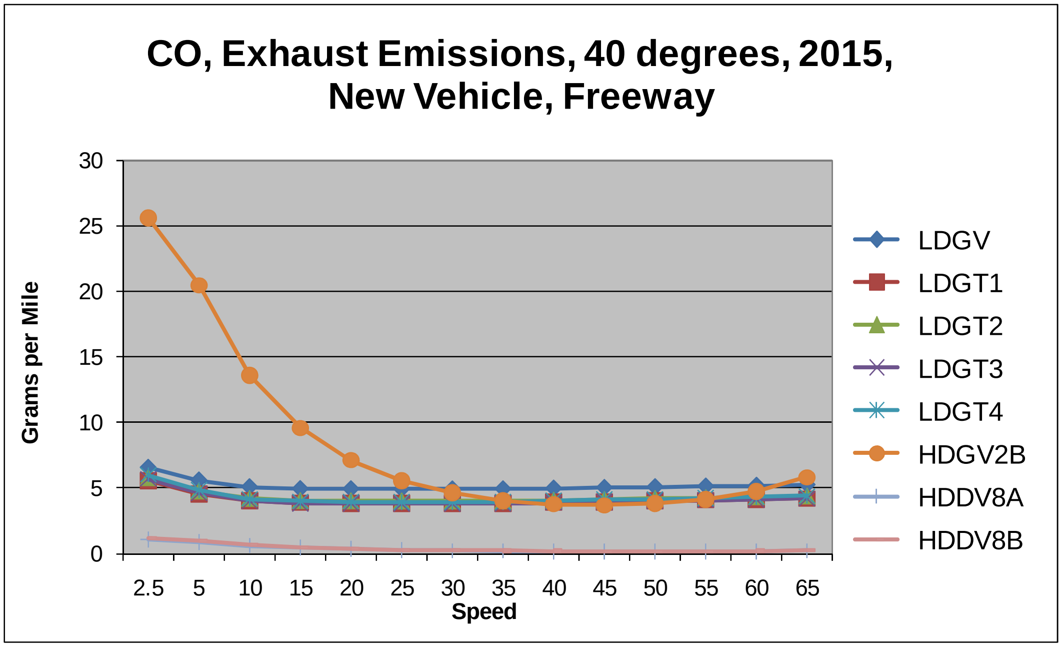


(d)

Figure D.2: NO_x Exhaust Emissions

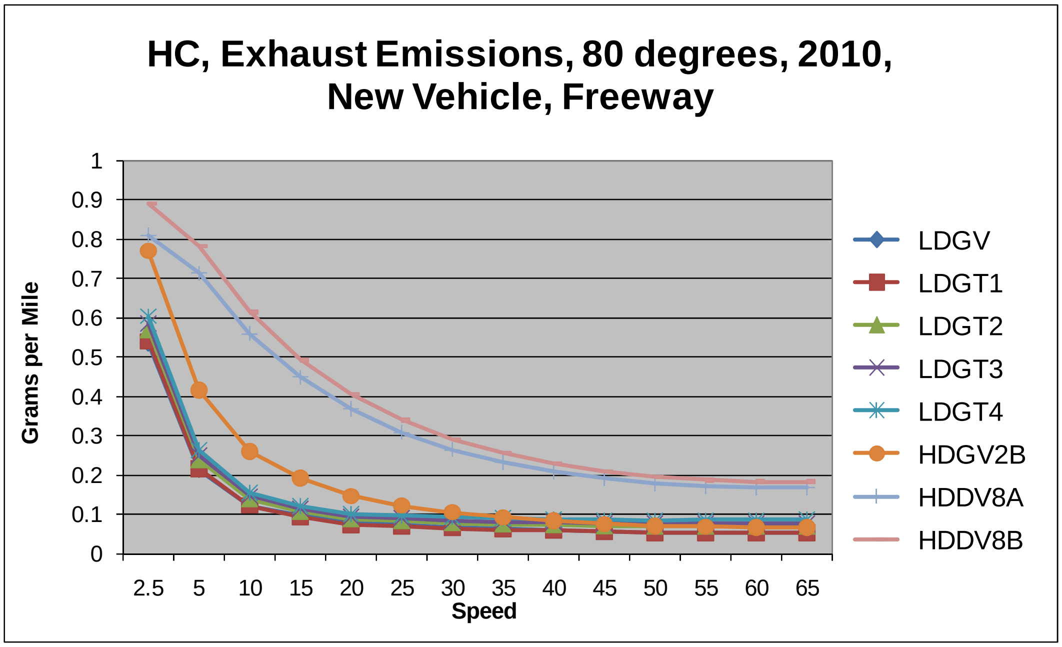


(a)

