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16. Abstract This report summarizes research for TxDOT Project No. 0-6487, which enhanced and expanded the open-source Project Evaluation Toolkit (PET) to evaluate operational strategies for transport project (and policy) impact evaluation. Such strategies include advanced traveler information systems, speed harmonization, shoulder use, incident management, and ramp metering. PET is a user-friendly, comprehensive sketch-level project evaluation planning tool, anticipating changes in travel demand, traffic patterns, crashes, emissions, traveler welfare, reliability, project net present values, benefit-cost ratios, and other performance metrics. PET also tracks project financing measures for a number of project types, including capacity expansion projects, tolling, and managed lane facilities. Beyond operational strategies, this project increased PET's scope, usability, and accuracy in other ways. For example, new transit and fixed-cost features allow for deeper and more meaningful mode choice and network modeling, while a network visualization module dramatically facilitates user generation and editing of modeled networks. New features also allow users to bypass PET's built-in travel demand model (TDM) to evaluate external TDM outputs directly. Such features allow more sophisticated modelers the chance to apply PET to their own TDM outputs, for a much wider variety of outputs than traditionally available to transportation planners and engineers. As noted, outputs include emissions, crash counts, reliability, toll revenues, and benefit-cost ratios, among others. PET capabilities include budget allocation tolls, multi-criteria assessment (of multi-faceted projects, using decision envelopment analysis), and sensitivity analysis (to produce distributions of project performance metrics, recognizing that many/most inputs have some uncertainty associated with them). Alongside these scope-enhancing changes are updates to crash and emissions estimation procedures, reflecting the latest Highway Safety Manual and EPA emissions (MOVES) estimation routines. This project also developed a variety of professional supporting materials for PET users, including an extensive User's Guide, presentation materials (for rapid training of new users), and four urban roadway networks (for Dallas-Fort Worth, Austin, Houston, and San Antonio). All these, along with several relevant papers and reports, are available at <a href="http://www.ce.utexas.edu/prof/kockelman/PET_Website/homepage.htm">http://www.ce.utexas.edu/prof/kockelman/PET_Website/homepage.htm</a>				
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## **A Project Evaluation Toolkit (PET) for Abstracted Networks**

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## Introduction

Appropriately quantifying the myriad effects of transportation system improvements has long been a challenge. Many benefits emerge in the form of travel time savings for existing travelers, but subtle benefits come from trip re-scheduling (to more preferred times of day), re-routing, new/better destination alternatives, and so forth. Moreover, the transportation planning paradigm is changing, with added emphasis on reliability, air quality, climate change and sustainability, accessibility, freight movement, and environmental justice. This evolution necessitates a new set of performance measures, capable of quantifying investment and policy benefits (and costs) from a different, more comprehensive perspective. Complex tradeoffs often exist: for example, travel time reductions may result in greater emissions due to the convexity of emissions rates curves (versus speed), longer trip-making, and/or different drive cycles. Moderation of local bottlenecks can harm network performance by generating bottlenecks elsewhere. Furthermore, an increasing reliance on public-private partnerships requires performance evaluation from multiple perspectives, recognizing the competing interests of diverse stakeholders.

To this end, this project enhanced and extended a performance-based methodology and user-friendly spreadsheet-focused tool for straightforward and equitable comparison of benefits (and costs) across any set of operational improvements and capacity expansion projects that Texas MPOs, TxDOT district offices, and others may be considering. Recognizing that congestion, safety, economic opportunity, asset valuation and emissions levels are key measures of project success, the **Project Evaluation Toolkit (PET)** developed here emphasizes multi-criteria evaluation for project metrics, along with sensitivity analysis, budget allocation across competing projects, and other tools for project planners. Competing projects' and policies' performance metrics emerge from PET's estimates of time savings, travel time reliability changes, safety improvements, and emissions reductions vis-à-vis project costs over each project's lifetime. These metrics, combined with summary measures (such as benefit-cost ratios and internal rates of return), highlight opportunities for optimal transportation investment and policy decisions, and reveal project limitations that may require remedy.

Work under Project 0-6487 spanned 3 years in the form of 17 unique tasks, all of which built upon a project analysis framework for PET established under project 0-6235 (Sketch Planning Techniques to Assess Regional Air Quality Impacts of Congestion Mitigation Strategies). Together, these two projects (0-6487 and 0-6235) resulted in an unusually comprehensive toolkit. This tool, spanning years of development and addressing numerous impact measures, is necessarily rich in methodology and structure. One major task of the 0-6487 was creation of a thorough User's Guide (a 130-page document), detailing how the Toolkit works and how it can be used. This final report follows the same general approach as PET's User's Guide, but with a broader focus.

The report is divided into six chapters. **Chapter 1: Project Impact Measures** describes the project impacts PET considers and how these measures are estimated. **Chapter 2: Project Types** describes intended applications, and thus the many project types that PET is designed to evaluate. Chapter 2 also explains why certain projects and policies are considered for analysis, how they can be compared, and their impacts on road networks. This section considers how operational projects can be compared against capacity expansion projects within PET, and some implications of these project comparisons. **Chapter 3: Toolkit Structure** discusses PET's software structure, providing a more technically detailed analysis of how PET performs

calculations within its framework and how data is handled. **Chapter 4: Using the Toolkit** delves further into this understanding by presenting user interface, and applications of project analysis. **Chapter 5: Case Studies** explores specific case study applications to give readers an idea of specific types of outputs that analysts can expect. **Chapter 6: Conclusions** summarizes the project's results. Finally, **Appendices A through C** describe the work that went into developing PET's emissions rate estimations and compares PET to previous emissions estimation efforts.

This report structure allows readers to understand what outputs PET delivers, what types of projects PET can be used for, how PET works, how to use PET in practice, and what case studies of actual PET applications look like. Many technical details are omitted in the interest of readability, but extensive documentation lies within the User's Guide, the toolkit itself, supporting documentation, and training slideshows, which can be found at [http://www.ce.utexas.edu/prof/kockelman/PET\\_Website/homepage.htm](http://www.ce.utexas.edu/prof/kockelman/PET_Website/homepage.htm)



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# Chapter 1. Project Impact Measures

## 1.1 Introduction

Many agencies use separate models to analyze distinct project impacts, including destination choices, congestion levels, vehicle emissions, and crashes. In contrast, the Project Evaluation Toolkit (PET) provides side-by-side metrics for a host of project types, including capacity expansion, new-link construction, flat-rate and variably-tolled corridors, managed lanes, and various other traffic management strategies (like advanced traveler information systems, speed harmonization, shoulder-lane use, ramp metering, incident management, and managed lanes). PET relies on a five-step model of traveler behavior, thoughtful trip table generation optimization routines, fast multi-class network assignment algorithms, the latest factors from the Transportation Research Board's Highway Safety Manual (AASHTO 2010), and the EPA's (2012) MOVES emissions modules for its calculations.

Four major impact areas are considered: **traveler choices** (and traffic conditions), **traveler benefits** (including travel time savings and travel time reliability improvements), **emissions** (across 14 species), and **crash counts** (by severity). All impacts are quantified, most are monetized, and the final three are presented relative to a base-case (e.g., no-build) alternative over the project or policy horizon (e.g., 20 to 30 years or more), and discounted to present dollar values (for equitable comparison of benefit-cost (B/C) ratios, internal rates of return, and other performance metrics). The following sections highlight key details of methods used for each impact category and why they are relevant considerations in PET's project modeling.

## 1.2 Traveler Choice and Traffic Conditions

Traffic impacts are modeled on a user-created abstracted network with a built-in travel demand model (TDM) module. The transportation network is modeled as a system of links and nodes, with each individual link containing a set of attributes, including functional classification, capacity, number of lanes, and free flow speed among others. Traveler benefit calculations are based off estimates from this network analysis.

PET contains a built-in travel demand forecasting module, which is designed to closely mimic large, full-size regional network TDM estimation results across different roadway facilities, times of day, and changed network conditions, while comparatively reducing computing times, data demands, and staff expertise requirements. PET compares demand impacts over time, for up to three network alternatives by using its built-in TDM module, which is seamlessly integrated with PET, using a C++coded implementation framework for optimal processing time. For abstracted networks with up to 300 links, PET can compute impacts for current and future impacts, and up to three network alternatives, in the matter of one to three hours of processing time. The TDM module is based off a five-step model, described in detail in Section 3.1.

## 1.3 Traveler Benefits

Changes in network travel times, costs, and congestion levels computed from PET's TDM module are used to calculate economic impact to travelers. Specifically, from these network changes, PET automatically tabulates *traveler welfare* or consumer surplus (essentially

one's willingness to pay to travel versus one's actual costs to travel, as shown in Figure 1.1) and link-time (and network) reliability. PET evaluates the benefits of travel time savings (or losses) and added (or lost) trip-making from new routes, reduced congestion, added tolls and other changes using changes in traveler welfare. Between a base-case network and an alternative scenario, traveler welfare values (which can be thought of as consumer surplus) are computed using the rule-of-half, which considers changes in origin-destination (O-D) flows and costs to travelers, in terms of both travel time and out-of-pocket costs. Different values of travel times (in dollars per hour) can be specified by PET analysts for various sets of transportation system users and/or vehicle types (e.g., passenger vehicle versus heavy-duty truck). For each O-D pair modeled in PET, the rule of half is calculated as follows in Equation 1.1:

$$TW_{ij,d}^k \cong \frac{1}{2} \left( w_{ij}^{b,k} x_{ij,d}^{b,k} + w_{ij}^k x_{ij,d}^k \right) \left( g_{ij,d}^{b,k} - g_{ij,d}^k \right) + w_{ij}^{b,k} x_{ij,d}^{b,k} \left( g_{ij,d}^{b,k} - g_{ij,d}^k \right) \quad (1.1)$$

where  $x$  is the O-D flow rate,  $g$  is the O-D generalized travel cost, and  $w$  is the vehicle occupancy rate. As shown in Figure 1.1, the benefit to users equals the shaded areas, in which the first and second terms of the above function represents areas 1 and 2, respectively. The above traveler welfare change values are summed over all traveler classes, all O-D pairs, and all time-of-day (TOD) periods, to properly reflect cost and benefit changes experienced by all travelers in the network. Essentially, traveler welfare the sum of two components: the travel cost savings multiplied by the original demand plus half of the change in travel cost savings multiplied by the induced demand.

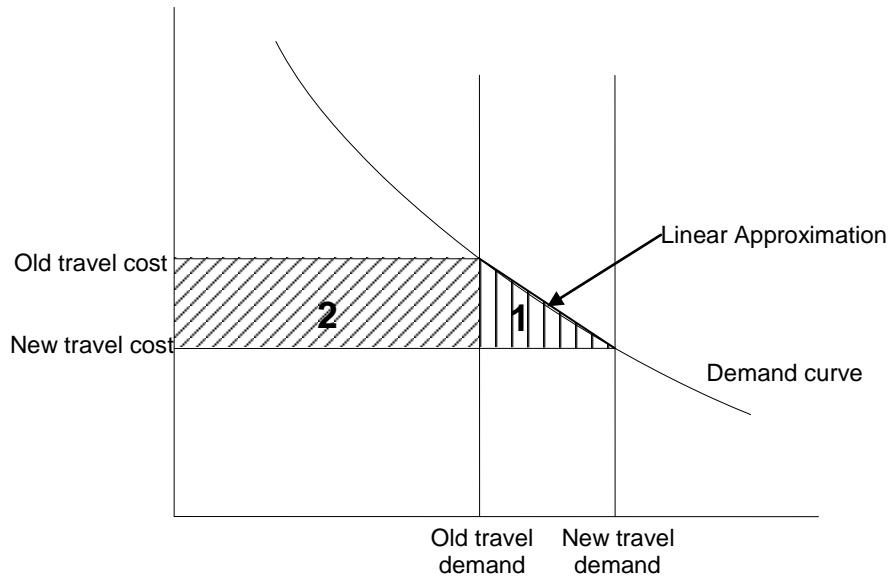


Figure 1.1: Rule-of-Half Showing Changes in Traveler Welfare as Travel Cost Falls

Associated with traveler time savings is the concept of *travel time reliability*, or the total uncertainty of a network summed for each O-D link. Such uncertainty is estimated as the convex relationship between freeway volume-capacity ratios and travel time variances using traffic data provided by Cambridge Systematics. The relationship is similar to a shifted version of the Bureau of Public Roads function for calculating link travel time, as follows in Equation 1.2:



$$r_a = r_a^0 \left( 1 + \sigma \left( \gamma + \frac{v_a}{c_a} \right)^\tau \right) \quad (1.2)$$

where  $r_a^0$  is the free-flow travel time variance of link  $a$ , and  $\sigma$ ,  $\gamma$  and  $\tau$  are function parameters, estimated using traffic data provided by Cambridge Systematics. The data were obtained from 2- to 5-mile long freeway segments in Atlanta, Los Angeles, Seattle, and Minneapolis (Margiotta, 2009), and the resulting estimates (by nonlinear least squares regression) are  $\sigma = 2.3$ ,  $\gamma = 0.7$ , and  $\tau = 8.4$ .

PET multiplies travel time variance (or “unreliability”) by each user’s value of reliability (VOR) and sums over all links to determine the total system reliability costs, as recommended by Horowitz (2010). The default value of VOR (in terms of hours of standard deviation in travel time) is assumed to equal each traveler type’s respective value of travel time (VOTT), which varies by the user.

## 1.4 Emissions

Evaluation of environmental impacts from transportation development projects is estimated in PET in the form of vehicle emissions. Previously, PET’s emission estimates were based on datasets derived from the EPA’s MOBILE6.2 (as part of TxDOT project 0-6325), which was replaced by a new mobile source emissions model (MOVES 2010) shortly after the completion of the original PET emissions datasets. A major task of this project was updating emissions estimates to MOVES-based rates, pivoting off previous MOVES analysis of Houston-Galveston-Brazoria (HGB) by the Texas Transportation Institute (2011). Shifting to MOVES as the official model behind PET emissions estimates allowed the Toolkit to take advantage of substantial improvements in emissions modeling software; compared to MOBILE 6.2, MOVES incorporated a substantially improved understanding of the relationship between vehicle activity, environmental variables, and emissions. In addition, MOVES included new emissions test data while accounting for recent changes in vehicle technology and regulations. Early analysis showed significant variation between the two models for applications in the HGB area (Kite, 2011), shown in Table 1.1.

**Table 1.1: Variations between Emission Estimates from MOBILE6.2 and MOVES2010**

Pollutant	Year 2006			Year 2018		
	MOBILE6	MOVES	Change	MOBILE6	MOVES	Change
NO <sub>x</sub>	206.7	292.7	42%	52.6	109.1	108%
VOC	90.7	107.6	19%	46.0	48.1	5%
CO	1,115.3	1,1013.2	-9%	733.2	617.8	-16%

(HGB estimated emissions from gas and diesel vehicles [preliminary] for years 2006 and 2018)

Source: Adapted from Kite, 2011

Though these emissions estimates demonstrated some variation, the methodology of link-level estimation developed in this project closely followed that developed under 0-6325. For thoroughness, however, this methodology is discussed below. (Further discussion on the development of the MOVES emissions tables is included in Appendices A through C, along with an extensive analysis of emissions comparisons between MOBILE6.2 and MOVES, and across inputs like traveling speed, temperature, humidity, and facility type.)

### 1.4.1 Emissions Estimate Methodology in PET

Emissions rates in PET depend on facility functional classification (freeway, arterial, local road, or ramp); vehicle speed (16 speed categories—from 2.5 mph and slower to 72.5 mph and faster); climate and seasonal context (three regions in Texas and two settings for winter or summer); analysis year (based on analysis year closest to 2010, 2015, 2020, or 2025, and impacting vehicle ages [and thus rates]); and vehicle classification (22 classifications). PET 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 running (per-mile) emissions as well as emissions rates per engine start.

PET estimates link-level emissions based on the total number of light (8500 lbs. and under) and heavy vehicles on a link as well as the link’s classification and speed estimates. PET estimates speed using the traffic flow result from the travel demand forecasting procedures described earlier. Seasonal context (summer or winter) and analysis year are provided by the user in PET’s parameter estimates portion. Additional vehicle fleet makeup information may be modified by the analyst as new information becomes available. Default fleet makeup values are derived from TxDOT vehicle registrations as compiled by the Texas Transportation Institute (2011).

Vehicle emission quantities in PET are estimated using a set of static rate tables, providing a total of 413,952 potential lookup values based on speed, context, vehicle type, and other previously noted information. These lookup tables estimate individual emission outputs in grams per mile for 14 species, as shown in Table 1.2.

**Table 1.2: Emissions Species Computed by PET**

Pollutant #	Pollutant Name
01	1,3-Butadiene
02	Acetaldehyde
03	Benzene
04	Methane (CH <sub>4</sub> )
05	Carbon Monoxide (CO)
06	Carbon Dioxide (CO <sub>2</sub> )
07	Formaldehyde
08	Nitrous Oxide (N <sub>2</sub> O)
09	Ammonia (NH <sub>3</sub> )
10	Oxides of Nitrogen (NO <sub>x</sub> )
11	Particulate Matter with diameter < 10µm
12	Particulate Matter with diameter < 2.5µm
13	Sulfur Dioxide (SO <sub>2</sub> )
14	Volatile Organic Compounds (VOCs)

As an example of the lookup table operation, an arterial link may be estimated to carry 1,000 light vehicles and 100 heavy vehicles in a given hour, operating at an average speed of 35 mph. The analysis may be for 2010 with an average summer temperature of 85 degrees. Using the default registration and age data, 16.21% of the light vehicles would be assumed to be 0 to 2 years old, 4.09% would be 3 to 7 years old, etc. The resulting hourly emissions rates would then be used to generate quantities of the 14 emissions on the link. This computation is

simultaneously performed for heavy vehicles on the same link and then summed over all links in the system. Daily values are estimated for a winter or summer context, as well as annual quantities for each scenario, in the design life year as well as in the initial analysis year. In this way, PET arrives at an average annual emissions tonnage for each species. PET also estimates the increase (or decrease) in emissions quantities for the base case and all alternative scenarios over the project design life due to traffic growth and fleet turnover.

Toolkit defaults do not monetize emissions, though values may be used as recommended by US Transportation Secretary Ray LaHood (2011) based on EPA analysis of the social costs of carbon emissions. These range from \$1,700 per metric ton of VOCs, \$4,000 per ton of NO<sub>x</sub>, \$16,000 per ton of SO<sub>2</sub>, and \$168,000 per ton of PM (all 2007 \$US), with variable CO<sub>2</sub> costs ranging from \$5 to \$136 per metric ton, depending on scenario, year, and discount rate used. PET allows users to easily specify values as one of the many inputs to the model.

### **1.4.2 Emerging Vehicle Types**

PET also incorporates alternate-fuel sourced vehicles when estimating emissions, specifically plug-in electric vehicles (EVs). Plug-in EVs include vehicles that run largely or purely off battery power for at least some portion of the time, and can be powered by the electricity grid, rather than always having to fill up at gas stations. This category does not include standard hybrid electric vehicles (HEV), such as the Toyota Prius HEV and Ford Escape HEV. (HEV fuel economies and emissions production are already reflected in MOVES emissions rates, for US fleet expectations.) While CO<sub>2</sub> levels can and do vary noticeably between HEVs and internal combustion engines (ICEs) for the same vehicle model, their other emissions are generally not so different, due to vehicle-by-vehicle emissions laws. It is EVs and PEVs that promise the greatest impact on MOVES rates, and require a look at the process of generating electricity, for emissions from power plants.

Users may specify the number of light-duty-vehicle (LDV) vehicle miles traveled (VMT) for two plug-in vehicle types: (1) battery-electric vehicles (BEVs), or vehicles relying only on batteries for their propulsion, like a Nissan Leaf or Ford Focus Electric, and (2) plug-in hybrid electric vehicles (PHEVs), which include an internal combustion engine (ICE) for use as the charge runs low, like the Chevrolet Volt. Since PHEV emissions impacts depend on how frequently the ICE is used, users can specify the average share of electric-powered/electrified PHEV miles. Figure 1.2 shows inputs for EV assumptions in both the initial and design years. Defaults represent US 2010 EV registrations and sales, since no data or projections exist for EVs' VMT (EIA 2010). Future market projections and efficiencies should reflect project lifetimes, since EV shares are expected to rise over time. Khan and Kockelman (2012) and EIA (2010) may be helpful sources, giving analysts a sense of electrified miles shares for EV-owning households and long-term EV sales shares. PET users can also change how efficient the average EV battery will be in their alternatives, in terms of miles per kWh; this assumption impacts how much electricity (and therefore energy) is required to operate the vehicle per mile.

Electric Vehicles Parameters		
Electric Vehicle VMT Share and Efficiency (PHEVs and BEVs)		
	Initial Yr	Design Yr
PHEV % of LDV VMT	0.05%	0.05%
PHEV % miles Electric	64%	64%
BEV % of LDV VMT	0.05%	0.05%
Average EV Efficiency (miles/kWh)	3.5	3.5
EV Emissions Modification Factor	0.999	0.999
Note that % VMT estimates are for light-duty vehicles (LDVs)		

Figure 1.2: Fleet Makeup and Parameters of EVs

Since EV battery power comes from upstream electricity generating facilities (like power plants and wind farms), users can specify a unique emissions profile based on a mix of power sources to better reflect the total emissions changes from scenarios that offer more EVs and more electrified miles. Per-mile emissions for five pollutants (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, NO<sub>x</sub>, and SO<sub>2</sub>) replace a standard LDV's MOVES-based emissions for initial and design years. Though electricity generation may produce other emissions, these five are the most prevalent. These species are also the only 5 reported (among the 14 species reported by PET) by the EPA's e-GRID (2010) database, which contains emissions information on all US power plants, by region. PET's default values are for the Energy Reliability Council of Texas (ERCOT) region in 2007, which covers nearly all of Texas, with an average year-long mix of 64% natural gas, 20% coal, 5% nuclear, and 10% renewable energy feedstocks. Figure 1.3 shows parameters for average power plant emissions in terms of grams per kilowatt-hour as seen in PET, though users may update this information if desired.

Pollutant Species	Average Powerplant Emissions (g/kWh)		EV Electrified Emissions(g/mi)	
	Initial Yr	Design Yr	Initial Yr	Design Yr
CO2	586.16	586.16	167.47	167.47
CH4	0.00806	0.00806	0.0023	0.0023
N2O	0.00635	0.00635	0.0018	0.0018
Nox	0.3348	0.3348	0.0957	0.0957
SO2	1.1592	1.1592	0.3312	0.3312

Figure 1.3: Equivalent Electricity Generation Emissions Conversion in PET

## 1.5 Crashes

PET estimates crashes by severity for each O-D pair using safety performance functions (SPFs) derived from AASHTO's (2010) Highway Safety Manual. 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 (PDO) crashes on each link in the system. Key factors are link functional classification, average annual daily traffic (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 coded roadway types, and intersection crashes are estimated for arterials and rural roads. All SPFs assume a base set of conditions applicable to the specific facility or intersection type. Any deviations from these base conditions should result in different predicted crash rates. Crash modification factors (CMFs) may be applied to individual links in order to obtain more accurate crash predictions.

Crashes may also be monetized; default costs are based on USDOT (Trottenberg and Rivkin, 2011) guidelines, specifically as recommended for the past TIGER grant analyses (USDOT 2012) and shown in Table 1.3. These values include market costs (in 2011 dollars), such as lost productivity, medical services, travel delay, and property damage, as well as non-market factors, such as the statistical value of life, pain and suffering, and values based on “willingness-to-pay” in order to avoid collisions.

**Table 1.3: Comprehensive Motor Vehicle Crash Cost Estimates**

<b>Crash Severity</b>	<b>Willingness-to-Pay (per Injured Person)</b>
Death	\$6,200,000
Incapacitating Injury	\$296,515
Non-Incapacitating Injury	\$80,761
Possible Injury	\$41,210
Property Damage Only	\$2,090

Other crash valuations may opt to consider only pure market/economic crash costs when using strict crash-to-dollar conversions. As such, pain and suffering and the statistical value of life using other methods may still be incorporated into final analyses, as PET reports anticipated crash changes at each level of severity. PET users who wish to value only include market costs may refer to the National Safety Council’s *Estimating the Costs of Unintentional Injuries* (NSC, 2010).

Analysts should note that crash costs in Table 1.3 are per injured person, rather than per crash (as required by PET). The Caltrans B/C model assumes an average of 1.15 fatalities per fatal injury crash and an average of 1.49 injuries per injury crash (Caltrans, 2010) and PET assumes this same distribution.

PET estimates crash severity based on TxDOT motor vehicle crash statistics (TxDOT 2009). The *Highway Safety Manual* (AASHTO 2010) SPFs do not provide crash estimates by severity for all scenarios, so PET relies on TxDOT (2010) crash severity data to estimate the likely distribution of crash severity, pivoting off the estimated total number of crashes.

A set of fixed shares of crash severity outcomes (proportions of fatal, incapacitating injury, non-incapacitating injury, possible injury, and property damage only) was assumed for all rural crashes and another set of fixed shares of crash severity outcomes for all urban crashes, regardless of functional classification, speed estimates, and other attributes. Users should use caution when investigating link-level crash severity, because crashes on lower-speed roadways tend to be less severe and certain road types can produce more severe crashes. For example, a crash occurring on an undivided, two-lane highway has a higher probability of being a head-on collision (with higher crash severities) than the probability of a head-on collision on an arterial with a divided median. Furthermore, Kockelman et al. (2006) estimated a model that predicted that “a speed limit increase from 55 to 65 mph on the average section would be associated with a

24% increase in the probability of an occupant being fatally injured, once a crash has occurred” (p. 9). For this reason, severity results should be viewed in aggregate rather than at the individual link level. Details on application of SPFs and value tables can be found in the User’s Guide.

## Chapter 2. Project Types

### 2.1 Introduction

One primary goal of this project was to be able to evaluate traditional large-scale capacity expansion projects side by side with operational strategies. To this end, PET was developed such that both broad project categories could be investigated, using the same measures and valuations for traveler welfare, reliability, crashes, and emissions impacts. This section of the final report discusses project types that may be evaluated within PET, as well as implementation details specific to each project type.

### 2.2 Capacity Additions

As stated previously, the transportation network is modeled as a system of links and nodes, with each individual link containing a set of attributes, including functional classification, capacity, number of lanes, and free flow speed among others. Travel times are assessed using the Bureau of Public Roads link performance function (TRB 2000) shown in Equation 2.1:

$$s_a = s_a^0 \left( \frac{1}{1 + \alpha \left( \frac{v_a}{c_a} \right)^\beta} \right) \quad (2.1)$$

where  $s_a^0$  is the link's free-flow speed,  $v_a/c_a$  is the link's volume-capacity ratio, and  $\alpha$  and  $\beta$  are behavioral parameters that vary by facility type (freeway, arterial, collector) and location (urban, suburban, rural). By changing the capacity, free flow speed, or functional classification of a given link, speeds on that link will correspondingly change as well. These changes may impact network travel patterns and as such require the TDM to be run for both the original (base-case) scenario as well as any alternative scenarios containing network links with changed link attributes. Traveler welfare is reported for alternative scenarios based on changes in O-D pair generalized costs and demand between the base case and alternative scenario. Changing link attribute values also impact other PET outputs, including the safety performance functions used in crash estimation, emissions rates used for air pollutant species, and reliability estimates.

### 2.3 Tolling

PET allows variable tolling to be conducted at the individual link level for each time of day (with a maximum of five, with defaults of AM-peak, mid-day, PM-peak, evening, and off-peak) and user class (max five; defaults of single occupancy vehicle [SOV], HOV2, HOV3+ [high-occupancy vehicle lanes for vehicles holding at least two and three or more persons], transit, and heavy truck). Therefore, up to 25 tolling rates may be specified per tolled link, though analysts may use just a single rate for all vehicles, or two rates (trucks vs. passenger vehicles) if desired. Like capacity expansion projects, tolling is typically assumed to impact traffic patterns; therefore, analysts are required to specify tolling changes between the base case and alternative scenarios and run the TDM on the base-case scenario and all scenarios with new tolling rates.

Tolls are assumed to increase generalized costs for travelers using tolled links, though tolling revenues are also fed back into PET's B/C module as an agency benefit. In this way, tolls

are modeled as being net-welfare or B/C neutral, increasing agency benefits by the same amount as is taken from traveler welfare. Additionally, PET uses a project financing module to assess changes in tolling revenues between the base-case and alternative scenarios, and compares those tolling revenue changes to project costs. PET uses these results to output valuable information for project financing, including estimated net present value, rate of return, and payback period, as shown in Figure 2.1.

	No Build		Freeway Upgrade	
Annual Tolling Revenues (Thousands \$)	Initial Yr	Design Yr	Initial Yr	Design Yr
Total	\$79,971	\$101,379	\$79,945	\$101,406
Change vs No Build Scenario	\$0	\$0	-\$26	\$26
Project Financing (Thousands \$)	No Build	Freeway Upgrade	Tollway Upgrade	Tolling by TOD
NPV of New Tolling Revenues	\$0	-\$88	\$118,251	\$142,075
NPV of Initial and Future Project Costs	\$0	\$122,729	\$137,829	\$137,829
Project Financing Perspective NPV	\$0	-\$122,817	-\$19,578	\$4,245
Project Financing Perspective IRR	N/A	N/A	6.0%	8.2%
Project Financing Perspective PP	N/A	> 20 years	> 20 years	17.8

Figure 2.1: PET Financing Module Summary Measures

## 2.4 Managed Lanes

Managed lanes are typically defined as a set of lanes where operational strategies are proactively implemented and managed in response to changing conditions. The principal management strategies can be categorized into three groups: pricing, vehicle eligibility, and access control. Examples of operating managed lane projects include reversible lanes, high-occupancy vehicle (HOV) lanes, high-occupancy toll (HOT) lanes, or exclusive or special use lanes, such as transit or taxi priority lanes. Each of these concepts offers unique benefits; careful consideration needs to be given to project goals and objectives in choosing an appropriate lane management strategy or combination of strategies. The FHWA (2005) graphically depicts variations and combinations of these strategies, as shown in Figure 2.2:



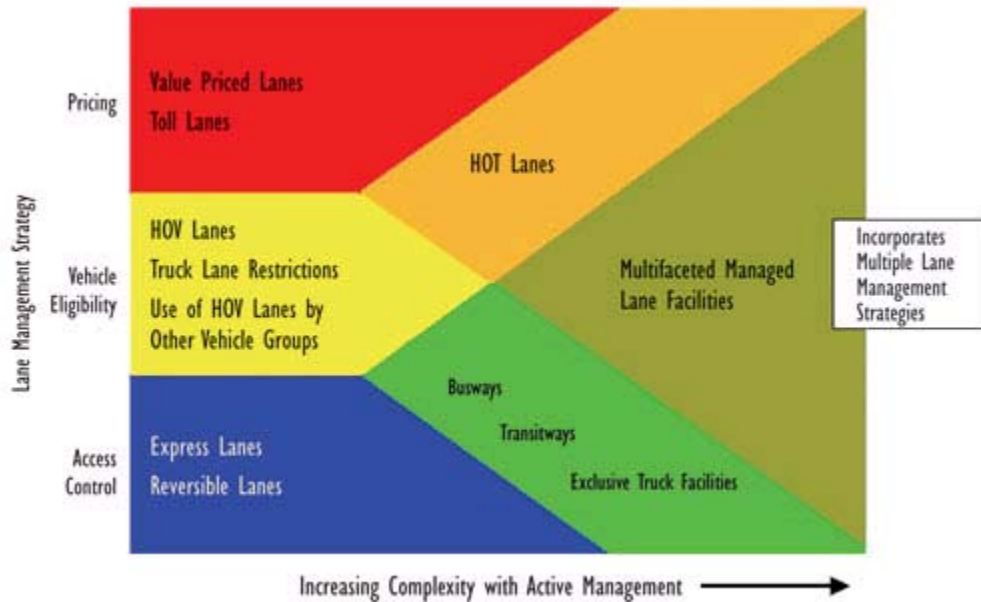


Figure 2.2: Example Managed Lane Applications

PET can accommodate most of these functions, with variable pricing by time of day and mode, as previously discussed. PET may limit vehicle eligibility by setting toll prices very high for all ineligible vehicles (for example, \$1,000 for all non-transit vehicles on a bus-only lane), then ignore all tolling revenues obtained on these links if one or two ineligible vehicles uses the link anyways.

To model reversible lanes, the user can exchange capacity and numbers of lane between reverse traffic directions of a roadway between different TOD periods. For example, analysts may specify northbound capacity for a given network link equivalent to three lanes during the AM-peak and mid-day periods and capacity at four lanes during the PM-peak and evening periods—while specifying the opposite for the corresponding southbound network link. To allow HOV or HOT lanes, the user should model these lanes as separate, parallel links to the original links set tolling rates accordingly. HOV and HOT settings can also vary over times of day. The TDM must be run for any alternative scenario that incorporates new managed lanes, similar to other capacity expansion and pricing scenarios.

## 2.5 Shoulder-Lane Use

PET estimates shoulder-lane use impacts by increasing capacity for times of day when travelers are allowed to use the shoulder as a travel lane. Previous experiences justified that using shoulder lanes during traffic peak hours or under emergency conditions to accommodate extra traffic is an effective capacity bottleneck relief strategy. This operational strategy is often used simultaneously with speed harmonization, though one strategy may be employed without the other. Experiences documented by Riegelhuth and Pilz (2007), Cohen (2004), and Middleham (2003) show that shoulder lane use increases capacity anywhere from 660 vehicles per hour (vph) to nearly 1,900 vph, or what would be expected by adding a traditional new traffic lane. Analysts incorporating shoulder lane use into alternative scenarios are encouraged to specify capacity expansion on the impacted links only during times when shoulder-lane use is expected

to be active. As with other capacity expansion and managed lanes scenarios, the TDM must be run for alternative scenarios where new shoulder lane usage is being investigated.

## 2.6 Ramp Metering

Ramp metering is a freeway traffic control system by which traffic entering the freeway's mainline through a ramp is "metered" so as to ensure the level of service on the mainline on an acceptable level. It is implemented using a ramp signal that ensures short delays occur at on-ramps and freeway-to-freeway intersections so that the merging flow is regulated and merge-related disruptions are minimized. Ramp metering plays an important role in improving freeway traffic conditions, by breaking up platoons of vehicles (to minimize merging-related disruptions), regulating flows that enter the freeway (to avoid exceeding capacity at downstream bottlenecks), diverting local traffic to less-congested arterials, and providing priority for buses and HOVs (Colman, 1997). Typical metering is rated ranging from 240 to 1,100 vehicles per hour per lane, with lower metering rates resulting in higher violation rates and longer ramp queues, but better freeway performance.

While various pre-timed and actuated metering control mechanisms are used in practice, the direct result of using a ramp metering system is to control the traffic passage time on the ramp and hence result in a reduction of the ramp's capacity in effect. To properly accommodate the traffic impact of a ramp meter, the user needs to identify the effective capacity of the ramp controlled by a metering device. When the entering flow rate on the ramp is relatively high, the link capacity reduction is approximately proportional to the reduction of the allowable traffic passage time; when the entering flow on the ramp is very light, the effective link capacity reduction may be ignored. To accurately quantify the capacity reduction effects, a microscopic simulation study under a variety of geometric and traffic conditions is preferable. If simulation is not feasible, ramp capacity may be estimated as a fraction of non-metered ramp capacity multiplied by the percentage of available green time in a given cycle.

## 2.7 Incident Management

An incident is a non-recurring event that causes a reduction of roadway capacity such as traffic crashes, disabled vehicles, spilled cargo, or brush fire. PET estimates incident management impacts as a combination of travel time savings and changes in emissions due to changes in travel speeds. Incident management is implemented by estimating the number of crashes that occur during peak periods on links that have been targeted with incident management strategies. From these figures, total numbers of lane-blocking incidents during peak periods is then estimated. PET then uses measures of before and after incident clearance times to estimate total upstream delay, using Wirasinghe's (1978) estimation of delay (Equation 2.2):

$$d = \frac{1}{2} t^2 \frac{(q_a - q_l)(q_c - q_l)}{(q_c - q_a)} \quad (2.2)$$

where  $d$  is the total delay caused by the incident (hours),  $t$  is the incident duration (hours),  $q_a$  is the arriving flow rate (vph),  $q_l$  is the leaving flow rate past the incident (vph), and  $q_c$  is the capacity of the roadway facility. It should be noted that no delay is estimated on the facility if the lane closure results in a capacity that still exceeds the arrival flow rate. PET assumes that incident management strategies will not affect every-day travel patterns, but rather impact traffic only when incidents occur. Therefore, this operational strategy is applied by running PET's

TDM for the base case scenario, then specifying incident management details for specific implementations within the network.