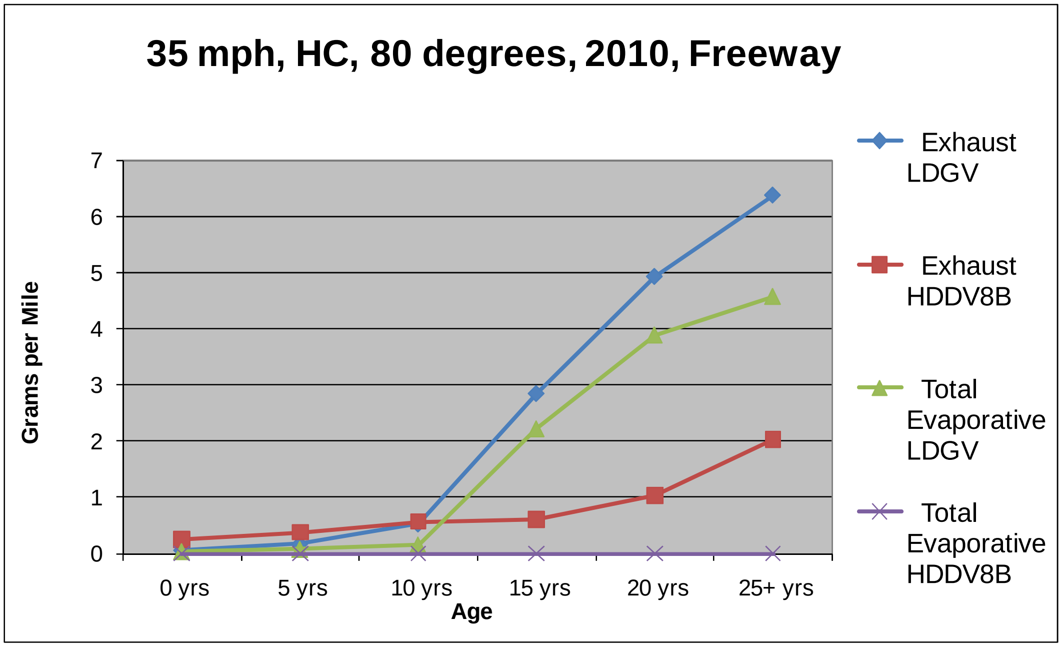


(b)

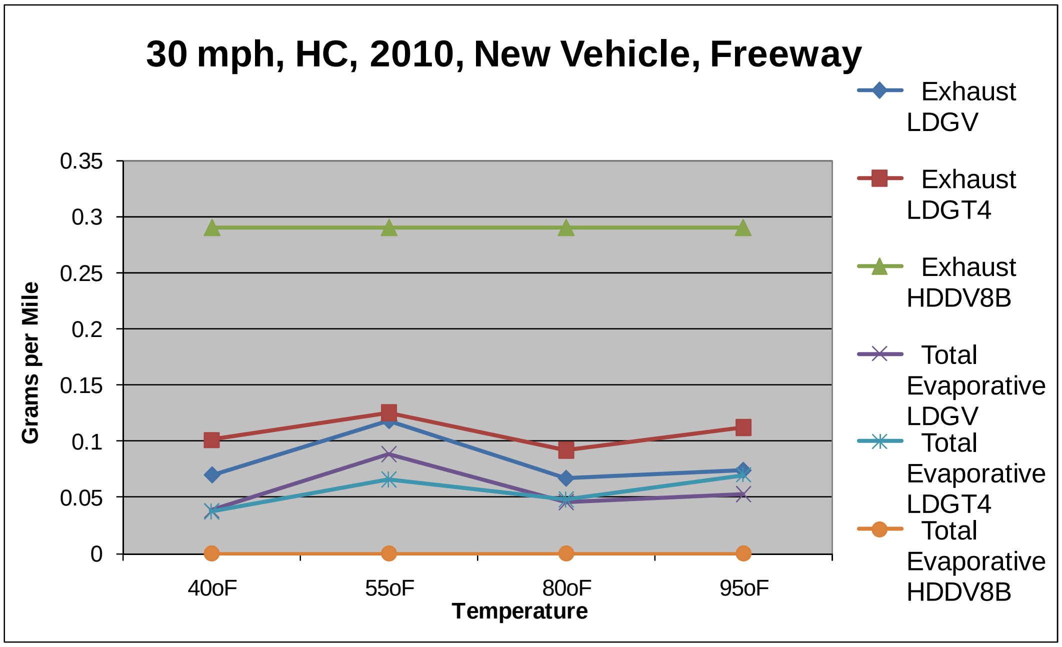
Figure D.3: CO Exhaust Emissions


HC, Exhaust Emissions, 80 degrees, 2010, New Vehicle, Freeway
Grams per Mile
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2.5
5
10
15
20
25
30
35
40
45
50
55
60
65
Speed
LDGV
LDGT1
LDGT2
LDGT3
LDGT4
HDGV2B
HDDV8A
HDDV8B

(a)


35 mph, HC, 80 degrees, 2010, Freeway
Grams per Mile
7
6
5
4
3
2
1
0
0 yrs
5 yrs
10 yrs
15 yrs
20 yrs
25+ yrs
Age
Exhaust LDGV
Exhaust HDDV8B
Total Evaporative LDGV
Total Evaporative HDDV8B

(b)



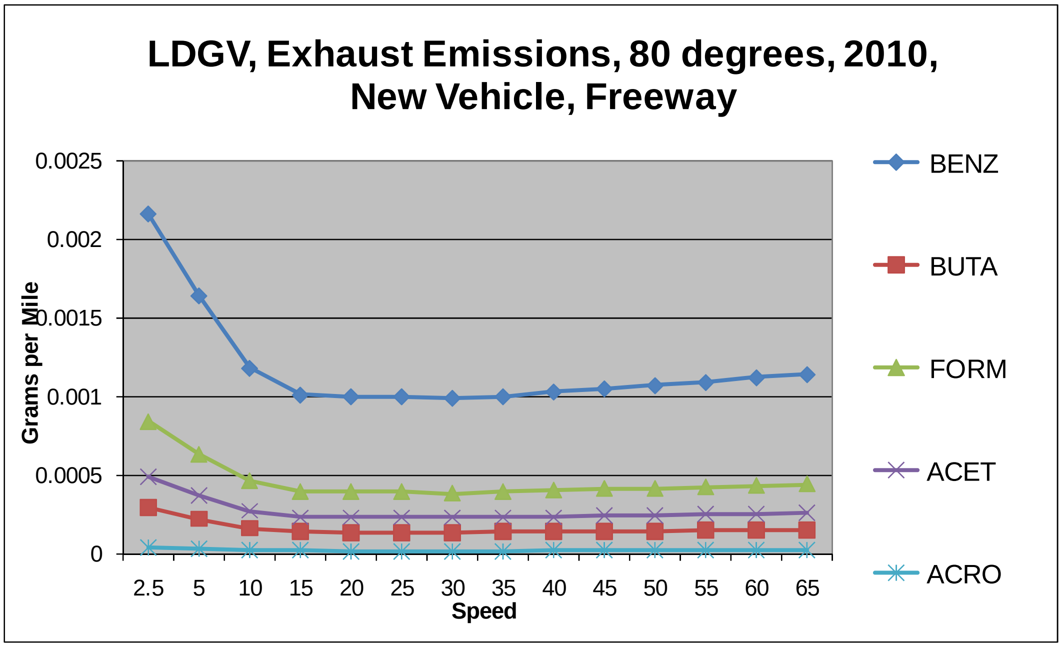
(c)

Figure D.4: HC Exhaust Emissions

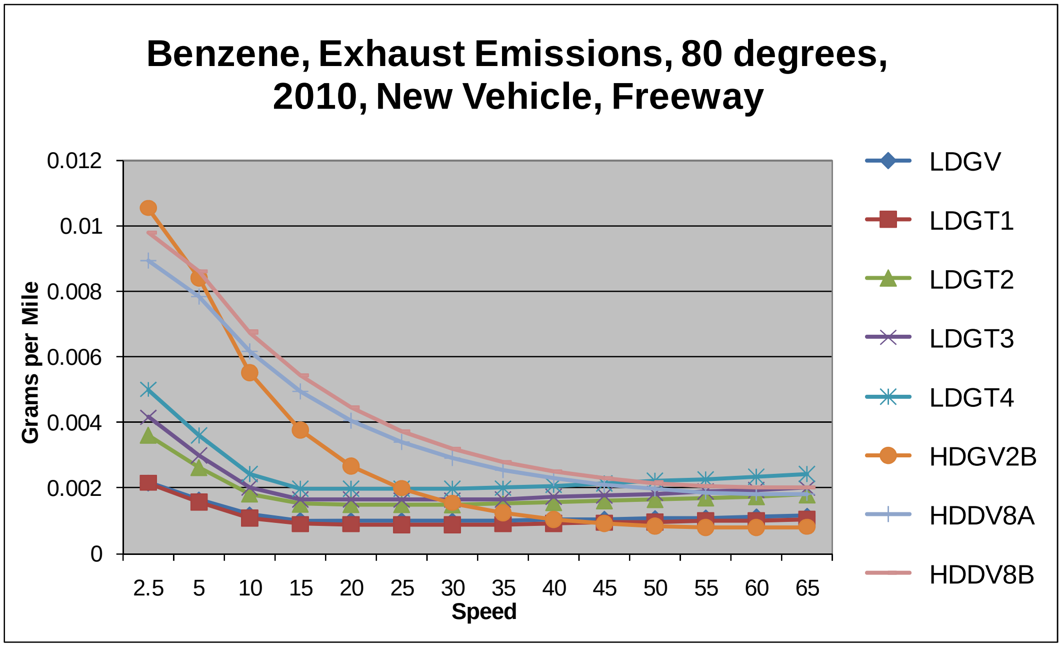
Note the jump in HC rates after 10 years of vehicle age. This is because a law went into effect in 2004 tightening the standards on non-methane HC emissions from HDVs, and the impact of this law is seen in the emissions rates.

D.5 Mobile Source Air Toxics (MSATs)

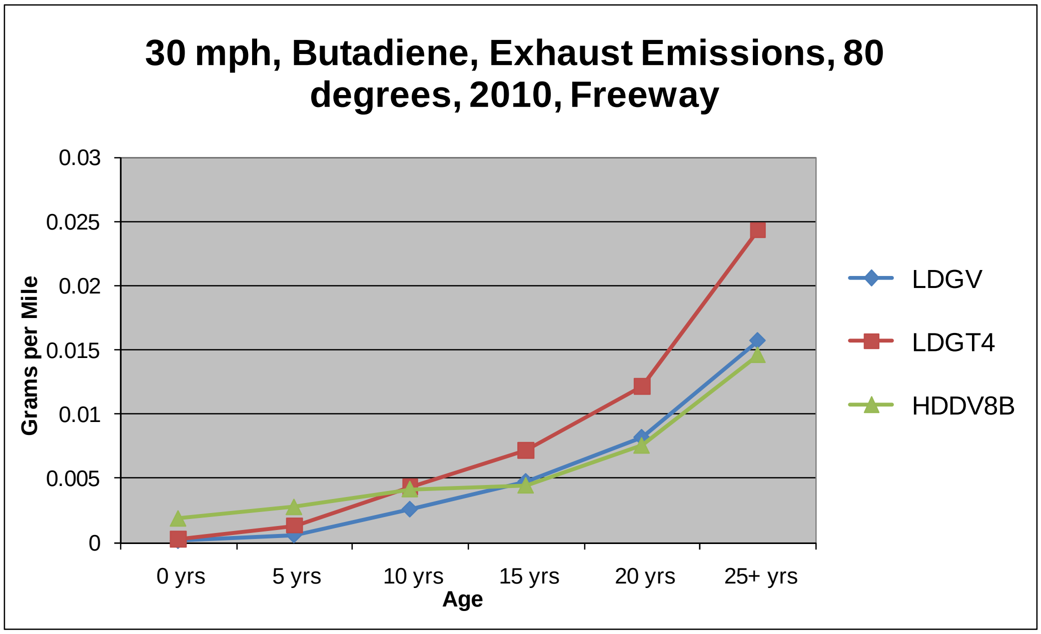
MSATs all fall under the category of HCs, and so any regulations affecting HC emissions will also impact MSAT emissions rates (Figure D.5).