## **2.8 Advanced Traveler Information Systems**

Similar to incident management, PET does not evaluate total network impacts from an advance traveler information system (ATIS) implementation project. Potential ATIS benefits are approximated by estimating non-recurring traffic congestion caused by incidents and alerting/guiding travelers to alternative routes. Benefits are then assessed in the form of monetized travel time savings.

PET enables user to evaluate different types of ATIS strategies, potentially including highway advisory radio (HAR), variable message signs (VMS), internet-based ATIS strategies, and other ATIS strategies that analysts wish to investigate. ATIS benefits are predicted by estimating the number of upstream links that could be impacted if an incident occurs, and estimating the number of travelers that will see the VMS, hear the HAR, or otherwise obtain information from the ATIS strategy. Travel time savings are then estimated by predicting the number of times alerted travelers will benefit from ATIS strategies by changing their route and saving time, and determining the average travel time savings and dollar value of those persons who are helped by ATIS. As with incident management strategies, PET assumes that ATIS strategies will not affect every-day travel patterns, but rather impact traffic only when incidents occur. Therefore, this operational strategy is applied by running PET's TDM for the base case scenario, then specifying ATIS details for specific implementations within the network.

## **2.9 Speed Harmonization**

PET estimates predicted benefits from speed harmonization in the form of crash reductions. To properly quantify the traffic and safety impacts of speed harmonization, PET estimates the number of crashes that are expected to occur during the periods when speed harmonization would be active, then applies a recommended 10–30% crash reduction factor to those crashes, depending on the figure determined by the analyst. The analyst may also choose to investigate both the high and low range to get a better understanding of the likely range of potential impacts.

Reference information and case studies in different regions and under different traffic congestion conditions can be found in a FHWA highway capacity summary report (FHWA, 2010). The report also provides estimates of safety benefits from implementing shoulder lanes and speed harmonization. In addition to projected safety benefits, the report notes that speed harmonization typically does not change capacity/throughput of a roadway to any substantial degree. Like incident management and ATIS strategies, PET assumes that speed harmonization strategies will not affect every-day travel patterns, but rather will apply a crash reduction factor for anticipated crashes that may occur during activation times. Therefore, this operational strategy is applied by running PET's TDM for the base case scenario, then specifying speed harmonization details for specific implementations within the network.



## Chapter 3. Toolkit Structure

The main PET software package includes four Microsoft Excel files with embedded Visual Basic for Applications (VBA) macros, along with two executable files that rely on C++ code. Any Windows-based machine with Microsoft Excel 2007 or 2010 should be able to run PET files. The user will interface with the Main Toolkit Excel file; the other three are supplementary files that help users create and edit networks (the Toolkit Upload Module) and evaluate multiple projects simultaneously—the Budget Allocation Module and the Multi Criteria Analysis Module (see Section 5: Evaluating Project Sets). For now, this discussion will focus on the Main Toolkit file.

PET's user interface lies solely within MS Excel sheets, facilitated by navigation buttons and menus. Analysts create base and alternate networks for project-impact modeling and comparisons, and results are displayed in summary output sheets and charts (see Chapter 4). Additional results sheets and other parameter sheets can be accessed easily by analysts. PET is designed to run with minimal inputs and sheet navigation; as mentioned earlier, the only required *inputs* for a project are link-level data (link length, roadway classification, number of lanes, AADT, and capacity). Analysts must also specify project cost estimations to calculate major project impacts.

PET users interface and navigate solely in a series of MS Excel spreadsheets, which is a familiar context to most users and allows an exceptionally high level of data manipulation, organization, and calculations. Embedded VBA macros manage many complex calculations and interactions with the external travel demand module. VBA coding also allows users to graphically navigate through spreadsheets with click-button macros, creating a more user-friendly environment within the typical Excel framework.

When a user runs PET's self-contained TDM, VBA-based scripts communicate automatically between two executable files stored in PET's main directory, as illustrated in Figure 3.1. These executable files are written in C++, which facilitates much quicker computation for large trip-table matrices over multiple iterations. (Such calculations would be extremely inefficient within Excel.) The interactions between Excel sheets themselves, and with the external travel demand module are shown in Figure 3.1.

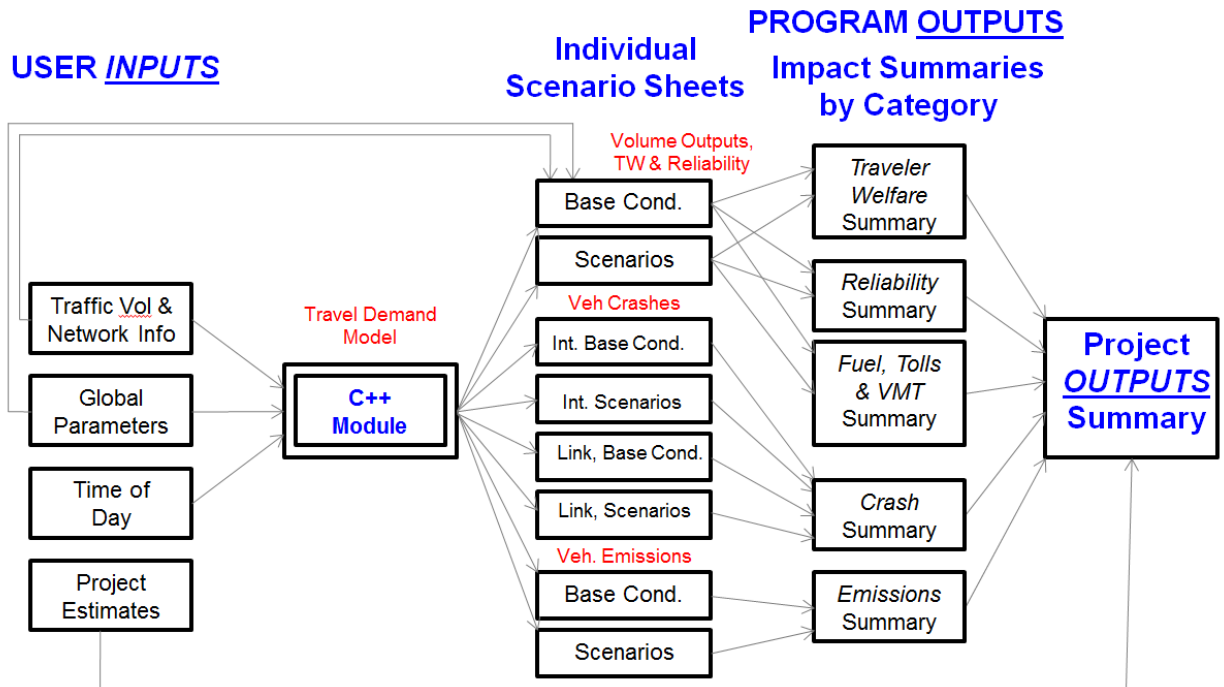


Figure 3.1: Data Flow Diagram within PET

### 3.1 Travel Demand Model Estimation Process

The TDM consists of two executable files: a trip-table estimator and a matrix estimator, which are both required to be run for network demand estimations. The TDM code first estimates a base-case trip table for observed/input link flows, by time of day, using the methodology described above. This routine ensures that model-estimated traffic counts closely match observed traffic counts, while providing a reasonable distribution of trip-making between all or most O-D pairs. Next, the TDM enters an iterative loop, where the following steps are repeated until convergence (or traffic equilibrium) is reached: 1) elastic demand functions are applied (to account for induced demand if travel costs fall [between each O-D pair] and lower demand if travel cost rise); 2) an incremental logit model is applied for mode split (to account for shifts toward and away from travel modes if mode-specific travel costs change); 3) an incremental logit model is applied for TOD splits (to account for shifts towards or away from various times of day, if TOD-specific travel costs change); and 4) traffic is assigned to the network using a static, user-equilibrium methodology.

Once convergence is achieved for the base case, travel patterns, link conditions, and trip costs are saved. New traffic patterns for all three network alternatives (e.g., involving new links, new lanes, new tolls, managed lanes, reversible lanes, ATIS, etc.) are then anticipated, by pivoting off the base case trip table and travel times and re-equilibrating the travel system. Changes in traveler welfare, link reliability, emissions, and crashes are estimated, and monetized (often by time of day, user class, and mode), in order to provide performance metrics for comparison of alternative projects and policies.

PET's TDM uses five major steps to assign traffic flows among transportation modes, across TOD periods, and over the network. These produce a base trip table estimate, elastic trip table estimates for each scenario, mode split, and TOD estimates, and link-based traffic

assignments (for each traveler class modeled). Once the traffic assignment process is complete, the model checks for convergence (using traffic flow stability as described later) and loops back to the elastic trip table estimation process if convergence has not been reached, as shown in Figure 3.2.

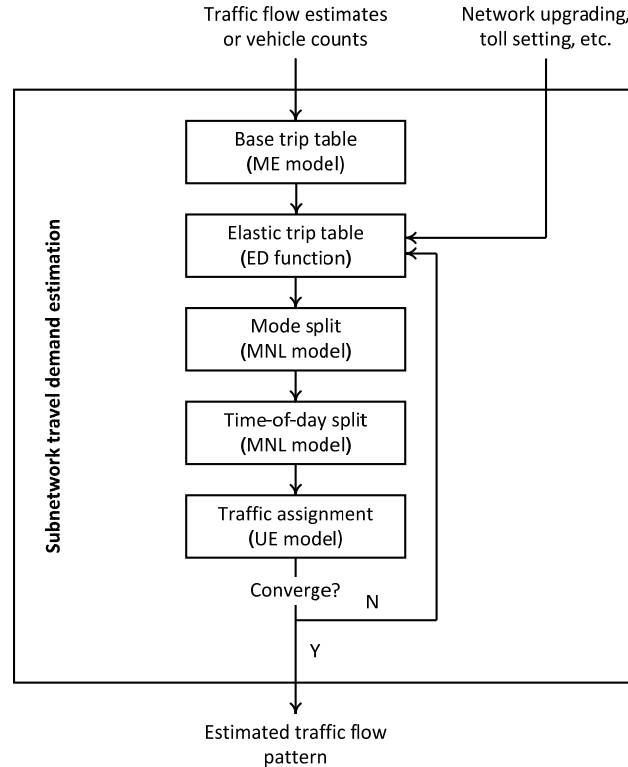


Figure 3.2: The Travel Demand Modeling Process

The first step’s estimate of the O-D trip table uses a “target” trip table and applies a least-squares approach to approximate both the target trip table and the link volumes simultaneously. This target trip table is obtained by a simple gravity model, but the method is “modular” and another methodology for generating the target trip table is easily accommodated. A stochastic user equilibrium (SUE) approach is used to decide which links will be used by the demand between two nodes. The code returns this trip table, as well as the SUE logit parameter that fits the link counts best.

The second step uses an elastic demand function to estimate cost-dependent O-D trip rates for all other scenarios by pivoting off of the base-case trip rates using an assumed demand elasticity for each time of day (e.g., by default, -0.69 for all TOD periods).

The third step, mode split, uses an incremental multinomial logit (MNL) model (Ben-Akiva and Lerman, 1985) to distribute the O-D trips (as developed in the second step) into different transportation modes, such as drive-alone, shared-ride modes, transit, and non-motorized modes.

The fourth step also uses an incremental MNL model to produce 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.

The fifth step, a multi-class, multi-mode traffic assignment problem, is also performed using the Frank-Wolfe algorithm, but in a modified version. The all-or-nothing traffic loading during the above Frank-Wolfe procedure is achieved using the Floyd-Warshall algorithm (Floyd, 1962), which is the most efficient method for finding all-to-all shortest paths over a network, because most of nodes in network cases to which PET is applied are both origin and destination nodes.

It should be noted here that the last four 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 trip table estimation event for the base-case condition, all other steps are part of the iterative process with a feedback mechanism, to ensure that flows and costs are in equilibrium, between different times of day, across transportation modes, and across network routes. The feedback process iterates over the last four steps until the consistency between traffic flows and travel costs are reached (such that the gap between successive flow estimates is sufficiently low). The convergence of the last steps is achieved by the method of successive averages (MSA).

The major structural difference between PET’s travel demand modeling process and the traditional four-step process lies in trip generation and distribution. PET generates an O-D trip table entirely based on observed traffic counts, while the traditional process estimates trip productions and attractions from land use and socioeconomic data in the investigated region.

The travel demand estimation module is coded in C++ and compiled into two executable programs, *tdm\_matrix.exe* and *tdm\_flow.exe*. The first program computes the base trip table estimation, while the second program performs the last four steps of the travel demand estimation process.

Given the modular nature of PET’s software structure, the travel demand estimation module must have its own input and output functions so as to communicate with the other parts of the toolkit. These functions are referred to as the input and output submodules for the *tdm\_matrix.exe* and *tdm\_flow.exe* programs. The input submodule for the *tdm\_matrix.exe* program is relatively simple, reading in the network file and link flow rate file for each TOD period; the output submodule for the *tdm\_matrix.exe* program outputs the O-D trip table for each TOD period. The input submodule for the *tdm\_flow.exe* program reads four groups of data files, including the original and alternative network files, base O-D trip table files, growth factor file, and parameter file. The output submodule for the *tdm\_matrix.exe* program includes the link flow rate files, elastic trip table files, and network summary file. The network summary file provides the network-wide performance measures resulting from the travel demand estimation process, such as traveler welfare change, total travel cost, vehicle hours traveled (VHT), and VMT.



## Chapter 4. Using the Toolkit

Though PET allows users to change and view many inputs and evaluate a number of results, navigating through the Toolkit is made intuitive with simple click-button macros and a Navigation Panel, which groups important sheets and provides a “home base” for users to return to as they create and evaluate projects. This Navigation Panel, shown in Figure 4.1, includes clickable buttons that take the user to specific worksheets.

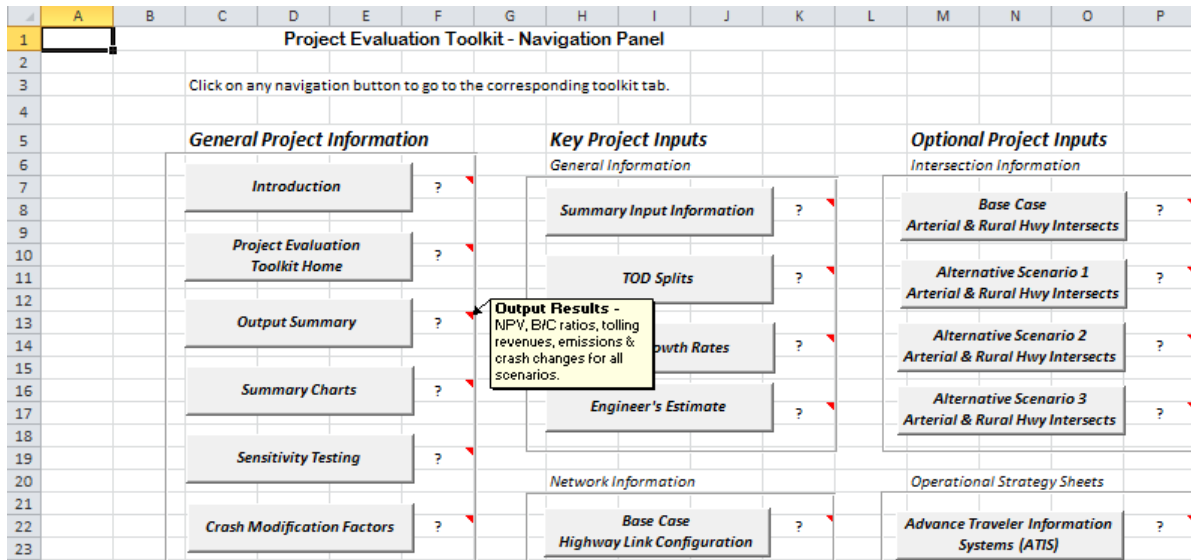


Figure 4.1: Navigation Panel (not all navigation buttons shown)

Furthermore, hovering the mouse over the question mark located next to each navigation button will reveal more information about the sheet’s use, and values or parameters that can be accessed there. The Navigation Panel is separated into nine different columns of sheets organized by relative importance, or likelihood of use, from left to right. Columns include the following categories:

1. *General Project Information* – Output results, information for using PET.
2. *Key Project Inputs* – Information required for scenario parameters and network characteristics.
3. *Optional Project Inputs* – Information that may be entered for conducting more detailed analyses or for special types of projects.
4. *Project Summaries* – Results for overall scenario impacts, as well as impacts by category.
5. *Individual Scenario Volume Outputs* – Estimated link-level traffic volumes, reliability, and speeds for each scenario, initial and design year.
6. *Individual Scenario Link Crashes* – Estimated link-level number of crashes for each scenario, initial and design year.

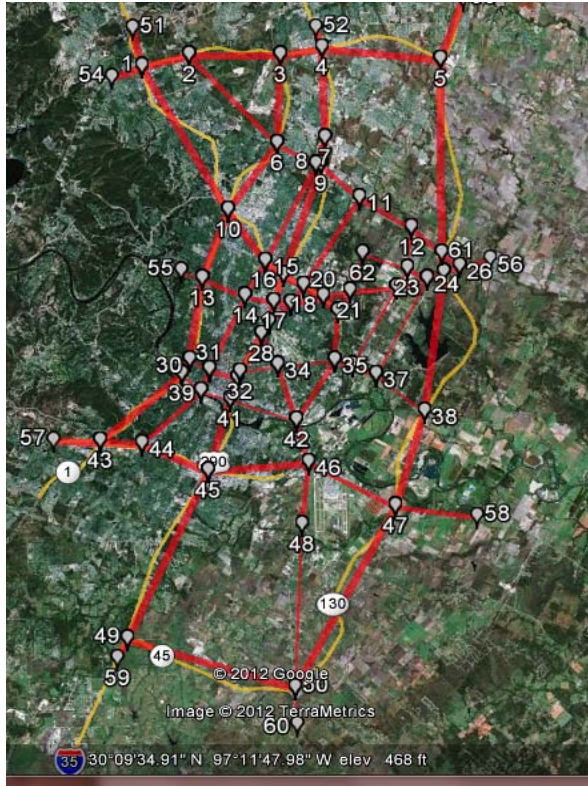
7. *Individual Scenario Intersection Crashes* – Estimated intersection-level number of crashes for each scenario, initial and design year.
8. *Individual Scenario Emissions Estimates* – Estimated link-level emissions quantities for each scenario, initial and design year.