LDGV, Exhaust Emissions, 80 degrees, 2010, New Vehicle, Freeway
Grams per Mile
0.0025
0.002
0.0015
0.001
0.0005
0
2.5
5
10
15
20
25
30
35
40
45
50
55
60
65
Speed
BENZ
BUTA
FORM
ACET
ACRO

(a)


Benzene, Exhaust Emissions, 80 degrees, 2010, New Vehicle, Freeway
Grams per Mile
0.012
0.01
0.008
0.006
0.004
0.002
0
2.5
5
10
15
20
25
30
35
40
45
50
55
60
65
Speed
LDGV
LDGT1
LDGT2
LDGT3
LDGT4
HDGV2B
HDDV8A
HDDV8B

(b)

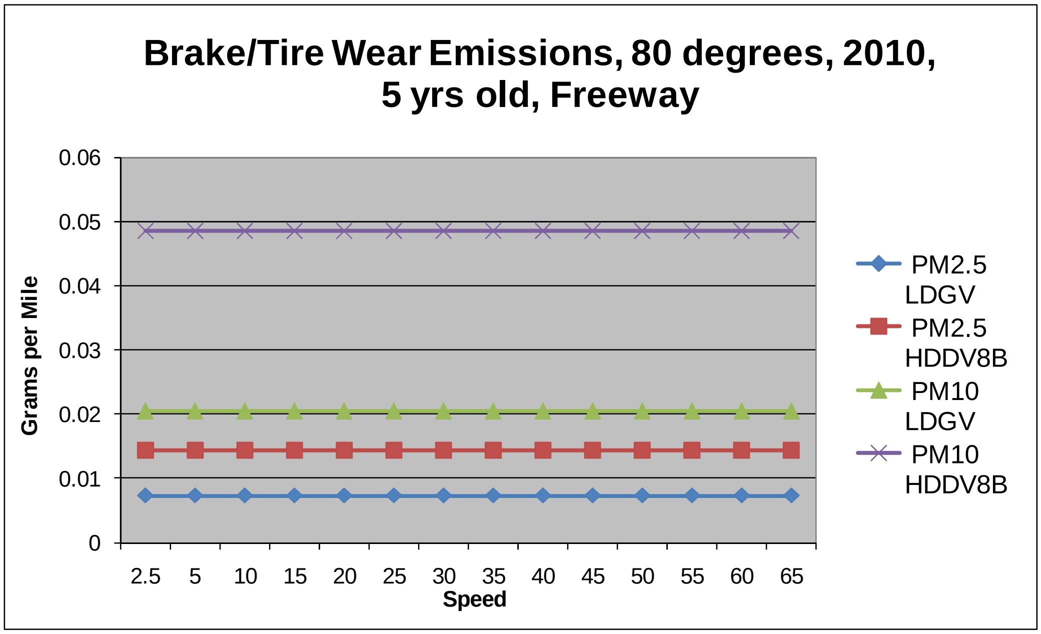


(c)

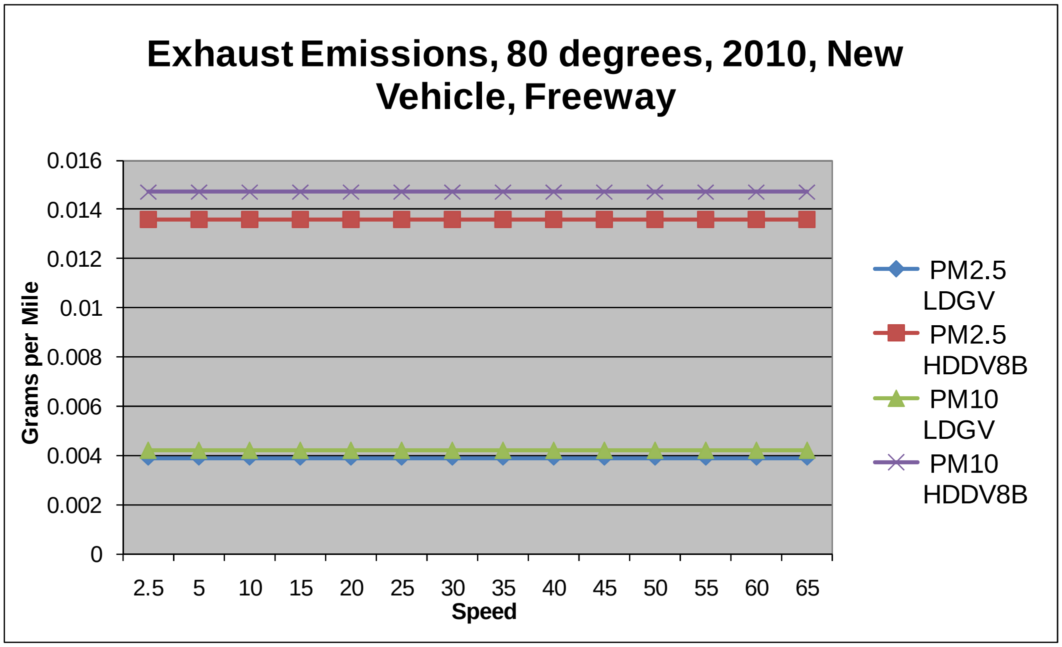
Figure D.5: MSAT Exhaust Emissions

D.6 Particulate Matter (PM)

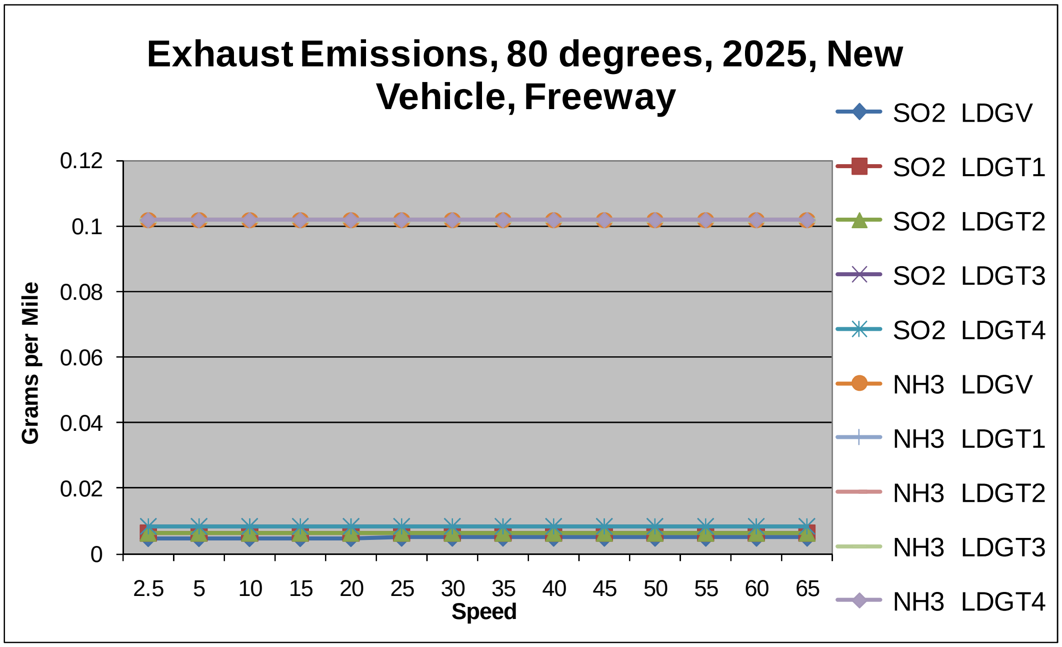
Primary PM emissions from brake and tire wear and, oddly, primary PM exhaust emissions do not depend on anything but vehicle type and particle size. Secondary PM emissions (SO_2 and NH_3) also do not change with any variable but vehicle type. Emerging information about MOVES indicates that MOBILE6 under-predicts PM emissions (Beardsley 2009), which would explain the relatively low emissions rates for exhaust PM emissions shown in Figure D.6.



(a)



(b)



(c)

Figure D.6: PM Emissions

D.7 The Relative Impacts of Input Assumptions

EPA (2002) researchers have produced a sensitivity analysis for MOBILE outputs as related to input assumptions, with common variations in inputs categorized as having either major, intermediate or minor effects on the various output rates, by pollutant species. “Major effects indicates that when the input parameter was perturbed by 20%, the emission factors changed by more than 20% (more than 1:1 ratio). Moderate effects indicate that the output changed between 5% and 20% (less than 1:1 ratio) and minor changes indicate a less than 5% change." The following table of results (for the 2007 model year, using MOBILE) suggests that the most important inputs are Average Speed, Fuel Reid Vapor Pressure, and Registration Distribution (Table D.1).

Table D.1: Summary of EPA Sensitivity Analysis of MOBILE6 Inputs

Source: EPA (2002)

Input Command or Data	**Major Effects**	**Moderate Effects**	**Minor Effects**
Absolute Humidity		NOx	CO
Air Conditioning			CO NOx
Altitude			CO NOx
Average Speed	CO NOx		
Facility Type			CO NOx
Fuel Program/Sulfur Content			CO NOx
Fuel Reid Vapor Pressure	CO NOx		
Hourly Temperature			CO NOx
Mileage Accumulation		CO NOx	
Min/Max Temperature		CO NOx	
Oxygenated Fuels			CO NOx
Registration Distribution	CO NOx		
Speed VMT		CO NOx	
Start Distribution			CO NOx
Starts Per Day			CO NOx
Temperature and Humidity			CO NOx
Temperature Cycles			CO NOx

Appendix E: Parameter Values Used in the Case Studies

- *Area Type*

Area type was assumed as urban for all roadway segments and intersections.

- *Time of Day*

Five (5) time-of-day periods were analyzed as follows:

AM Peak:	6 AM – 11 AM	5 hrs
Mid Day:	11 AM – 2 PM	3 hrs
PM Peak:	2 PM – 7 PM	5 hrs
Evening:	7 PM – 11 PM	4 hrs
Off Peak:	11 PM – 6 AM	7 hrs

Automatic Traffic Recorder (ATR)-collected data from six (6) reference stations were used for time-of-day traffic shares. These stations are as follows:

IH 35:	0.3 Mi. S of FM 1626	Austin
US 290:	4.2 Mi. W of FM 1826	Austin
SH 71:	3.58 Mi. E of US 183	Austin
US 183:	3.3 Mi. S of SH 71	Austin
IH 35:	N of Town Lake Bridge	Austin
LOOP 1:	Under 35th St Overpass	Austin

Note: Modeled routes that did not have one or more reference station were typically assumed to have similar time of day traffic distributions as the US 290 ATR reference station.

- *User Types*

Four (4) user types were used, each with the following characteristics (Table E.1):

Table E.1: Modeled Characteristics of User Types

Value of Time and Reliability ($/hr)			
User Type	**VOT**	**VOR**	**% of Pop.**
1	$50.00	$50.00	10%
2	$30.00	$30.00	10%
3	$10.00	$10.00	20%
4	$5.00	$5.00	60%

VOT = Value of time
VOR = Value of Reliability
User Type 1 is exclusively heavy-duty truck drivers.

- *Mode Split*

For all user types other than User Type 1 (heavy-truck drivers), mode split was assumed to be 55.5% single-occupancy vehicles (SOVs), 26.2% two-person vehicles, 16.3% vehicles with 3 or more persons (3.2-persons average vehicle occupancy [AVO]), and 2% transit (12-person AVO).

- *Crash Distributions*

Crash distributions were estimated as follows for all urban and suburban segments and intersections (as was the case in this scenario):

Property Damage Only:	60.92%
Possible Injury:	25.10%
Non-Incapacitating Injury:	12.17%
Incapacitating Injury:	1.35%
Fatal Crash:	0.46%

This distribution is based on data from TxDOT's motor vehicle crash statistics (2008). The statistics provided did not separate non-incapacitating injuries and incapacitating injuries. Therefore, estimates were obtained from the forthcoming upcoming Highway Safety Manual (2010). For most facilities the HSM did not contain separate information for non-incapacitating injury and incapacitating injury crashes; however, it did separate data for rural two-lane highways. This was used to establish a rural injury severity breakdown. The HSM severity data was combined with the TxDOT severity data to estimate the proportion of injury crashes that likely result in incapacitating injuries.