## **4.1 Creating Networks and Alternatives**

Analysts who wish to use the self-contained TDM must first define an abstracted network of major roadway links. The project team has already developed such networks for Dallas, Houston, Austin, San Antonio, and Tyler/Longview, to provide a starting point and tutorial for new users. These networks can also be altered as desired by users, or new networks can be developed from scratch. PET includes a visualization tool that helps users keep track of their nodes and link locations on a network. To maintain a relatively quick run-time, abstracted networks are capped at 300 links. Therefore, for modeling major urban networks, typically only freeways and major arterials can be modeled. Alternatively, users could model a smaller-scale network by reducing the geographic range of a study area. Each link modeled within PET must include beginning and end node points, length, number of lanes, capacity, AADT, and facility type. Additional inputs can be added as well, including land use (residential, commercial, industrial), area type (urban, suburban, rural), and presence of medians.

### **4.1.1 Visualization Tool**

Network creation can be aided with PET's Visualization module, which relies on Google Earth and communicates with PET through macro scripts. Users may model their network links visually within Google Earth or Bing Maps, but must enter specific link attributes manually, including necessary inputs of link length, capacity, AADT, number of lanes, and facility type. (Many other optional inputs that improve model accuracy can be specified as well.) By dropping specifically numbered placemarks to represent network nodes, users can create and save keyhole markup language (KML) file that can be directly imported into PET. Once the user connects the nodes with route link information (as described in 4.1.2), PET can automatically export this network as a KML file, which shows relationship of node-to-node links, as shown in Figure 4.2.



*Figure 4.2: Google Earth Visualization of Austin Network, Created by PET*

Users are encouraged to use this technique to build and edit PET networks, since KML can be saved and edited over time as users make changes to their networks for project evaluation. Additionally, this medium allows for further visualization changes to network representations for more advanced users, potentially representing link-level data such as volume-to-capacity (v/c) ratios or capacity with line thickness or variations in color. Currently, line width relates to functional classification, where thicker lines represent freeway facilities and thinner lines represent arterials.

#### **4.1.2 Specifying Networks in PET**

PET requires development of a base network for analysis. Users must first create a base network representing current conditions, which may be copied and manipulated for each alternative scenario or project. For instance, a user may increase the capacity for several links in an alternative scenario, providing a distinct difference between the base case and alternative network. Users may also specify tolls (which can be set for up to five times of day and five vehicle classes, for each network link), operational factors, intersection details, safety parameters, or other attributes for the base and alternative scenarios. Up to three alternative scenarios can be evaluated simultaneously in one run. See Figure 4.3.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Project Evaluation Toolkit - Base Highway Link Configuration												
2													
3	Go To Navigation Panel				Notes: All links are directional (including # of lanes in each link)								
4					Link Class: 1=Freeway, 2= Principal Arterial, 3 = Major Arterial								
5	4=Minor Arterial, 5 =Collector, 6=Ramp												
6	Area Type: 1=Urban, 2=Suburban, 3=Rural												
7	Land Use: 0=Rural/Residential, 1=Industrial, 2=Commercial, 3=Office												
8	Median: 0=None, 1=TWLTL, 2=Restrictive Median												
9													
10	Link Characteristics												
11	Link #	From Node #	To Node #	Link Name	Length (mi)	Link Class	Area Type	FF Speed (User Entered)	FF Speed	FF Time	# Lanes	CMF	AADT
12	1	51	1	183: N of TT45 - TT45	1	1	1		55	1.1	3		16500
13	2	1	51	183: TT45 - N of TT45	1	1	1		55	1.1	3		16500
14	3	1	10	183: TT45 Loop 1	7.8	1	1		55	8.5	3		75000
15	4	10	1	183: Loop 1 - TT 45	7.8	1	1		55	8.5	3		75000
16	5	10	15	183: Loop 1 - Lamar	2.9	1	1		55	3.2	3		69500
17	6	15	10	183: Lamar - Loop 1	2.9	1	1		55	3.2	3		69500

Figure 4.3: Base Network Link Worksheet

### 4.1.3 Tolls

User can set existing tolls by vehicle class and by time of day for each link in the network. Tolls for links, modes, or times of day that are not tolled may be left blank. The toll settings sheet is the same for the Base Case and each Alternate Scenario, and the base toll settings can be copied with the same procedure as base network copying. Figure 4.4 shows the toll setting worksheet in PET.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Project Evaluation Toolkit - Base Case Toll Settings												
2													
3	Go To Navigation Panel												
4													
5													
6													
7													
8													
9													
10						AM Toll Settings					Mid Day Toll Set		
11	Link #	From Node #	To Node #	Link Name	Length	Vehicle Class 1	Vehicle Class 2	Vehicle Class 3	Vehicle Class 4	Vehicle Class 5	Vehicle Class 1	Vehicle Class 2	Vehicle Class 3
12	1	51	1	183: N of TT45 - TT45	1	\$2.00	\$2.00	\$2.00	\$2.00	\$2.00	\$2.00	\$2.00	\$2.00
13	2	1	51	183: TT45 - N of TT45	1	\$2.00	\$2.00	\$2.00	\$2.00	\$2.00	\$2.00	\$2.00	\$2.00
14	3	1	10	183: TT45 Loop 1	7.8								
15	4	10	1	183: Loop 1 - TT 45	7.8								
16	5	10	15	183: Loop 1 - Lamar	2.9								

Figure 4.4: Toll Settings

### 4.1.4 Fixed Costs

Users may specify a node-specific fixed cost by time of day and/or vehicle class for each network node. These optional costs may represent parking costs, time delays due to walking, or any other cost associated with a specific node. The values are empty by default but the user may manipulate them through the “Fixed Costs” sheets, available for the base case and all three scenarios in both initial and design years. While these costs may influence travel behavior when running the TDM, they are considered private payment transfers and are not added back into the summary measures (i.e., fixed costs will be added to total travel costs, but will not be added back in to the user benefits, as tolls are). To illustrate this point, if a user wants to consider effects of

increased parking costs on city-owned parking areas, this revenue will not be captured in the financial analysis. See Figure 4.5.

Project Evaluation Toolkit - Base Case Fixed Cost Settings - Initial Year																
1																
2																
3																
4		Go To Navigation Panel														
5																
6																
7		Analyst Notes														
8																
9																
10			AM Fixed Costs					Mid Day Fixed Costs					PM Fixed Costs			
11	Node	Cost Description (Optional)	Vehicle Class 1	Vehicle Class 2	Vehicle Class 3	Vehicle Class 4	Vehicle Class 5	Vehicle Class 1	Vehicle Class 2	Vehicle Class 3	Vehicle Class 4	Vehicle Class 5	Vehicle Class 1	Vehicle Class 2	Vehicle Class 3	Vehicle Class 4
12	1	Parking Garage	\$5.00	\$5.00	\$5.00	\$5.00		\$5.00	\$5.00	\$5.00	\$5.00		\$5.00	\$5.00	\$5.00	\$5.00
13	2	Parking Garage	\$5.00	\$5.00	\$5.00	\$5.00		\$5.00	\$5.00	\$5.00	\$5.00		\$5.00	\$5.00	\$5.00	\$5.00
14	3	Surface Parking														
15	4	Surface Parking														

Figure 4.5: Fixed Costs Settings

### 4.1.5 Transit Network Features

This project introduced optional transit features into the network modeling, allowing users to create “arcs” of transit service across several nodes. Each arc represents a service line that can connect up to 10 nodes in a network (as a series of stops along the bus route, for example). For a given arc, users must specify all nodes and transit service headways (time between arriving transit vehicles). If the route operates in both directions (e.g., northbound/southbound or eastbound/westbound), each direction must be specified as a separate route in PET. Additionally, users may specify unique headways by time of day, to reflect variations in route service levels across peak and off-peak periods. The specific form of public transit is not specified and may capture any rail or bus system. See Figure 4.6.

Project Evaluation Toolkit - Base Case Scenario Transit Settings - Initial Year																				
1																				
2																				
3																				
4		Go To Navigation Panel																		
5																				
6																				
7		Analyst Notes																		
8																				
9																				
10			Transit Arc - AM										Transit Arc - Mid-Day							
11	Route #	Transit Line Description (Optional)	Headway	Stop 1	Stop 2	Stop 3	Stop 4	Stop 5	Stop 6	Stop 7	Stop 8	Stop 9	Stop 10	Headway	Stop 1	Stop 2	Stop 3	Stop 4	Stop 5	Stop 6
12	1	Green Line NB	60	30	31	32	33	34	35	36	37			55	30	31	32	33	34	35
13	2	Green Line SB	60	37	36	35	34	33	32	31	30			55	37	36	35	34	33	32
14	3	Orange Blossom Special EB	30	12	15	19	25	26	30					28	12	15	19	25	26	30
15	4	Orange Blossom Special WB	30	30	26	25	19	15	12					28	30	26	25	19	15	12
16																				

Figure 4.6: Transit Settings

## 4.2 Project Costs and Evaluation Parameters

Users must specify project cost estimates in order for PET to automatically compute a project summary and financing measures, such as B/C ratios and internal rates of return. Users must specify total project costs, which can developed from a number of other items if desired, including design, right-of-way, construction engineering, construction costs, contingencies, and overhead and indirect costs. Users have the option of included a salvage value for each alternative as well, since in some cases a brand-new facility may have far more salvage value than shoulder widening or lane addition on an existing roadway.

Finally, some scenario alternatives may require significant interim expenditures (e.g., major rehabilitation and maintenance projects for base-case scenarios) before the project’s design life elapses. In these cases, the analyst should input the anticipated interim project construction year and comprehensive interim project cost. For example, a lane-add project could have a 20-year design life but require existing lanes to be repaved within ten years of the expected project completion date. One scenario may add new lanes while not modifying any existing lanes, while a second scenario may reconstruct the entire roadway. In the first scenario (and in the no-build scenario), the analyst should input the year and value of the anticipated interim project construction (for repaving the existing lanes). See Figure 4.7.

Project Evaluation Toolkit - Engineer's Estimate										
Go To Navigation Panel		Analyst Notes								
	Lane Miles	Const Cost per Lane Mile	ITS / Signal / Electrical	Bridges & Structures	Utility & Other Fixed Costs	Construction Subtotal	Traffic Control	Environmental Construction		
No Build						\$0	0.0%	0.0%		
Freeway Upgrade	20.8	\$5,732,000				\$119,225,600	0.0%	0.0%		
Tollway Upgrade	20.8	\$5,732,000	\$6,316,000			\$125,541,600	0.0%	0.0%		
Tolling by TOD	20.8	\$5,732,000	\$6,316,000			\$125,541,600	0.0%	0.0%		
ATIS						\$0	0.0%	0.0%		
Incident Management						\$0	0.0%	0.0%		
Speed Harmonization						\$0	0.0%	0.0%		
	Design as % of Const Costs	Design	ROW Purchase	Construction Engineering	Construction Engineering	Contingencies	Contingencies	Overhead & Indirect Costs		
No Build	0%	\$0	\$0	0.0%	\$0	0.0%	\$0	0.0%		
Freeway Upgrade	10%	\$11,922,560	\$0	0.0%	\$0	0.0%	\$0	0.0%		
Tollway Upgrade	10%	\$12,554,160	\$0	0.0%	\$0	0.0%	\$0	0.0%		
Tolling by TOD	10%	\$12,554,160	\$0	0.0%	\$0	0.0%	\$0	0.0%		
ATIS	0%	\$0	\$0	0.0%	\$0	0.0%	\$0	0.0%		
Incident Management	0%	\$0	\$0	0.0%	\$0	0.0%	\$0	0.0%		
Speed Harmonization	0%	\$0	\$0	0.0%	\$0	0.0%	\$0	0.0%		
	Design	ROW Purchase	Construction Engineering	Construction Cost	Contingencies	Overhead & Indirect Costs	Total Initial Project Costs			
No Build	\$0	\$0	\$0	\$0	\$0	\$0	\$0			
Freeway Upgrade	\$11,922,560	\$0	\$0	\$119,225,600	\$0	\$0	\$131,148,160			
Tollway Upgrade	\$12,554,160	\$0	\$0	\$125,541,600	\$0	\$0	\$138,095,760			
Tolling by TOD	\$12,554,160	\$0	\$0	\$125,541,600	\$0	\$0	\$138,095,760			
ATIS	\$0	\$0	\$0	\$0	\$0	\$0	\$0			
Incident Management	\$0	\$0	\$0	\$0	\$0	\$0	\$0			
Speed Harmonization	\$0	\$0	\$0	\$0	\$0	\$0	\$0			

Figure 4.7: Project Costs Worksheet

### 4.3 Input Parameters

Numerous parameters may be edited in either the “Summary Input Information” sheet of the Main Toolkit File, shown in Figure 4.8, or the Toolkit Upload File. The eight general parameter categories include *General Project Information*; *Capacity and Reliability*; *Operating Costs*, *User Groups and Modes*; *Motor Vehicle Safety*; *Emissions and Fuel Use*; *Operational Parameters*; *Sensitivity Testing*, and *Travel Demand Model Estimation Procedure*.

	A	B	C	D	E	F	G	H	I	J	K
1											
2		Go To Navigation Panel		Analyst Notes				Project Evaluation Toolkit - Summary Input Info			
3											
4											
5		Project Name	Austin 290 Upgrade	General Project Information							
6		Analyst	D. Fagnant								
7		Date	8/28/2012								
8				Project Costs (thousands)							
9		Total # Alternative Scenarios (not incl. no-build)	1	Design	ROW	Construct.	Add. Annual Maintenance	Salvage Value			
10		No Build		\$0	\$0	\$0	\$0	\$0			
11	Scenario 1	Freeway Upgrade		\$11,922,560		\$0	\$119,225,600	\$644,800	\$0		
12	Scenario 2	Tollway Upgrade		\$12,554,160		\$0	\$125,541,600	\$1,414,400	\$0		
13	Scenario 3	Tolling by TOD		\$12,554,160		\$0	\$125,541,600	\$1,414,400	\$0		
14											
15		Projected Traffic Growth Rate		Discount Rate		7%					
16		Annual Growth Rate	1.0%	Initial Construction Year		2015					
17		Linear Growth (0) or Exponential Growth (1)	1	# of Construction Years		1		Whole number >= 1			
18		Total Traffic Growth over Project Life	22.72%	Initial Year of Operation		2015					
19				Proj. Design Life (yrs)		20		Max Proj Design Life = 50 yrs			
20				Future Year		2035					
21				Use External TDM Outputs (1/0)		0					
22											
23											

Figure 4.8: Summary Input Information Worksheet

The **General Project Information** parameters contain basic inputs including the number of scenarios, scenario names, initial years for construction and operation, traffic growth rate, project design life and discount rate. The **Capacity and Reliability** parameters include free-flow speeds, a heavy vehicle-to-passenger car equivalency factor (for use in v/c estimates), and parameters that impact estimated speeds and reliability. The **Operating Costs, User Groups and Modes** parameters include values of time and reliability for various population groups (as well as population group proportions), average vehicle occupancy for transportation modes, modal operating costs and probabilities that given travelers of various types will select certain modes. The **Operational** parameters apply solely for operational project analyses including advance traveler information systems, speed harmonization, and incident management. Here, users should specify project life and incident growth rate, and may change detailed values such as average vehicle occupancy, average VOTT, average incident duration and frequency for specific times of day. The **Motor Vehicle Safety** parameters influence the estimated value of crashes, distribution of crash severity and frequency of crashes. The **Emissions and Fuel Use** parameters are used for estimating emissions, emissions costs, and fuel usage. The user should select location corresponding to closest climate region and season for analysis (either summer or winter). The **Sensitivity Testing** parameters denote the number of sensitivity testing trials that the analyst wishes to conduct, and the inherent uncertainty in parameters that the analyst wishes to vary. The **Travel Demand Estimation Procedure** has just a single parameter that specifies the maximum allowable average link flow error when estimating a trip table from observed traffic link counts.

#### 4.3.1 Time-of-Day Splits

Links are directed (one way) in PET, and the user may set up to five TOD period settings to represent the AM peak, mid-day, PM peak, evening, and off-peak periods. This is accomplished by setting the start times for each of the five TOD periods. Once this is conducted, the analyst may enter up to 12 TOD traffic distribution references or “stations.” Essentially, different road types or different locations may experience very different TOD splits in traffic

(AM versus PM flow splits on a link headed into the downtown, for example), so each link can be tied to a different distribution. The duration of each TOD period should be chosen such that traffic volumes and patterns are relatively uniform/stationary within each TOD period, as much as possible.

The term “station” comes from the notion of an automatic traffic recorder (ATR) station. For example, recreationally used roads on a region’s periphery may have high off-peak splits, outbound in the AM and returning in the PM. Links leading to a region’s employment-rich CBD may have very high peak splits (with AM heading inward [e.g., southbound] exceeding those of the PM in that same direction/on that same link, but better matching the adjacent [northbound] directed link’s PM flow, as commuters return home in the evening). Directionality is important for many routes, and PET allows analysts to reflect such TOD imbalances from one link and one direction of one corridor to the next. Up to 12 such traffic split distributions or “stations” may be used, each with up to five TOD shares (i.e., proportions of daily traffic). See Figure 4.9.