- *Crash Costs*

Motor vehicle crash costs were used with assumed values based on the crash severity as follows:

Property Damage Only:	$7,500
Possible Injury:	$11,900
Non-Incapacitating Injury:	$21,000
Incapacitating Injury:	$65,000
Fatal Crash:	$1,130,000

- *Emissions Costs*

Dollar value costs were not assigned for emissions. Only total emissions and changes in emissions were estimated.

- *Vehicle Speeds*

Default free-flow vehicle speeds were used for all links, and assumed to be as follows (Table E.2):

Table E.2: Default Vehicle Speeds

Facility Type	Area Type		
	Urban	Sub-Urban	Rural
Freeway	55 mph	60 mph	65 mph
Arterial	45	50	55
Collector	40	45	50
Ramp	40	40	40

Minimum speeds were assumed to be 2 mph for each link (thus helping avoid excessively long travel times).

Appendix F: Reviewers' Comments and Project Team's Responses

F.1 Review of Phase 1: Toolkit Framework

F.1.1 Project Objectives

Chris Williges wondered what the focus of the project is, because the formal title is "Sketch Planning Techniques to Assess Regional Air Quality Impacts of Congestion Mitigation Strategies," but the toolkit is designed to be comprehensive, tackling questions of traveler welfare, travel time (un)reliability, vehicle crash rates changes, costs, and so forth. The May 2010 TxDOT Planning Workshop title is likely to be "Comprehensive Evaluation of Competing Projects: A Toolkit for Sketch Planning," which better reflects the work's contribution.

F.1.2 Toolkit Design

The project team presented the toolkit's software architecture design in Tech Memo 4 and a data flow diagram in Tech Memo 5. The system design seems quite a bit more complicated and demanding of users, so reviewers raised questions about this. We then explained that existing toolkits require all the demand modeling work take place upstream, outside the toolkit, or allow only simple networks and simple tradeoffs in demand (like two parallel and competing links). In contrast, we choose a complete travel demand modeling procedure to estimate traffic flows in sketch networks. That estimation (hidden to the user, in fast-running C++ code) is iterative and computationally intensive. It also is cutting edge (and will soon be published in the Transportation Research Record series).

Of course, the toolkit's user interface and other benefit-cost modules run in Microsoft Excel, which is widely used and preferred by many planners and modelers for data manipulation and analysis. The input and output data are all stored in Excel spreadsheets, and communication between the spreadsheet data interface and the C++ programs is achieved via spreadsheet-embedded VBA macros. Specifically, the VBA macros function as exchanging input and output data and parameters between the spreadsheets and the external C++ programs.

The toolkit's modular design enables us to conveniently extend its functionality by modifying its existing modules and adding new modules. All computational modules (except the travel demand module) are in Excel spreadsheets, so these calculations are completely transparent to user. Also, computation details and results of the travel demand estimation are stored in self-contained text files and can be accessed by advanced users who want to examine the travel demand estimation process. The code can be made open-source with no problem.

The experts are generally excited to hear about the added functionality of this emerging toolkit. We think it has tremendous application ability, and far more accurate results than other models (which largely ignore demand impacts of network improvements, or require much work upstream of their application).

F.1.3 Model Complexity, Computation Cost and Data Adequacy

Chris Williges wondered several times in his review comments about the model complexity, computation cost, and data requirements. His Cal-B/C (California Benefits/Costs) model for Caltrans is exclusively spreadsheet-based, and requires that users know all delays, speeds, and other outputs under all scenarios before using the model. Assuming they know all this, Cal-B/C is much easier/faster to use. Thus, Cal-B/C is typically used downstream, when budgeting projects, rather than identifying projects for further study.

This is related to the design and choice of multiple models used in the travel demand process. Obviously, our travel demand modeling procedure is relatively more comprehensive and complex than the procedure used in previous sketch planning tools. So the questions around this concern from Chris Williges are whether such a complex design is necessary, how much computation source is required, what would be the required input data, and whether these required data are readily available.

We are providing a sketch planning tool for a variety of transportation network/project evaluations, including capacity expansions, road tolling, HOV/HOT lane use, etc. In other words, it is designed to be applicable to almost all highway-capacity-expansion (and road-tolling) projects regions may consider. Plus, considering the temporal shifts of traffic flows over the day (and project scenarios like variable tolling), it is necessary for us to form a multimodal, multiclass, multiperiod travel demand model, so that network changes can be properly reflected from the traffic flow shifts. (In other words, if we ignore demand shifts, we may be missing the boat entirely.)

The code runs fast, so that is no concern at all. In our experiments with a 58-link Austin sub-network (as described in Tech Memo 6), we find that the entire travel demand estimation procedure takes only a few seconds to run on a mainstream desktop (assuming a 0.01 convergence criterion for both the trip table estimation and demand modeling-with-traffic assignment processes). We are confident that our software package will run fast, considering that most sketch networks will have fewer than 200 links.

While the toolkit allows for a relatively large amount of input data (e.g., traffic counts by time of day), it also provides plenty of defaults for users to rely on, in case they wish to input only the most basic information (nodes, links, capacities, free-flow speeds, and 24-hour counts).