Project Evaluation Toolkit - Time of Day Splits							
Time of Day Splits (% of AADT in Period)							
Ref #		AM Peak	Mid Day	PM Peak	Evening	Off Peak	Equal to 1
1	US 175, 1.2 MI SE of 635	25.0%	17.0%	33.1%	15.4%	9.5%	0.751
2	IH 35, 1.6 MI SE of SH 356	27.0%	18.8%	36.0%	13.5%	4.7%	0.818
3	IH 30, 5 MI W of Loop 635	27.4%	16.6%	34.9%	13.8%	7.3%	0.789
4	SH 180, 2.7 MI W of FM 157	27.8%	14.8%	35.7%	13.3%	8.4%	0.783
5	IH 30, 3.2 MI W OF IH 35W	24.2%	17.8%	29.3%	17.3%	11.4%	0.713
6	IH 820 W End of L Worth Bridge	27.5%	18.8%	32.8%	15.1%	5.8%	0.791

Time of Day Settings		Demand Elasticity	TOD Start
AM Peak Begins	6:00 AM	-0.69	6
Mid Day Begins	12:00 PM	-0.69	12
PM Peak Begins	4:00 PM	-0.69	16
Evening Begins	7:00 PM	-0.69	19
Off Peak Begins	10:00 PM	-0.69	22

Time of Day Hours	
AM Peak	6.00
Mid Day	4.00
PM Peak	3.00
Evening	3.00
Off Peak	8.00

Time of Day Splits (% of AADT per hour)	
TOD Scale Paramter	

Figure 4.9: TOD Splits Worksheet

#### 4.4 Running the Toolkit to Estimate Impacts

Many calculations in PET are performed immediately, as data is entered by the user. For instance, emissions and crash estimates are based on formulas and data tables embedded within the Toolkit, and are linked to appropriate cells through formulas. These estimates, along with most other estimates, such as welfare and financial impacts require future traffic volumes to be estimated before they can be computed. On abstracted networks, this traffic projection is completed by running the TDM after all inputs have been addressed. Users can check these inputs are completed and run the TDM by simply clicking a macro button. Running the demand model will create a set of text files for input to PET’s TDM, which is automatically run with this data. The demand model may take up to an hour or longer to compute initial and design year results for 4 scenarios on networks with up to 300 links. (However, this evaluation is much quicker than demand modeling on complex networks, which can take upwards of days to



compute.) Users are notified of computation progress as the demand model runs and interacts with PET. External TDM results are saved in text files and imported back into the Toolkit, whereby PET automatically performs impact calculations through pre-filled cell formulas.

## 4.5 Results and Outputs

After running PET's TDM, users can view major results in the *Output Summary* sheet, which shows major project impacts and financial summary measures for each alternative, compared to the base case (no build) scenario. For initial and design years, impacts of traveler welfare, reliability, tolling revenues, and crash costs are computed and compared against base case, along with net present value (NPV), internal rate of return (IRR), B/C ratios, and payback period (PP) for the project, based on expected monetized benefits versus project costs. This summary sheet also includes a quick comparison of changes in crashes, emissions, and VMT splits for each alternative. PET automatically graphs much of the summary data in the *Summary Charts* sheet. Twenty charts display changes in impact measures between initial and design years, typically comparing each alternative within the same graph. Annual changes are exponentially interpolated for interim years, since PET only computes initial year and design year impacts. More detailed results can be viewed for each scenario and each analysis year. Summary sheets provide more detailed information on changes in traveler welfare, reliability, crashes, emissions, tolls, fuel use, and VMT. Additionally, the *Link Comparison* sheet allows users to select key links for evaluation and comparison (perhaps links with changes made, or connected or parallel links) by initial and design years, between scenarios. This sheet allows more detailed analysis of network changes to be evaluated and gauge the micro-scale impacts of a project. Further, users may investigate individual scenario output sheets for all project impacts. For instance, users may view the link-by-link estimates of emissions or link estimates (e.g., volume by user class, travel time, v/c ratios) for initial or design year of any alternate or base scenario.

Once changes in all impact categories are assessed for the base case scenario vs. alternative scenarios, PET performs a financial accounting for summary measures of all scenarios' outputs. This is conducted by assessing the NPV, B/C ratio, PP, and IRR of each scenario. In order to accomplish this, direct agency costs previously entered in the engineer's estimate are compared against project impacts.

### 4.5.1 Monetized Summary Measures

Monetized social benefits, including traveler welfare and reliability, and emissions and crash impacts (if users wish to monetize these) are used in conjunction with scenario costs, to assess each scenario's economic summary measures: NPV, IRR, B/C ratio, and PP. Benefits and economic summary measures are shown in Figure 4.10:

	No Build	290 Freeway Upgrade	290 Tolled Freeway	290 Tolling by Vehicle Class
Initial Year Monetary Benefits	\$0	\$22,262,068	\$2,289,177	\$1,959,306
Traveler Welfare	\$0	\$14,250,951	-\$5,706,191	-\$6,015,091
Reliability	\$0	\$7,296,550	\$7,298,079	\$7,297,628
Crashes	\$0	\$714,567	\$697,290	\$676,768

	No Build	290 Freeway Upgrade	290 Tolled Freeway	290 Tolling by Vehicle Class
Design Life Year Monetary Benefits	\$0	\$75,178,848	\$43,636,550	\$53,175,156
Traveler Welfare	\$0	\$29,713,993	\$3,279,426	\$7,081,037
Reliability	\$0	\$44,429,506	\$39,317,391	\$45,002,714
Crashes	\$0	\$1,035,348	\$1,039,732	\$1,091,406
Net Present Value	\$0	\$449,553,640	\$116,195,343	\$147,567,514
Internal Rate of Return	N/A	53.77%	13.57%	14.90%
Benefit / Cost Ratio	N/A	9.07	2.60	3.03
Payback Period	N/A	3.2	11.7	11.1

Figure 4.10: Overall Project Measures

After examining the overall estimated benefits and costs, the analyst may wish to examine project financing measures, which compares anticipated tolling revenues with project costs, as shown in Figure 4.11:

	No Build		290 Freeway Upgrade	
Annual Tolling Revenues (Thousands \$)	Initial Yr	Design Yr	Initial Yr	Design Yr
Total	\$122,046	\$141,480	\$122,046	\$141,636
Change vs No Build Scenario	\$0	\$0	\$0	\$156

	No Build	290 Freeway Upgrade	290 Tolled Freeway	290 Tolling by Vehicle Class
Project Financing (Thousands \$)				
NPV of New Tolling Revenues	\$0	\$782	\$199,087	\$231,440
NPV of Initial and Future Project Costs	\$17,540	\$73,246	\$90,080	\$90,080
Project Financing Perspective NPV	-\$17,540	-\$72,464	\$109,007	\$141,361
Project Financing Perspective IRR	N/A	N/A	22.2%	26.6%
Project Financing Perspective PP	N/A	> 20 years	6.6	5.5
NPV of Project Impacts	\$0	\$505,259	\$188,735	\$220,107
Agency Perspective NPV	-\$17,540	\$432,795	\$297,742	\$361,467

Figure 4.11: Project Financing Measures

#### 4.5.2 Crash and Emissions Summary Measures

In addition to economic summary measures and monetary costs and benefits, PET's output summary sheet provides users a method to quickly compare impacts that may not be monetized by the user, such as crashes and emissions. Changes in crashes (by severity) and emissions (by species) are reported for each scenario's initial year and design year, as shown in Figure 4.12.

		No Build		290 Freeway Upgrade	
Average Annual Crash Changes		Initial Yr	Design Yr	Initial Yr	Design Yr
Severity	Fatal	0	0	-0.2	-0.3
Category:	Major Injury	0	0	-0.6	-0.9
	Minor Injury	0	0	-5.4	-7.8
	Possible Injury	0	0	-11.1	-16.1
	Property Damage Only	0	0	-26.9	-39.0
Total Injury + Fatal		0	0	-17.3	-25.0

		No Build		290 Freeway Upgrade	
Average Annual Emissions Changes (tons)		Initial Yr	Design Yr	Initial Yr	Design Yr
Emissions	HC	0	0	-83.3	-849.2
(Tons)	CO	0	0	142.4	-484.6
	NOx	0	0	10.8	0.5
	CO <sub>2</sub>	0	0	7.9	-775.6
	PM10	0	0	0.0	0.0

Figure 4.12: Output Summary Crashes and Emissions Changes

### 4.5.3 Travel Behavior Changes

The final major output summary component shows travel behavior and changes among the various scenarios. In the initial and design years the VMT percent splits by each TOD period is noted, as are the percent splits by mode. Total VMT for each scenario in the initial and design year is also reported, as shown in Figure 4.13.

		No Build		290 Freeway Upgrade	
VMT Splits by Time of Day		Initial Yr	Design Yr	Initial Yr	Design Yr
	AM Peak	26.1%	26.1%	26.1%	26.1%
	Mid Day	17.5%	17.5%	17.5%	17.5%
	PM Peak	33.1%	33.1%	33.1%	33.1%
	Evening	11.0%	11.0%	11.0%	11.0%
	Off Peak	6.0%	6.0%	6.0%	6.0%
	Total VMT	5315.6	6142.0	5315.6	6143.6

		No Build		290 Freeway Upgrade	
VMT Splits by Travel Mode		Initial Yr	Design Yr	Initial Yr	Design Yr
	Mode 1	72.5%	72.5%	72.5%	72.5%
	Mode 2	12.7%	12.7%	12.7%	12.7%
	Mode 3	3.2%	3.2%	3.2%	3.2%
	Mode 4	0.2%	0.2%	0.2%	0.2%
	Mode 5	11.3%	11.3%	11.3%	11.3%

Figure 4.13: Output Summary VMT and Splits by Time of Day and Travel Mode

### 4.5.4 Summary Charts

In addition to providing numerical results, PET also offers a number summary charts that are automatically created and display graphical results for scenario comparison. Nineteen charts are automatically generated, such as the one shown in Figure 4.14.

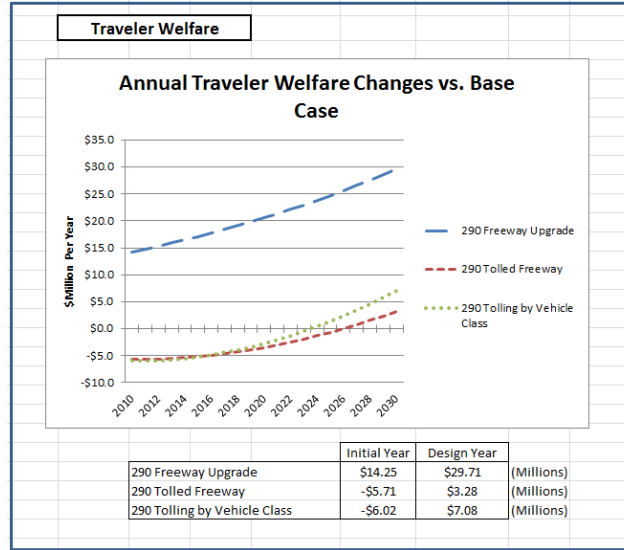


Figure 4.14: Summary Chart for Traveler Welfare

Each chart tracks a given key evaluation measure or impact over time. Some charts display changes of measures in alternative scenarios vs. the base case scenario (e.g., how many more or fewer crashes there are for a given alternative relative to the base case scenario), while other charts track the measure itself over time (e.g., how many *total* crashes do we expect each year in each scenario). The initial and design year values for the tracked measures are displayed below the chart for each scenario. The 19 charts that are automatically generated are as follows:

1. Annual Traveler Welfare vs. the Base Case Scenario
2. Annual Reliability vs. the Base Case Scenario
3. Annual Reliability Costs
4. Annual Crash Cost Savings vs. the Base Case Scenario
5. Annual Crash Costs
6. Annual Change in # of Fatal and Injury Crashes vs. the Base Case Scenario
7. Annual # of Fatal and Injury Crashes
8. Annual Emissions Changes vs. Base Case Scenario
9. Annual Emissions Quantities
10. Annual Emissions Comparison, Base Case Scenario
11. Annual Emissions Comparison, Alternative Scenario 1
12. Annual Emissions Comparison, Alternative Scenario 2
13. Annual Emissions Comparison, Alternative Scenario 3
14. Annual Change in Tolling Revenues vs. Base Case Scenario
15. Annual Tolling Revenues
16. Annual Change in VMT vs. Base Case Scenario

- 17. Annual VMT
- 18. Annual Change in Fuel Use vs. Base Case Scenario
- 19. Annual Fuel Use

#### 4.5.5 Link Comparison

The analyst may also wish to compare the estimated traffic volumes and speeds between scenarios on certain links, which may be conducted by examining the *Link Comparison* sheet, shown in Figure 4.15.

Project Evaluation Toolkit - Link Comparison											
Go To Navigation Panel											
Initial Year					AADT				Average Daily		
Link #	From Node #	To Node #	Link Name	Length (mi)	Base Case	290 Freeway Upgrade	290 Tolloed Freeway	290 Tolling by Vehicle Class	Base Case	290 Freeway Upgrade	
141	17	19	290: 35 - Dessau / Cameron	0.5	30366	30366	30366	30366	53.2	53.2	
142	19	17	290: Dessau / Cameron - 35	0.5	31001	31001	31001	31001	53.1	53.1	
143	19	20	290: Dessau / Cameron - 183	1.3	29499	29499	29499	29499	53.6	53.6	
144	20	19	290: 183 - Dessau / Cameron	1.3	29499	29499	29499	29499	53.6	53.6	
145	20	21	290: 183 - Springdale	1.2	20500	20500	18224	18689	35.3	54.8	
146	21	20	290: Springdale - 183	1.2	20500	20507	18224	18689	35.3	54.8	
147	21	22	290: Springdale - Harris Branch / Gile	1.9	20500	20513	20500	20501	23.8	54.8	

Figure 4.15: Link Comparison Worksheet

This sheet provides link-specific initial year and design year information for traffic volumes, average speeds, and PM peak speeds (typically the most congested TOD period) for each scenario. Total traffic and estimated speeds are reported, as well as changes between the base case and alternative scenarios. Users may simultaneously select up to 20 links at a time for traffic and speed comparisons between scenarios.

#### 4.5.6 Individual Scenario Sheets

Some users may wish to understand what PET is estimating at the individual link level. This is where PET estimates the actual reliability costs, fuel consumption, tolling revenues, number of crashes and emissions quantities. Users should be cautioned, however, from reading too much into the individual link-level results. While PET is structured to perform well in the aggregate sense, the accuracy at the individual link-level contains much greater uncertainty.

PET has four types of individual scenario sheets: *Volume Output*, *Link Crash*, *Intersection Crash*, and *Emissions Estimate*. Each type of individual scenario sheet has eight sheets: one for each scenario's initial year and one for each scenario's design year.

The *Volume Output* sheets take data directly from the TDM in the form of traveler welfare and traffic link volumes by time of day, user type, and mode. This information is then used to estimate average speeds, travel times, tolling revenues, fuel use, travel time variance, and variance costs on each link for each time of day. Key scenario summary information is also reported including total traveler welfare, variance costs, tolling revenues, fuel use, and VMT, as shown in Figure 4.16.

Project Evaluation Toolkit - Traffic Volume Output, Alternative Scenario 1 Initial Year

<a href="#">Go To Navigation Panel</a>																		
Notes: All links are directional (including # of lanes in each link)																		
Tot Ann. Traveler Welfare		\$14,250,951				% AM Peak Traffic		% Mid Day Traffic		% PM Peak Traffic		% Evening Traffic		% Off Peak Traffic				
Total Variance Cost		\$239,723,015				26.1%		17.5%		33.1%		11.0%		6.0%				
Total Ann. Toll Revenue		\$122,045,537																
Total Annual Fuel Use		62,935,194				% Mode 1		% Mode 2		% Mode 3		% Mode 4		% Mode 5				
Annual Million VMT		5,315.56				72.5%		12.7%		3.2%		0.2%		11.3%				
Link																		
						AM Peak		Mid Day		PM Peak		Evening		Off Peak				
Link #	From Node #	To Node #	Link Name	Link Length	FF Speed	Total Flow Veh/Hr	Avg Speed	Total Flow Veh/Hr	Avg Speed	Total Flow Veh/Hr	Avg Speed	Total Flow Veh/Hr	Avg Speed	Total Flow Veh/Hr	Avg Speed			AADT
1	51	1	183: N of TT45 - TT45	1	55	917	55.0	814	55.0	1178	55.0	398	55.0	144	55.0			16498
2	1	51	183: TT45 - N of TT45	1	55	918	55.0	814	55.0	1178	55.0	398	55.0	144	55.0			16499
3	1	10	183: TT45 Loop 1	7.8	55	4150	44.9	3628	49.4	5329	29.0	1756	54.3	652	55.0			74345
4	10	1	183: Loop 1 - TT 45	7.8	55	3708	48.0	3700	49.1	4799	34.6	1810	54.3	627	55.0			69675
5	10	15	183: Loop 1 - Lamar	2.9	55	2797	53.3	3429	51.0	3795	46.9	1677	54.5	589	55.0			58146
6	15	10	183: Lamar - Loop 1	2.9	55	3047	53.1	3429	51.0	4006	47.1	1677	54.5	547	55.0			60032
7	15	16	183: Lamar - 35	1	55	2506	54.0	3429	51.0	3694	48.2	1677	54.5	565	55.0			55986
8	16	15	183: 35 - Lamar	1	55	2693	53.6	3429	51.0	3684	48.4	1677	54.5	541	55.0			56627

Figure 4.16: Traffic Volume Output Individual Scenario Worksheet (Shown for Alternative Scenario 1 for Initial Year)

The *Link Crash* individual scenario sheets estimate the total number of crashes per year by severity on each traffic link and estimate total crash costs. The *Intersection Crash* individual scenario sheets act similarly for intersections. Again, it should be noted that predicting crashes and crash severity at the individual link or intersection level using PET is a *rough estimation process*. PET is not intended to be used to predict that certain traffic links will show a much higher or lower number of crashes than in the base case scenario, unless a specific crash modification factor is applied. Total crash changes are intended to be interpreted in the aggregate.

The *Emissions Estimate* individual scenario sheets estimate emissions at the individual link level for 14 different species, then summarizes impacts for the scenario. As with crashes, users are cautioned against reading too much into individual link impacts and are encouraged to view the results in aggregate.

#### 4.6 Running the Back-End of PET

Although PET includes its own TDM to analyze networks up to 300 links, many modelers already have a TDM for their region and may prefer to use PET to estimate traveler welfare, crashes, reliability, and emissions impacts, while using their own TDM outputs to anticipate changes in travel patterns across much more detailed networks. Users with proper link-level output from a TDM can upload their data into PET for quick project evaluation and comparison in aspects not considered outside of extensive evaluations.

To evaluate an external TDM's outputs in PET, users must first format their data for uploading into PET (see the PET Guidebook). Import features have been created in the Toolkit that will automatically import text files to the appropriate fields, provided text files are formatted properly by the user. External TDM can be imported from the *Project Evaluation Toolkit Home* sheet, as shown in Figure 4.17.

External TDM Upload Procedure	
<b>Import External TDM Data</b>	
<b>Import External Travel Demand Model for... (0/1)</b>	
1	Base Case
1	Alt 1
0	Alt 2
0	Alt 3
1	Initial Year
0	Design Year
1	Use Tolls
1	Traveler Welfare Skims
<b>Status</b>	
Alt Scenario 3, Link 601 of 776 links.	
Notes: This procedure may be used to utilize PET's back-end calculations from regional travel demand outputs for crashes, reliability, emissions and other impacts. This procedure over-writes existing network and tolling information. Also, "Use External TDM Outputs" must be set to 1, located in the "General Information" section of the "Summary Input Information" sheet. For more information, see PET guidebook chapter X.X.	

Figure 4.17: External TDM Upload Procedure

Importing files into PET requires some processing time, especially if many links are imported. The upper limit of rows available for import of external TDM data is 300,000. PET processes this data 300 links at a time and can take up to one minute to import and compute data for each set of 300. Thus, a data set of 20,000 links may take PET about an hour to import, process, and compute final results. The status bar shown in Figure 4.17 indicates the current progress of the import and computation process to provide user feedback through the process.

If all data has been imported properly, results can be analyzed in the *TDM Summary* sheet. The *TDM Summary* sheet provides monetary impacts (traveler welfare, reliability, crash costs, and emissions cost), crash data (total, fatal, and injurious), annual emissions for 14 species, and other impacts (e.g., toll revenues, fuel consumption, and VMT) for the base case and each alternative, for both initial and design years. These results are presented in two formats: (1) Change vs. Base Case, for quick relative analysis of alternatives, and (2) System Impacts, which shows total impacts for all scenarios. Figure 4.18 shows the *TDM Summary* sheet, with data for Change vs. Base Case outputs.

Go To Navigation Panel									
Change vs. Base Case	Initial Year						Design Year		
	Base Case (No Build)	Alt 1	Alt 2	Alt 3	Base Case (No Build)	Alt 1	Alt 2	Alt 3	
<b>Monetary Impacts</b>									
Traveler Welfare	\$0	-\$586,509	-\$587,422	-\$586,296	\$0	-\$444,251	-\$445,163	-\$444,7	
Reliability	\$0	\$274,965,600	\$298,745,100	-\$1,312,518,000	\$0	-\$1,024,477,600	\$442,454,300	-\$638,188,0	
Crash Cost	\$0	\$1,679,900	\$2,211,700	\$923,353,800	\$0	\$2,270,700	\$2,940,400	\$917,887,1	
Emissions Cost	\$0	\$37,510,700	\$28,246,100	\$26,010,000	\$0	\$18,562,400	\$31,152,200	-\$852,5	
<b>Crashes</b>									
Total	0	19	25	223	0	25	33	1	
Fatal	0	0	0	135	0	0	0	1	
Fatal + Injury	0	8	10	-322	0	10	13	-3	
<b>Annual Emissions (Tons)</b>									
1,3-Butadiene	0	2	2	2	0	1	2		
Acetaldehyde	0	6	5	5	0	3	5		
Benzene	0	13	10	9	0	6	11		
CH4	0	25	19	18	0	13	22		
CO	0	7,731	4,787	4,610	0	5,885	9,684	1	
CO2	0	1,618,294	1,107,619	1,005,935	0	1,022,167	1,694,327	-34,8	
Formaldehyde	0	8	7	6	0	3	6		
N2O	0	26	21	20	0	9	15		
NH3	0	84	53	46	0	64	104		
Nox	0	635	276	224	0	739	1,168		
PM10	0	317	259	235	0	114	199	-	
PM25	0	113	89	82	0	48	82		
SO2	0	31	21	19	0	20	33		
VOC	0	850	671	631	0	352	605	-	
<b>Other Impacts</b>									
Tolling Revenues	\$0	-\$5,377,495,300	-\$5,375,490,100	-\$2,607,469,200	\$0	-\$5,394,663,000	-\$5,392,613,100	-\$2,615,672,4	

Figure 4.18: TDM Summary Worksheet Output for External TDM Data

Other results (such as NPVs, B/C ratios, and project financing measures) may be found in the *Output Summary* sheet, the *Impact Summary* sheets, and the *Summary Charts*.

## 4.7 Evaluating Project Sets

As an extension of PET’s analysis of up to three alternative scenarios alongside three operational analyses, two modules were created to consider larger sets of projects. The Budget Allocation Module and the Multi-Objective Decision-Making Tool are separate spreadsheet files that allow users to compare project costs and benefits in light of constrained budgets. These modules can be used to evaluate a number of analyses in PET or elsewhere and are operated outside of the main Toolkit file.

### 4.7.1 Budget Allocation Module

The Budget Allocation Module may be used to perform an optimal project selection function by identifying a preferred mix of potential projects in order to achieve the maximum benefits. This component solves a discrete optimization problem (i.e., maximization of total benefits caused by project implementation) subject to, for example, budget limits and equity considerations, such as ensuring that various regions have minimum expenditure levels. Moreover, the budget allocation module requires the analyst to specify a pre-determined level of required investment for every candidate project, under the assumption that one project’s costs will not impact another project’s cost. In this regard, the budget allocation decision-making process will choose mix of projects that will deliver the maximum benefits, within the limits of budget and other constraints.

The standard budget allocation problem is the classic 0-1 “knapsack problem” (Martello and Toth, 2003). Given a set of candidate projects, each of which is associated with a fixed cost (e.g., design and construction cost) for its implementation and known monetized benefits (e.g., increases in consumer surplus and travel time reliability), and given a total-budget constraint (to cover selected project costs), the objective is to find an optimal subset of projects to be



implemented so that total benefits (or net benefits) are maximized without violating/exceeding the budget constraint.

Figure 4.19 illustrates the setup used in the example problem, with one input column for project costs, one for project benefits setting, as well as individual project regions and project types. Users may specify available budget constraints, as well as placing minimum and maximum funding limits for regions and project types in order to satisfy geographic and funding pool requirements. The current version of this add-in can accommodate up to a maximum of 200 decision candidate projects.

Note: If "Recommended Projects for Funding" value between 0 and 1, press "options" in the Solver window and un-check "Ignore Integer Constraints"							Total cost	\$659,703
							Total benefit	\$1,685,028
<b>Legend</b>								
User Inputs								
Key Outputs								
								<b>Recommended</b>
								<b>Projects for Funding (1/0)</b>
	Project	Name	Cost	Benefit	Region	Project Type		
	1	Aus Hwy	\$138,506	\$282,191	1	1		1
	2	Aus Trans	\$95,905	\$102,530	1	2		0
	3	Aus PdBike	\$141,893	\$88,243	1	3		0
	4	DFW ITS	\$85,190	\$162,184	2	4		1
	5	DFW Maint	\$116,260	\$62,828	2	5		0
	6	DFW Hwy	\$105,494	\$181,549	2	1		0
	7	Hou Trans	\$8,737	\$22,055	3	2		1
	8	Hou PdBike	\$144,007	\$143,497	3	3		1
	9	Hou ITS	\$104,161	\$127,270	3	4		0
	10	SA Maint	\$48,320	\$197,392	4	5		1

Figure 4.19: Using the Solver Add-In to Solve an Example Budget Allocation Problem

#### 4.7.2 Multi-Objective Decision-Making Tool

PET’s multi-objective decision-making tool (MODMT) enables engineers, planners, and others to select one or more optimal projects or scenarios from among competing alternatives subject to multiple criteria that are not all monetized or reduced to a single type of unit (e.g., not all are resolved in minutes saved or dollars saved). The MODMT uses a Data Envelopment Analysis (DEA), a methodology that uses an “efficiency” value to rank different scenarios. Scenarios whose efficiency is less than one are clearly dominated by other scenarios, and are not recommended; the scenarios with an efficiency greater than or equal to one are candidates which are potentially optimal, depending on one’s relative valuation of the different criteria. The magnitude of the efficiency value reflects the degree to which these scenarios are dominated (or not) by the others. This method is not sensitive to the units used for each criterion, and can be understood intuitively with a geometric figure, which make it a useful choice for the toolkit.

DEA has been implemented as an Excel spreadsheet, in which the user specifies each of the scenarios, and the values of each of the corresponding measures of effectiveness. Further, the user specifies whether each of these metrics is either a “benefit” (a higher value is better, such as with traveler welfare or revenue) or a “cost” (a lower value is better, as with emissions, crash rates, or construction and maintenance costs). MODMT outputs sort scenarios by their efficiency values, giving analysts effective project prioritization rankings.

The MODMT serves a similar purpose as the Budget Allocation Module, with the ability to select multiple alternatives from among competing choices. However, whereas the existing Budget Allocation Module uses a single objective function (maximizing total monetized benefits of chosen projects), the MODMT evaluates competing alternatives across multiple benefits (or

costs), that do not necessarily have “fixed” tradeoffs. Having both components enables analysts to choose the method that best suits their particular situation.

## Chapter 5. Case Studies

One task directly associated with this project involved analyzing case studies with PET, while a related implementation project (5-6325) developed these further, on more networks (including Houston and Dallas-Fort Worth.) For this project directly, two test-case scenarios were conducted on both the Austin and Houston networks. Major findings from these case studies are discussed in this chapter. Other case study applications in PET include sensitivity analysis of an Austin case study by Fagnant and Kockelman (2012).

### 5.1 Capacity Expansion in Austin: US 290

The first test case scenario involved three alternatives surrounding a highway grade separation project in Austin, Texas. The primary differences between the alternatives involved the pricing structure used: the first alternative was not tolled, in the second alternative all vehicles were tolled at a flat rate, and in the third alternative vehicles were tolled at a variable rate, depending on mode (SOV, HOV, transit, and heavy truck).

#### 5.1.1 Project and Alternative Scenario Descriptions

Three capacity expansion and tolling scenarios were conducted for the 194-link Austin network on the 5.2-mile segment of highway US 290 between highways 183 and 130, as shown in Figure 5.1.

The three scenarios evaluated upgrading a four-lane segment (two through lanes in each direction) from an arterial to a grade-separated freeway or tollway, while retaining the configuration of two lanes in each direction. Capacity was estimated as increasing from a bi-directional capacity 3,080 vph of to a bi-directional capacity of 7,640 vph after the improvements. Grade separation also involved the elimination of seven intersections between US 290 and minor streets in the alternative scenarios. The three alternative scenarios were formulated such that the first scenario was modeled with the enhanced segment as a freeway, the second as a tollway with constant fares at \$0.20 per mile and heavy trucks at \$0.60 per mile, and a third scenario with half fares during off-peak times and double fares during peak times. A 20-year design life was assumed with a 1% annual growth rate for all origins and destinations.

Project costs were estimated at \$131 million for Alternative 1 (Freeway Upgrade) and \$138 million for Alternatives 2 and 3 (Tollway Upgrade and Tolling by TOD). Each scenario was assumed to require increased annual funding for facility maintenance and operations, at \$645 thousand per year for Alternative 1 and \$1.41 million per year for Alternatives 2 and 3 (not accounting for toll collection offsets). A year-10 (mid-life) \$30 million pavement reconstruction project was also required for the base-case alternative (since the main facility remained, and would need rehabilitation before 20 years passed). Project construction, operations, road maintenance, and reconstruction cost estimates were obtained from Austin Tollway Expert Wes Burford (2011) regarding the similar although more extensive Manor Expressway project currently under construction, as well as other sources including TxDOT (2008) and the Victoria Transport Policy Institute (2009). A 7% discount rate was assumed, consistent with the 7% required by the Office of Management and Budget (OMB) for federal projects and TIGER grant applications (LaHood 2011).

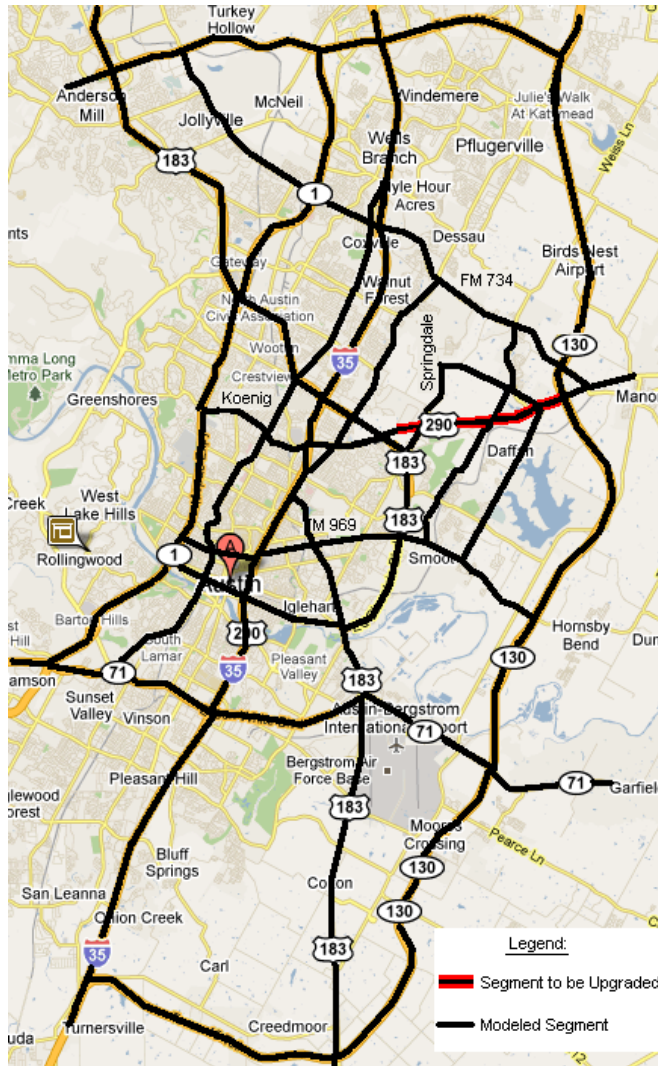


Figure 5.1: The Austin Network, US 290 Case Study

### 5.1.2 Summary Impacts

PET estimates indicated that the Freeway Upgrade scenario yielded the greatest benefits, as shown in Table 5.1:

Table 5.1: Project Summary Measures

	Base-Case: No Build	Alternative 1: Freeway Upgrade	Alternative 2: Tollway Upgrade	Alternative 3: Tolling by TOD
Net Present Value	\$0	\$690 M	\$376 M	\$265 M
Benefit-Cost Ratio	N/A	6.6:1	3.7:1	2.9:1
Internal Rate of Return (from Tolling)	N/A	N/A	6.0%	8.2%
Payback Period (from Tolling)	N/A	N/A	> 20 years	18 years

The Freeway Upgrade scenario showed the highest initial year benefits, design year benefits, B/C ratio, and NPV. From a traveler's perspective this alternative would be preferable to all others. However, the Freeway Upgrade scenario also requires significant investment for construction, maintenance, and operation, all of which must be funded out of general revenues. The uniform tolling and tolling by vehicle class scenarios both provide financing mechanisms with IRRs at 6.0% and 8.2% for the Tollway Upgrade and Tolling by TOD scenarios. Therefore, if agency budgets are financially constrained, planners may wish to pursue the tolling by vehicle class alternative scenario as revenues are projected to nearly equal that of the uniform tollway, but benefits to the traveling public are projected to be much higher.

### **5.1.3 Specific Impacts**

Over the entire 20-year evaluation period, PET also estimates that the Freeway Upgrade alternative results in the fewest fatal and injury crashes. This scenario resulted in 1,708 F+I fewer crashes than the base-case scenario over 20 years. This compares to the 26.8 thousand total system crashes in the base case scenario and thus amounts to a 6.4% reduction in total predicted crashes. Similar reductions are estimated for the tolling alternatives.

PET estimates that total system VMT increased by just 0.35%, -0.04% (decrease), and -0.15% (decrease) in the initial year (from 5.31 billion annual VMT) and by 0.75%, 0.39%, and 0.27% in the design year (from 6.55 billion) for the Freeway Upgrade, Tollway Upgrade, and Tolling by TOD alternatives, respectively. While improved travel times resulted in reduced emissions for most pollutant species, some emissions, more sensitive to VMT, increased (e.g., NH<sub>3</sub> increased by 0.6%–0.8% in the Freeway Upgrade alternative). The Freeway Upgrade alternative showed the greatest overall emissions benefits (particularly in the design year), with VOCs, BUTA, ACET, BENZ, and CH<sub>4</sub> all falling by over 4%, while emissions changed by less than 1% in the other two scenarios. Traffic volumes and (flow-weighted) average speeds along the altered corridor increased from 20,500 AADT at 31 mph in the base-case initial year to 25,278 AADT, 17,000 AADT, and 15,180 AADT—all at 54 to 55 mph—under the Freeway Upgrade, Tollway Upgrade, and Tolling by TOD alternatives, respectively. In the design year traffic volumes and speeds along the corridor increased from an average of 24,800 AADT at 21 mph (base case conditions) to an average of 36,500 AADT at 50 mph, 25,900 AADT at 53 mph, and 23,400 AADT at 54 mph in the Freeway Upgrade, Tollway Upgrade, and Tolling by TOD alternatives, respectively.

### **5.1.4 VMT and Link Speeds**

Emissions were reduced in all scenarios, which may be largely tied directly to changes in total VMT and increased speeds through the project corridor. Total VMT was increased in all three alternative scenarios in the initial year, by 0.96 to 1.3 million, likely due to induced demand as travel times (and therefore travel costs) fell. However, by the design year, VMT was down 3.3 million (in the tolling by vehicle class scenario) to 10 million (in the uniform tollway scenario), even though traffic volumes rose on the project segment by an average of 870 to 1,080 AADT in each direction versus the base case scenario. VMT likely fell overall in the design year because the segment became congested in the base case scenario, slowing to an average daily speed of 23 mph and 16 mph during the PM peak, while traffic kept moving briskly at over 50 mph in the alternative scenarios throughout the day. This in turn likely caused some trips in the base case scenario to take an alternate and longer route (distance-wise), leading to the increased VMT when compared to the alternative scenarios.