F.1.4 Travel Time Reliability

Modeling travel time reliability in travel choice models and travel demand estimation procedures is an emerging task, in both theory and practice. No widely recognized single method yet rules the roost. We employ the definition of “buffer index” to define travel time (un)reliability and quantify the travel time variance based on data provided by Rich Margiotta (of Cambridge Systematics). Chris Williges commented that this approach may be “too simplistic” but may also address the reliability issue under recurring congestion. Whether travel time reliability should be used as part of travel cost in route choice and other travel choice behaviors is a debatable issue among Chris and Dan Beagan, another reviewer. Because no evidence yet exists as to how much travelers consider travel time reliability in making their travel choices, we have decided to not include the travel time reliability term in the default version of the generalized travel cost function. But the code exists to have it, and in the final version of the code users can elect that option. And, of course, the toolkit values reliability either way (either endogenously in travel demand model routines, or at the end of the modeling runs). There are more discussions about the use of travel time reliability from the phase II review, below.

F.1.5 Modeling Internal-External Interactions

Both Dan Beagan and Patrick DeCorla-Souza wondered about modeling traffic interactions at the sub-area within a larger transportation network. For example, the smaller the modeled sub-network, the more likely that local improvements will draw trips from outside the modeled network. Thus, our model allows for internal-external interactions via demand elasticities on all OD pairs. While we believe that this is a relatively simplified, aggregate method for capturing the complex behaviors of internal-external, external-internal, and external-external flows going through the subarea, at least it offers a rational way to approximate the effect.

F.1.6 O-D Flow Estimation

Dan Beagan discussed the team's O-D flow estimation method at length with the team. He has previous experience coding a Maximum Entropy-User Equilibrium (ME-UE) method and was interested in a comparison of his method and our ME method. We were able to quickly explain why ME-UE methods of the past are not applicable here. First, a seed trip table (required by ODME and other existing methods) is typically not available to our toolkit users. Second, that approach presumes that link use probabilities can be transferred from the old network (associated with the seed trip table) to the current network. Third, a traffic assignment process (such as the Frank-Wolfe algorithm) cannot guarantee a unique set of link choice probabilities. The generated link choice probabilities depend on the specific traffic assignment algorithm as well as the order of O-D pairs that are assigned with traffic during the computational process. That is to say, if we use different traffic assignment algorithms or change the order of origin and destination nodes in the input pair, we will likely get different link choice probabilities, even though we use exactly the same network data and these algorithms provide exactly the same (link) traffic flow pattern. In this case, which set of choice probabilities one should use is in question. The ME method offers a simpler model but resorts to a more complex algorithm; the ME-UE method has a relatively more complex model, but a relatively simple solution methodology (with less computing time). Dan Beagan was very satisfied with our answers, and happy to learn something new.

Dan Beagan also questioned the requirement of path enumeration in our method. As we explained, thanks to the use of a column generation ME method, we avoid path enumeration requirements and achieve a very efficient implementation. More details about the column generation method can be found in Tech Memo 4 and the project team's TRB 2010 paper (http://www.ce.utexas.edu/prof/kockelman/public_html/TRB10ODME.pdf).

F.2 Review of Phase 2: Case Studies and the Excel Component of the Toolkit

F.2.1 Traveler Welfare

Ken Cervenka noted differences in ratios of welfare benefits to savings in vehicle hours traveled under the base year and future year conditions. He noted that the ratio of welfare to time savings was 13.5 (dollars per hour saved) in the base year, versus 56.7 ($/hour) in design year. While factors other than (expected) travel time savings are calculated in traveler welfare estimates (for example, a traveler may prefer to drive during peak hours), the project team found the comparison of such ratios, and the significant difference, somewhat illuminating. It coincides very nicely with our expectations that project improvements in travel time reliability are carrying a great deal of weight in the future years, when the modeled network becomes highly congested (thanks, in part, to an overly generous 2.5% annual trip growth rate assumption that needs to be moderated). The project team is currently re-assessing all methods used in the project toolkit for calculating traveler welfare benefits of the improvements, and many remedies will be employed.

F.2.2 O-D Flow Estimation

In order to address some of the discrepancies between VHT reductions and traveler welfare benefits, Ken Cervenka recommended that the project toolkit hold trip tables constant between scenarios, as a simplification of reality, to enhance transparency for users and avoid some of the noise that comes with a sophisticated demand model allowing for various behavioral shifts across scenarios. (Currently, each scenario enjoys its own trip table for the current year and expands that trip table to the future year. This reflects the fact that abstracted study networks may receive plenty of new trip-making from "outside" the studied links, but it also introduces more variation than some analysts may seek, in an effort to compare apples with apples.) The project team had already intended to implement Ken Cervenka's recommendation, so that the analyst may opt to hold trip tables constant across scenarios. If this option is selected, the trip table for the current year would be the same for all scenarios and the trip table for the future year would be the same for all scenarios. Ken was delighted to hear this.

F.2.3 O-D Relationship between Traveler Welfare Estimates and Travel Time Reliability

Dan Beagan investigated the toolkit methodology for evaluating traveler welfare estimates. He was thinking that the BPR link performance function may already account for travelers' response to travel time unreliability, if its parameters are calibrated to match flows on link (rather than speeds, which supposedly are routinely under-estimated by MPOs [according to Dan and Ken]). Thus, by including travel time unreliability in the traveler welfare estimates (based on link-cost functions that include unreliability terms), we may be double-counting travel time unreliability impacts. His interesting comment also helped bring to the project team's attention that both the C++ code and the Excel benefits-accounting codes were estimating the impacts of travel time reliability improvements, so certainly there was double-counting to begin with (thus the excessive benefit-cost ratios in Tech Memo 6). Travel time unreliability is therefore at least double-counted in the current toolkit model, and possibly triple counted (if the link-performance functions somehow implicitly account for traveler welfare). The project team will work to ensure that benefits of travel time reliability improvements are evaluated only once.