## 5.2 Speed Harmonization in Houston: IH 10

Speed harmonization was investigated as a potential operational improvement on the 17-mile segment on IH 10 in Houston, between Bingle Road and Federal Road as shown in Figure 5.2:

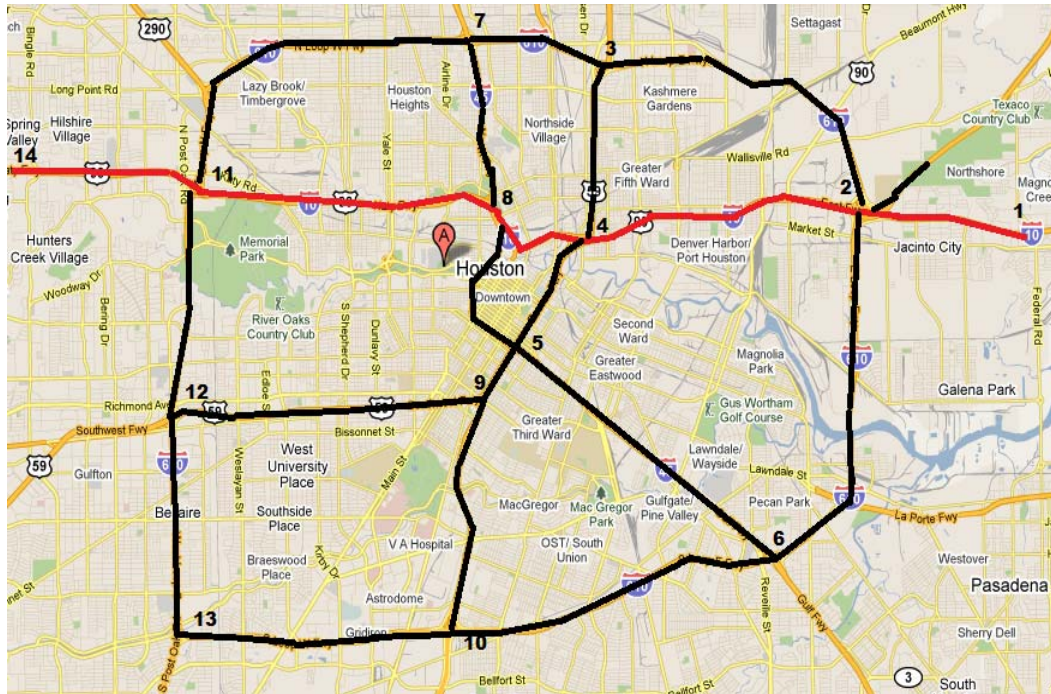


Figure 5.2: Houston, TX Speed Harmonization Project Limits Shown in Red

AADT on the IH 10 freeway analysis segment varied between 124,000–242,000 vehicles. Initial installation costs were assumed to be \$3.2 million per directional mile for a four-lane section (WSDOT 2008). PET assumed that speed harmonization would reduce the number of crashes on IH 10 by 20% when speed harmonization was active, which was projected to be from 6:00 a.m. to 11:00 p.m. Using national crash data records, PET assumed that 89.4% of crashes predicted to occur on this segment would occur while speed harmonization was active. PET was then used to estimate the number of crashes and crash reductions as a result of employing speed harmonization.

Assuming comprehensive crash costs (assigning a value to human life, pain and suffering, loss of companionship, and other non-market values [National Safety Council 2009]), the total initial year monetary benefits were estimated to be \$10.6 million, increasing to \$11.3 million by the design year. Using a discount rate of 5%, PET estimated a total NPV of \$92.6 million and a B/C ratio of 2.97. These results indicate that this project would likely be a good candidate when prioritizing project funding. However, it should be reiterated that these reasonably good summary measures depend on the assumption that comprehensive crash costs are accounted for, rather than pure economic costs only.

### 5.2.1 Crashes

In addition to reporting summary measures for the speed harmonization operational strategy, PET also produced an estimate of the actual number and severity of predicted crashes averted. This is a particularly key measure for project evaluation, particularly if the value of life and other comprehensive crash costs are not directly accounted for, but are rather evaluated using a multi-criteria decision-making processes. The output results showed that of the 1,149 total crashes that were predicted to occur in the base case scenario's initial year, implementing speed harmonization should likely reduce this number by 205 crashes. Over the project scenario's 20-year design life, the total number of crashes averted was estimated at 4,471, with around 23 to 24 lives saved. See Table 5.2.

**Table 5.2: Speed Harmonization Crash Reduction Impacts**

	<b>Initial Year</b>	<b>Design Year</b>
	<i>2011</i>	<i>2031</i>
Crashes per year on impacted links	1,149	1,234
% of crashes when SH is active	89%	89%
SH Crash Reduction Factor	20%	20%
Total # of Fatal <sup>1</sup> Crashes Prevented	0.94	1.01
Total # of Injury <sup>1</sup> Crashes Prevented	79.3	85.2
Total # of Crashes Prevented	205	221

### 5.3 Case Study Discussion

These case studies illustrate PET's ability to quantitatively assess the impacts of potential projects. The projects investigated are quite different in nature, yet their outcomes may be directly compared on a number of measures. Analysts may review the differences in B/C ratios between projects, NPVs, or absolute changes in crashes between the various case studies and alternative scenarios within the two case studies. In this, even though the capacity expansion and pricing projects impact more measures than the speed harmonization (for example, traveler welfare, emissions, and reliability), analysts may use these common measures in order to directly compare very different project types when conducting evaluations and selecting projects to fund.

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<sup>1</sup> Note: this evaluation assumed that an average of 1.15 fatalities occurred per fatal crash and 1.49 injuries occurred per injurious crash.





## Chapter 6. Conclusions

PET provides users a relatively quick method of project assessment and comparison by using a spreadsheet-based network analysis tool to compute project impacts and financial measures. PET's major focus is on travelers' economic impacts, in terms of traveler welfare and reliability, and crash and emissions impacts. Economic impacts can be evaluated for (smaller) abstracted networks with a self-contained travel demand module, or users may determine impacts on their own (larger) networks by analyzing previously generated TDM results. PET compares up to three scenarios and presents results in a user-friendly manner, providing clear comparisons through charts and output summaries. PET allows users to quickly evaluate a number of project types, including capacity expansion projects, tolling, managed lanes, operational strategies, fixed cost, transit, and others. PET's capabilities have grown throughout its development and aim to fill a gap for transportation planning and modeling by providing a comprehensive approach to assessing project costs and benefits, safety, and air quality impacts.

In summary, this project has greatly improved PET's capabilities as a quick-response, self-contained toolkit designed for evaluating transportation projects on the sketch planning level. With new considerations for operational project analysis, enhanced crash and emissions estimation methodology, and improved usability with the network visualization module, PET is more versatile and widely appealing as a modeling tool. Case study applications show PET's value in real applications and showcase how projects can be evaluated and considered from a sketch level. For more details on PET, and the programs themselves, please visit the PET site at [http://www.cae.utexas.edu/prof/kockelman/PET\\_Website/homepage.htm](http://www.cae.utexas.edu/prof/kockelman/PET_Website/homepage.htm).



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## **Appendix A. Comparison of MOBILE and MOVES Emissions Rates**

Although MOBILE was modified multiple times from 1978 to 2003 to incorporate new data on vehicle emissions and to better address new vehicle emission standards, the emissions estimation methodology has remained unchanged (EPA, 2003). MOBILE uses grams-per-mile emission rates (based on dynamometer tests of pre-defined driving cycles such as the Federal Test Procedure) and average speed as the primary descriptor of vehicle activity. It is broadly recognized as a macroscopic model because average aggregate network parameters are used to estimate network-wide emissions factors (Vallamsundar and Lin, 2010). Emissions (calculated as the product of VMT and emission rate) may be adjusted by correction factors that account for variables such as temperature, vehicle deterioration, and inspection/maintenance (I/M) programs. Without taking vehicle operation mode into account, the average-speed-based method used by MOBILE may inaccurately reflect emissions from actual driving behavior (Bai, et al., 2009).

The development of MOVES represents a fundamental change in on-road vehicle emissions estimation methodology. In contrast to MOBILE, MOVES is a microscopic emissions tool, a modal model that estimates emissions based on second-by-second vehicle performance characteristics for various driving schedules (Vallamsundar and Lin, 2010). Similar to MOBILE, MOVES incorporates input data such as vehicle fleet composition, fuel information, and meteorological parameters. However, MOVES uses default (or user-input) driving cycles to categorize vehicle operating modes into one of 23 operating mode bins defined by speed and vehicle-specific power (VSP). These operating modes, for example, correspond to vehicle activities such as accelerating, braking, cruising, or idling. The emission rates (grams per unit of time) in MOVES are directly related to VSP, which has been demonstrated to be better correlated with emissions than average vehicle speeds. In contrast, emission rates from MOBILE are defined by average speed bins that are associated with the embedded VSP distribution fixed by the underlying driving cycles.

In concept, the modal nature of MOVES allows the user to estimate emissions at scales ranging from an individual transportation project to large regional emissions inventories. MOVES includes a database of hourly county-specific meteorology, and default vehicle fleet, vehicle activity, fuel, and emission control programs data for the entire US. In theory, the user could rely entirely on the default dataset for emissions estimation. Since the default dataset does not necessarily represent the most recent information, emissions calculated for a local area typically includes, at minimum, inputs such as vehicle fleet and activity.

The basic activity in MOVES is vehicle population and VMT for base year 1999. The Total Activity Generator (TAG) module grows the 1999 population and VMT to the target year using the appropriate growth factors. TAG also provides the data conversion from a VMT and vehicle population basis to an activity basis. Emissions rates in MOVES, with the exception of vehicle starts, are computed based on activity in units of time. For example, evaporative and running exhaust emissions are defined in terms of source hours operating as opposed to VMT. This is substantially different from MOBILE, which uses VMT directly to estimate running exhaust.

Compared to MOBILE, MOVES provides emissions that are aggregated from a more comprehensive breakdown of vehicle activities, road types, engine technologies, and fuel categories. MOVES classifies vehicles based on activity patterns as well as emissions

performance that better connects activity and emissions data in terms of characterizing vehicles. For the purposes of this project, notable differences between MOBILE and MOVES that directly impacts the structure of the lookup emissions rate table used by PET include the following:

- MOBILE6 uses 28 vehicle categories based on weight, vehicle type, and fuel (e.g., light-duty gasoline vehicles, Class 8b heavy duty diesel vehicles). MOVES uses 13 vehicle type categories defined by observable characteristics and typical use (e.g., passenger car, combination long-haul truck) combined with fuel type (e.g., gasoline, diesel). The MOVES vehicle classifications directly map to the FHWA Highway Performance Monitoring System (HPMS) for reporting VMT and to those used in local vehicle registration systems.
- Roadway types in MOBILE6 consist of four categories: freeways, arterials, ramps, and local roadways. MOVES uses four basic roadway types for on-road activities: urban restricted, urban unrestricted, rural restricted, and rural unrestricted. In addition, a fifth category was created for off-network (e.g., parking lots, driveways) emissions. The MOVES road types are aggregations of the HPMS functional facility types. The urban/rural distinction is used primarily for national level calculations and the emissions rates using MOVES default data are not substantially different between the urban and rural categories.
- MOBILE6 estimates emissions in units per distance travelled (e.g., grams per VMT) for exhaust running, exhaust start, and evaporative emissions associated with hot soak and diurnal processes. MOVES estimates emissions from all significant vehicle activities, including on-road running processes (e.g., exhaust, crankcase exhaust, brake wear, tire wear, and evaporative processes such as venting, permeation, and leaks) as well as off-network emissions associated with parked and stationary running vehicles (e.g., idling, start exhaust, crankcase start exhaust, evaporative emissions). Emissions from off-network processes are estimated on a per-vehicle basis (as opposed to units of grams per VMT) that is not well associated with the underlying emissions activity or location.
- Average vehicle speed is used in MOVES to convert VMT into Source Hours Operating (SHO) and to select the appropriate driving cycles to calculate operating mode distributions. MOBILE6.2 uses 14 average vehicle speed bins with a maximum speed of 65 mph. MOVES expands the number of average speed bin categories to 16, ranging from 2.5 mph to  $\geq 72.5$  mph.



## Appendix B. MOVES Applications for Texas

The EPA MOVES run configuration and input datasets for PET were based on those developed by TTI as documented in the report entitled “Development and Production of Statewide, Non-Link-Based, On-Road Mobile Source MOVES Emissions Inventory” dated July 2011 (TTI, 2011a). TTI developed by-county hourly on-road summer (June 1–August 31) emissions using hourly HPMS virtual link data for each combination of vehicle source and fuel type, pollutant, and emissions process (e.g., running exhaust, evaporative, off-network) by year (2006, 2008, 2012, and 2018) and day type (weekday, Friday, Saturday, and Sunday). TTI estimated emissions for the gaseous pollutants VOC, CO, NO, NO<sub>2</sub>, NO<sub>x</sub>, CO<sub>2</sub>, SO<sub>2</sub>, and ammonia (NH<sub>3</sub>), and for total and speciated components (i.e., organic carbon, elemental carbon, and sulfate [SO<sub>4</sub>]) of PM<sub>2.5</sub> and PM<sub>10</sub>. Table B1 presents a results summary for statewide summer weekday (e.g., 24-hour) emissions for selected pollutants for each of the four MOVES base years for all vehicle types.

**Table B1: Statewide summer weekday VMT (miles) and MOVES-based, on-road mobile source emissions estimates from gas and diesel vehicles (tons/day)**

Year	VMT	VOC	CO	NO <sub>x</sub>	PM <sub>10</sub>	PM <sub>2.5</sub>	NH <sub>3</sub>	SO <sub>2</sub>	CO <sub>2</sub>
2006	683,081,226	556.2	6,430.8	1,841.6	85.0	71.3	30.8	11.9	422,396.6
2008	676,522,711	473.4	5,399.1	1,459.6	65.2	52.7	27.2	8.9	412,360.6
2012	726,268,000	363.4	3,986.4	1,074.3	50.4	37.4	23.3	5.9	439,157.0
2018	801,394,716	238.9	3,087.8	585.6	34.4	19.4	19.4	6.0	457,838.9

Source: Adapted from TTI, 2011a

TTI used 2010 Texas data as the preferred basis for developing inputs for year 2012. PET is designed to estimate emissions for four base years: 2010, 2015, 2020, and 2025. Since several local datasets (e.g., vehicle age distributions, fuel/engine fractions, fuel formulations, I/M programs) are generally held constant in the PET MOVES simulations for the four base years, the TTI MOVES dataset for 2012 served as the basis for all PET runs. Using TTI year 2012 incorporates information from the most recent complete year (2010), when available.

TTI modeled 22 unique combinations of MOVES source use type (SUT) and fuel as shown in Table B2. All five road type categories in MOVES (rural restricted access, rural unrestricted access, urban restricted access, urban unrestricted access, and off-network) were simulated. TTI replaced the national default fuel engine fractions from MOVES with local Texas data, which estimated no compressed natural gas (CNG) vehicles or gasoline transit buses in the Texas vehicle fleet. Based on the Texas fuel engine fractions, TTI decided to model only emissions associated with gasoline and diesel fuels (which dominate on-road fuel usage); emissions from CNG and electricity fuel types were not considered. As shown in Table B3, emissions were estimated for the 11 MOVES emissions processes. Note that evaporative emissions processes (permeation, fuel vapor venting, and fuel leaks) are estimated by MOVES from parked vehicles as well as from on-road running conditions.

**Table B2: TTI-simulated SUT and fuel combinations**

<b>MOVES SUT ID</b>	<b>SUT Description</b>	<b>Fuel Type</b>
11	Motorcycle	Gas
21	Passenger Car	Gas and Diesel
31	Passenger Truck	Gas and Diesel
32	Light Commercial Truck	Gas and Diesel
41	Intercity Bus	Diesel
42	Transit Bus	Diesel
43	School Bus	Gas and Diesel
51	Refuse Truck	Gas and Diesel
52	Single Unit Short-Haul Truck	Gas and Diesel
53	Single Unit Long-Haul Truck	Gas and Diesel
54	Motor Home	Gas and Diesel
61	Combination Short-Haul Truck	Gas and Diesel
62	Combination Long-Haul Truck	Diesel

**Table B3: MOVES emissions processes and processes estimated by TTI**

<b>MOVES Process ID</b>	<b>Emissions Process</b>	<b>TTI?</b>
1	Running Exhaust	Y
2	Start Exhaust	Y
9	Brake Wear	Y
10	Tire Wear	Y
11	Evaporative Permeation*	Y
12	Evaporative Fuel Vapor Venting*	Y
13	Evaporative Fuel Leaks*	Y
15	Crankcase Running Exhaust	Y
16	Crankcase Start Exhaust	Y
17	Crankcase Extended Idle Exhaust	Y
18	Refueling Displacement Vapor Loss	
19	Refueling Spillage Loss	Y
90	Extended Idle Exhaust	
99	Well-to-Pump	

\*Evaporative processes were estimated for both on-road running and parked vehicles.

TTI created 44 different MOVES scenarios to represent various groupings of Texas counties. The scenarios were developed by the intersections of four different geographic regions of input data aggregations. The first geographic consideration was time zone, which affected only the El Paso area. The second geographic regions were the 25 TxDOT districts that were used to define the SUT/fuel type VMT allocations by road type. The MOVES local input datasets for each of the 25 TxDOT districts were age distributions and fuel/engine (i.e., diesel) fractions. For year 2012, these latter datasets were based on the latest available county registrations data for mid-year 2010 and MOVES defaults, as needed. The fuel engine fractions

were developed by TTI to be consistent with the SUT/fuel types in each TxDOT district VMT mix.

The third geographic regions considered by TTI were fuel regulation districts. Fuel formulations were based on survey data (when available) for five sample cities (Amarillo, Dallas, El Paso, Houston, and San Antonio) as well as consideration of state and federal summertime Reid Vapor Pressure (RVP) limits. For year 2012, the fuel properties used a combination of the latest Northrop Grumman Mission Systems (NGMS) for summer 2009, MOVES defaults, and expected values for ethanol volume based on Department of Energy forecasts that showed 2012 as the saturation year for ethanol at 10% of transportation sector fuel. Diesel sulfur input estimates were based on survey data or MOVES defaults. For PET, we used fuel composition estimates developed by TTI for a similar Texas project that provided fuel compositions for both summer and winter (TTI, 2011c). The fuel compositions for Waco, DFW, and HGB are shown in Table B4.