F.2.4 O-D Quantifying Travel Time Reliability

Alan Horowitz questioned the project team's use of travel time variance in the link-cost equations. He noted that reliability was stated as a standard deviation, rather than variance, the last time he saw reliability measures discussed in a planning study. He then posed the question of why the project team believed that travelers would view variance as the best measure of travel time reliability. The team explained that summing variances across links is permitted (in a statistical sense, if one assumes independent unreliability terms from link to link), much like summing costs and times from link to link, and this is not feasible with standard deviations. He seemed pleased with this answer, in part because summing variances (after they have been normalized to time-equivalent units, using a value of reliability, as described in Tech Memo 5) helps reduce the path's uncertainty (if one looks at the standard deviation of path travel time versus mean travel time). Nevertheless, it is not clear whether travelers are aware of unreliability in the links and paths they may choose, or that they value the variance, rather than the standard deviation. This is just one of many behavioral assumptions in any travel demand model. But the default approach for the toolkit's use is to not include unreliability in link costs, and, instead, account for reliability benefits at the end of the calculations (assuming the analyst's link performance functions are not already accounting for unreliability costs).

F.2.5 O-D Speed Estimates and Speed Post-Processing

Ken Cervenka and Dan Beagan both noted that speed estimates based on the link performance functions do not always match observed speeds. They both noted that speeds estimated using in our network assignment routines may need to be increased using post-processing, in order to provide effective inputs to MOBILE6 for emissions rates estimates. (Ken Beagan and Dan Cervenka estimated that post-processing would likely be required for well over 50% of links.)

Dan Beagan and Ken Cervenka noted that link performance functions are often chosen to better reflect traffic counts, rather than speeds (because, presumably, engineers and policymakers care more about flows than speeds?). The research team will further investigate these claims, through some validation exercises with Austin speed and count data where possible. It also will alert toolkit users to this notion of making sure speeds are appropriate for emissions rates lookup. There will be no direct post-processing of speed in the toolkit, however, because many MPOs are now having luck with finer time-of-day modeling and better model feedback to match flows and speeds. Moreover, Alan Horowitz argued against post-processing speed estimates as very bad modeling, citing his own models to show that it is possible for traditional models to arrive at good average flows and speeds.

As a result of these discussions, the team is likely to provide details about how to conduct speed post-processing for emissions estimates, if toolkit users wish to pursue this. This way, if an agency believes that speed post-processing is needed to produce more accurate emissions estimates, the agency can opt to use certain measures. In fact, speed post-processing could be accomplished in two steps: first the analyst would input the required model data and run the traffic assignment portion of the model normally, for counts. Next, the analyst would adjust free-flow speeds and/or alpha and beta link performance parameters to achieve new emissions results with post-processed speeds. This would also change the link-level reliability estimates and the corresponding values in reliability benefits (or disbenefits). However, at this time there is no proposed methodology to assess changes in traveler welfare after speed post-processing, as this is handled in the C++ component during traffic assignment.

F.2.6 User Input Requirements

Madhusudhan Venugopal postulated that it may be easier from the users' perspective to include all inputs on the same sheet. The project team intends to continue to use multiple input sheets because of the variable number of links and arterial intersections for the transportation networks. Furthermore, global parameters apply to all scenarios and would not fit well in the same sheet as any one of the scenario network configurations. The project team understands Madhusudhan Venugopal's concerns that a user may forget or not realize that he or she needs to input required data into certain sheets. The project team intends to alleviate this confusion with the addition of navigational controls. A button will be included linking to a Required User Input form that will include links to all sheets where user input is required. Furthermore, the project team intends to include an input checklist so that the user can verify that input values have been entered on all required input forms.

Dan Beagan noted that the toolkit requests a high number of input fields for each link. He postulated that this may be time-consuming for analysts and thereby limit the toolkit's potential use. The project team is aware of this issue and is in the process of developing measures to reduce the number of required link-level inputs. This is being accomplished by implementing default values (for example, average freeway exit ramp spacing) that the analyst can opt to use in place of values obtained at the individual link level.

F.2.7 Additional Testing

Madhusudhan Venugopal recommended that the project team test the toolkit results with a full travel demand model. The project team has not accomplished this and is currently focused on ensuring the completeness of the toolkit's methodology and integration between the C++ and Excel modules. As per Madhusudhan Venugopal's recommendation, the project team intends to test the project toolkit results against a full travel demand model once the toolkit has undergone further testing and refinement.

F.2.8 Additional Comments

Dan Beagan noted that much of the input data for link attributes can be obtained from TxDOT's RHiNO database. The project team currently does not have access to that data, but toolkit users from TxDOT or Texas MPOs would likely have access to that data source.

Dan Beagan suggested that FHWA's Highway Economic Requirement System data could be used to develop default toolkit-generated link capacity estimates when RHiNO data is not available to the analyst.

Dan Beagan, Ken Cervenka, Alan Horowitz, and Madhusudhan Venugopal all posed questions that will be useful in further developing the toolkit's documentation. The project team will ensure that the toolkit users will find answers to all such potential questions.

Appendix G: Toolkit User's Guide

The Toolkit User's Guide provides users with a detailed description of the structure, functions, and operations of the Toolkit, as well as its advantages and limitations for project evaluations. This Toolkit addresses the need to comprehensively evaluate multifaceted projects, in the initial year of project implementation and over time, in order to more cost-effectively prioritize and allocate budget monies and other resources. The Toolkit uses a self-contained travel demand model to predict future and alternative scenario traffic volumes, speeds, crash counts, emissions and toll revenues, while providing project-level performance measures, including net present value and benefit-cost ratios. The toolkit was developed in the spirit of sketch planning, because only abstracted networks—or sub-networks—and traffic counts are required, rather than a full urban planning model. The Toolkit is geared towards the evaluation of roadway projects that alter roadway capacity, free-flow speeds, tolling policies, and many other network conditions.

The User's Guide is quite long, and so is provided as a PDF file on the CD that accompanies this final report. The CD also contains the Toolkit software. For details on installing and using the Toolkit, users should first read the User's Guide.