**Table B4: Summer 2012 gasoline property input estimates**

Season	Area/ Market Share	RVP (psi)	Sulfur (ppm)	ETOH (vol%)	Aromatics (vol%)	Olefins (vol%)	Benzene (vol%)	E200	E300
Winter	Waco/91%	13.23	30	10	19.93	12.51	0.5915	51.5845	86.9871
	Waco/9%	13.23	30	0	19.93	12.51	0.5915	51.5845	86.9871
	HGB&DFW	11.71	30	10	19.492	11.729	0.55	56.0743	86.9795
Summer	Waco/91%	7.8	30	10	26.77	10.603	0.6615	54.3257	87.2487
	Waco/9%	7.8	30	0	31.77	10.603	0.6615	44.855	81.708
	HGB&DFW	6.973	30	9.84	16.022	10.559	0.511	48.434	84.109
Both	Diesel	--	11	--	--	--	--	--	--

Source: Adapted from TTI, 2011c

The fourth and final geographic regions TTI considered were emissions control areas. Table B5 summarizes the emissions control strategies addressed by TTI for year 2012. By default, MOVES generally assumes that I/M programs are active for all regions of the US. A review by TTI of the default I/M information for Texas resulted in the generation of a completely new I/M dataset. TTI reviewed the currently existing State Implementation Plans (SIPs) and state rules to develop a set of MOVES I/M program parameters. Six I/M test standards have been historically or are currently applicable in one or more Texas areas. TTI categorized counties into one or more of seven I/M coverage groups that specify the years for which an I/M standard is applicable as well as the SUT and model years included under each standard. For reference, the TTI I/M coverage groupings for DFW and HGB are provided in Table B6.

**Table B5: Approaches to emissions controls strategies by TTI for year 2012**

Strategy	Approach
Federal Motor Vehicle Control Program Standards	MOVES defaults
Federal Low Emissions Heavy-Duty Diesel Engines Rebuild Program	MOVES defaults
Conventional Gasoline Properties	Used a combination of regulatory limits (e.g., RVP with ethanol waivers as appropriate, sulfur content), latest survey data or MOVES default data, and Energy Information Administration's (EIA) Annual Energy Outlook 2011 motor gasoline and ethanol volume projections (national averages).
Reformulated Gasoline Properties	Latest available NGMS summer 2009 survey data
Diesel Sulfur	MOVES defaults
Texas Low-Emission Diesel (TxLED)	Applicable to 110 eastern Texas counties for NO, NO <sub>2</sub> , and NO <sub>x</sub> . Used evaluation year-specific reduction factors provided by TCEQ (4.8% and 6.2% reductions for 2002 and later, and 2001 and earlier model years, respectively).
I/M Program	TTI developed MOVE I/M program parameters using latest Texas SIP and rules (refer to text discussion). The compliance factor was set to 93.12% per the EPA's <i>Technical Guidance</i> .

Source: Adapted from TTI, 2011

**Table B6: Texas MOVES IMCoverage input descriptions for DFW and HGB**

MOVES I/M ID	YearID	begModel Year	endModel Year	Test Standard	Sourcetype
30	2002 thru 2019	ModelYr minus 24	1995	23 (A2525/5015 Phase)	LD
51		ModelYr minus 24	1995	41 (Evp Cap)	LD
40		1996	ModelYr minus 2	51 (Exh OBD)	LD
60		1996	ModelYr minus 2	45 (Evp Cap, OBD)	LD
20		ModelYr minus 24	ModelYr minus 2	12 (2500 RPM/Idle)	HD
41	2020 thru 2050	ModelYr minus 24	ModelYr minus 2	51 (Exh OBD)	LD
61		ModelYr minus 24	ModelYr minus 2	45 (Evp Cap, OBD)	LD
20		ModelYr minus 24	ModelYr minus 2	12 (2500 RPM/Idle)	HD

Source: Adapted from TTI, 2011a

A fundamental aspect of TTI’s emissions rates modeling was that MOVES was used to produce “per activity” emissions rates instead of the “per vehicle” default emissions generated by MOVES. The TTI MOVES activity inputs were essentially MOVES defaults divided to unity in the production of emission rates via post-processing of the MOVES activity and emissions output. The county-specific vehicle activity datasets (e.g., population, VMT, speed estimation, source hours parked/operating/idling) were not directly input into MOVES. Instead, total emissions for each county were calculated external to the MOVES application using the MOVES-predicted unit-based emissions rates and the county-specific vehicle activity datasets. Table B7 presents the emissions rate units with associated processes and activity factors used by TTI. The generation of unit-based emissions rates is appropriate to the development of the PET emissions rates as well.

**Table B7: Emissions rates by process and activity factor**

<b>Emissions Process</b>	<b>Activity*</b>	<b>Emissions Rate Units</b>
Running Exhaust	VMT	g/mile
Brake Wear	VMT	g/mile
Tire Wear	VMT	g/mile
Evaporative Permeation	VMT; SHP	g/mile; g/SHP
Evaporative Fuel Vapor Venting	VMT; SHP	g/mile; g/SHP
Evaporative Fuel Leaks	VMT; SHP	g/mile; g/SHP
Crankcase Running Exhaust	VMT	g/mile
Start Exhaust	Starts	g/start
Crankcase Start Exhaust	Starts	g/start
Crankcase Extended Idle Exhaust	SHI	g/SHI
Extended Idle Exhaust	SHI	g/SHI

\*SHP = Source Hours Parked; SHI = Source Hours Idling

Source: Taken from TTI, 2011a



## Appendix C. MOVES Sensitivity Studies

The publicly available TTI MOVES runscripts and databases for year 2012 were obtained from the Texas Commission on Environmental Quality (TCEQ) website ([ftp://amdaftp.tceq.texas.gov/pub/Mobile\\_EI/Statewide/mvs/](ftp://amdaftp.tceq.texas.gov/pub/Mobile_EI/Statewide/mvs/)) by Gary McGaughey during early November 2011. Sensitivity testing to establish the PET MOVES run configurations and final input datasets were performed using a non-specific set of input parameters based on the county group that included the Houston-Galveston-Brazoria (HGB) area. TTI simulated emissions for weekday, Friday, Saturday, and Sunday day types; however, our simulations were limited to the weekday scenario.

A number of changes were made to the TTI scripts and databases in support of the PET runs. The MOVES Run Specifications (MRS) and County Input Databases (CDB) are used to specify the MOVES run configuration and non-default (i.e., local) input data, respectively. When modeling at the county level, MOVES allows only one year to be simulated at a time, therefore, all occurrences of year in the MRS and CDB files were updated from 2012 to the appropriate base year (e.g., 2010). TTI used actual hourly temperature and relative humidity (obtained from TCEQ) for each of the 25 TxDOT districts to capture observed hourly meteorological conditions. For PET, the hourly temperature and relative humidity data were replaced with appropriate representative temperature and relative humidity values.

Table C1 shows the complete list of possible MOVES pollutants and the pollutants estimated in support of PET. VOC is a “chained” pollutant so that the explicit estimation of additional hydrocarbon compounds (Total Gaseous Hydrocarbons, Non-Methane Hydrocarbons, and Methane) were required but were subsequently dropped from the MOVES output during post-processing. In addition, the calculation of Total Energy Consumption (TEC) was needed to predict pollutants such as CO<sub>2</sub>.

TTI used one MRS for each combination of county group, day type, and year; however, for PET’s purpose, we expanded the number of MRS scripts for a given base year and county group to two. Since hour of day does not affect the predicted emissions rates for most on-road processes (e.g., running exhaust, crankcase running exhaust, brake wear, tire wear), one set of MRS input files were developed so that a single hour could be used for each combination of temperature and relative humidity. For most evaporative and off-network processes, (e.g., parked vehicles, engine starts, idling, and fuel vapor venting), the estimated MOVES emissions rates depend on temperature and hour of day. The hourly dependence of off-network emissions rates is associated with the assumptions of vehicle activity built into the MOVES model for processes such as hot soak times (e.g., hours since engine shut-off), number of engine starts, and idling activity. Thus, a second set of MRS scripts were developed for most off-network emissions that maintained a constant temperature for a daily (e.g., 24-hour) period.

Numerous MOVES simulations were performed to establish the final PET MOVES configurations and inputs. Commonly, sensitivity studies were conducted on various run parameters in order to establish the essential range of input variables for Texas. Given the relatively high CPU time of MOVES relative to MOBILE6 (hours versus minutes), sensitivity studies were necessarily focused and limited in scope. As appropriate, results from the most directly relevant studies are presented here. All sensitivity studies used the MOVES 2010 scenario for a non-specific Texas area based on the HGB county group.

**Table C1: MOVES pollutants and pollutants estimated in support of the PET project (highlighted rows)**

<b>MOVES Pollutant ID</b>	<b>Pollutant Or Process</b>	<b>Estimated?</b>
1	Total Gaseous Hydrocarbons	Y*
2	Carbon Monoxide (CO)	Y
3	Oxides of Nitrogen (NO <sub>x</sub> )	Y
5	Methane (CH <sub>4</sub> )	Y
6	Nitrous Oxide (N <sub>2</sub> O)	Y
20	Benzene	Y
21	Ethanol	
22	MTBE	
23	Naphthalene	
24	1,3-Butadiene	Y
25	Formaldehyde	Y
27	Acrolein	
30	Ammonia (NH <sub>3</sub> )	Y
31	Sulfur Dioxide (SO <sub>2</sub> )	Y
32	Nitrogen Oxide (NO)	
33	Nitrogen Dioxide (NO <sub>2</sub> )	
79	Non-Methane Hydrocarbons	Y*
80	Non-Methane Organic Gases	Y*
86	Total Organic Gases	
87	Volatile Organic Compounds (VOC)	Y
90	Atmospheric CO <sub>2</sub>	Y
91	Total Energy Consumption	Y*
92	Petroleum Energy Consumption	
93	Fossil Fuel Energy Consumption	
98	CO <sub>2</sub> Equivalent	
99	Brake Specific Fuel Consumption (BSFC)	
100	Primary Exhaust PM <sub>10</sub> – Total	Y
101	Primary PM <sub>10</sub> – Organic Carbon	Y*
102	Primary PM <sub>10</sub> – Elemental Carbon	Y*
105	Primary PM <sub>10</sub> – Sulfate Particulate	Y*
106	Primary PM <sub>10</sub> – Brakewear Particulate	Y
107	Primary PM <sub>10</sub> – Tirewear Particulate	Y
100	Primary Exhaust PM <sub>2.5</sub> – Total	Y
101	Primary PM <sub>2.5</sub> – Organic Carbon	Y*
102	Primary PM <sub>2.5</sub> – Elemental Carbon	Y*
105	Primary PM <sub>2.5</sub> – Sulfate Particulate	Y*
106	Primary PM <sub>2.5</sub> – Brakewear Particulate	Y
107	Primary PM <sub>2.5</sub> – Tirewear Particulate	Y
100	Primary Exhaust PM <sub>2.5</sub> – Total	Y

\*Required by MOVES but not maintained for input into PET.



## Road Types

MOVES calculates emissions for four on-road types as well as off-network activity. The MOVES road categories are aggregations of HPMS functional facility types that correspond to EPA Source Classification Codes (SCCs). Table C2 shows the road type mapping between MOVES and HPMS.

**Table C2: MOVES road types mapped to HPMS functional types**

MOVES Road Type ID	MOVES Road Type	HPMS Functional Type
1	Off Network	Off Network
2	Rural Restricted Access	Rural Interstate
3	Rural Unrestricted Access	Rural Principal Arterial, Minor Arterial, Major Collector, Minor Collector, & Local
4	Urban Restricted Access	Urban Interstate & Urban Freeway/Expressway
5	Urban Unrestricted Access	Urban Principal Arterial, Minor Arterial, Collector, & Local

Source: EPA (2010c)

Default drive cycles are used by MOVES to describe vehicle activity for each of the road type categories shown in Table C2. Restricted roads are accessed via an on-ramp; all other roads are captured by the unrestricted access categories. The MOVES driving cycles for unrestricted roads assume significant stop and go driving, with multiple accelerations, decelerations, and idling. In comparison, the driving cycles for restricted access roads have relatively higher fractions of cruise activity. For restricted roads, on-ramp driving can be specified in MOVES as a fraction of the overall vehicle activity; however, as assumed by TTI, the PET simulations maintained ramp activity at 0%.

Analysis of the MOVES results demonstrated that the emission rates for some SUT/fuel/pollutant combinations were substantially different between the unrestricted and restricted categories. Figure C1 compares rural restricted and unrestricted CO emissions rates for gasoline school buses, binned by vehicle speed. The 0–2.5 mph speed bin has the largest difference in CO emissions rates, with unrestricted and restricted emissions of 107.3 g/mile and 148.4 g/mile, respectively. On average across all school bus speeds, restricted emissions (51.4 g/mile) are 39% greater than unrestricted emissions (37.0 g/mile). For comparison of the school bus results to those for a more populous SUT, Figure C2 shows the CO results for gasoline passenger cars. The average emissions rate for rural unrestricted roads (2.93 g/mile) is 7.2% greater than that (2.74 g/mile) for rural restricted roads.

The differences in emissions rates shown in Figures C1 and C2 are driven by differences in the underlying drive cycles (e.g., fraction and simulated patterns of stop-and-go driving) associated with the restricted and unrestricted road types. Additional analysis demonstrated that the SUTs with the largest differences in emissions rates between the two road types are buses (school, inter-city, and transit) and refuse trucks.

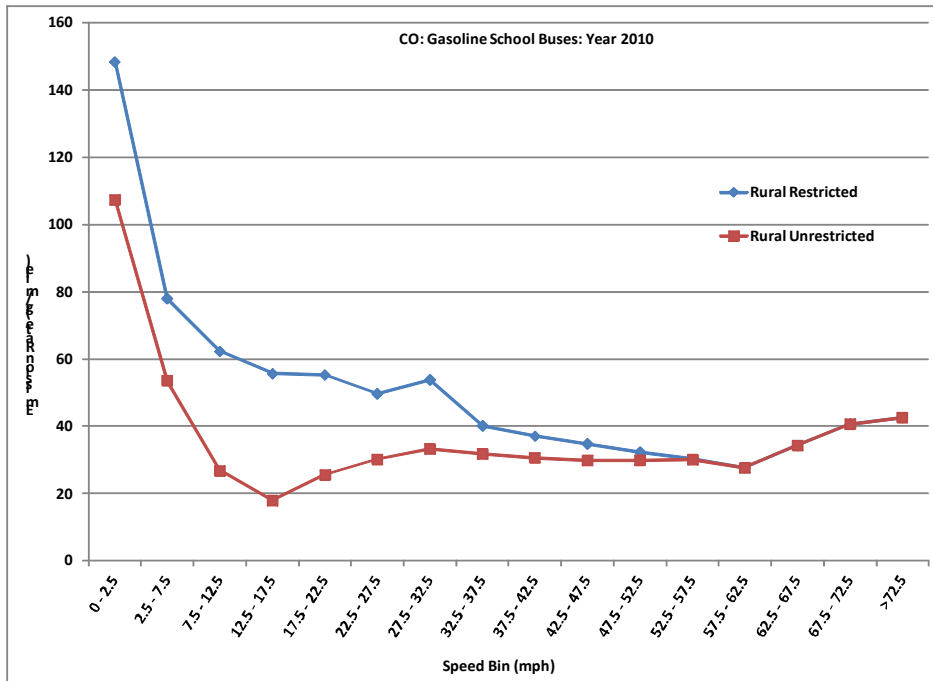


Figure C1: CO emissions rates (g/mile) by speed bin for gasoline school buses (model year 2010, relative humidity = 60%, temperature = 70F) for rural restricted and unrestricted roads

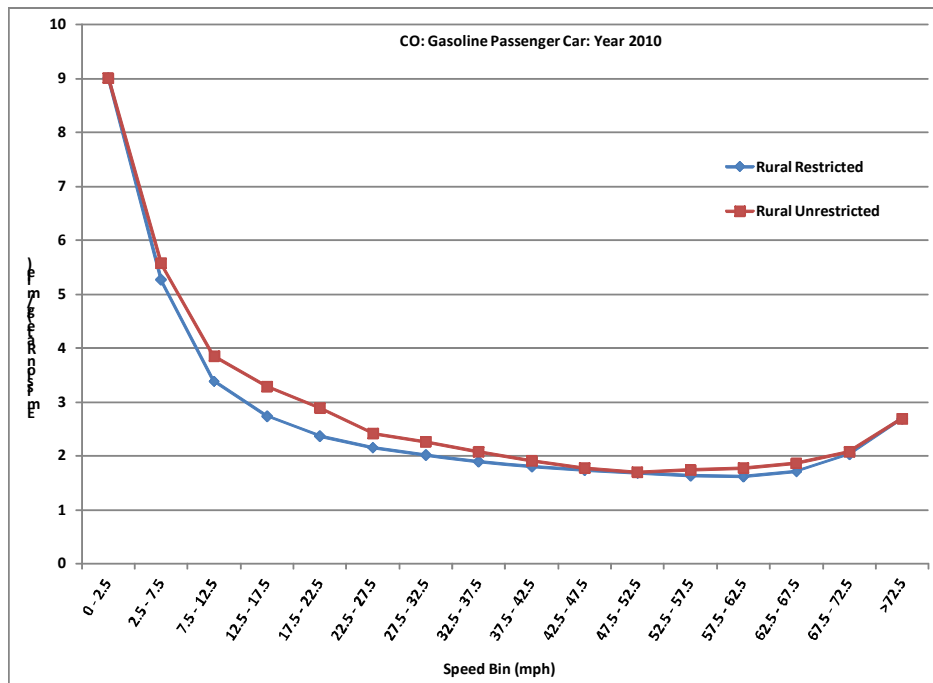


Figure C2: CO emissions rates (g/mile) by speed bin for gasoline passenger cars (model year 2010, relative humidity = 60%, temperature = 70F) for rural restricted and unrestricted roads

In contrast to the sometimes large differences in emissions rates between unrestricted and restricted roads, the predicted emissions rates for rural and urban roads were similar. There were no differences in emissions between the rural restricted and urban restricted categories for the 2010 HGB county group. In addition, differences between unrestricted road types were minimal. Figure C3 compares unrestricted rural and unrestricted urban NO<sub>x</sub> emissions rates for gasoline passenger cars (characterized by the largest urban/rural differences for any SUT/fuel/pollutant combination in our study) binned by vehicle speed. Significant differences are limited to the 32.5–62.5 mph range, with a maximum difference of 18% for the 42.5–47.5 mph category (0.39 g/mile for rural vs. 0.33 for urban). On average across all vehicle speeds in Figure C3, the rural unrestricted emission rate is 3.9% greater than the urban unrestricted emissions rate. The vast majority of SUT/fuel/pollutant categories for unrestricted roads were characterized by no differences between the rural and urban classifications.

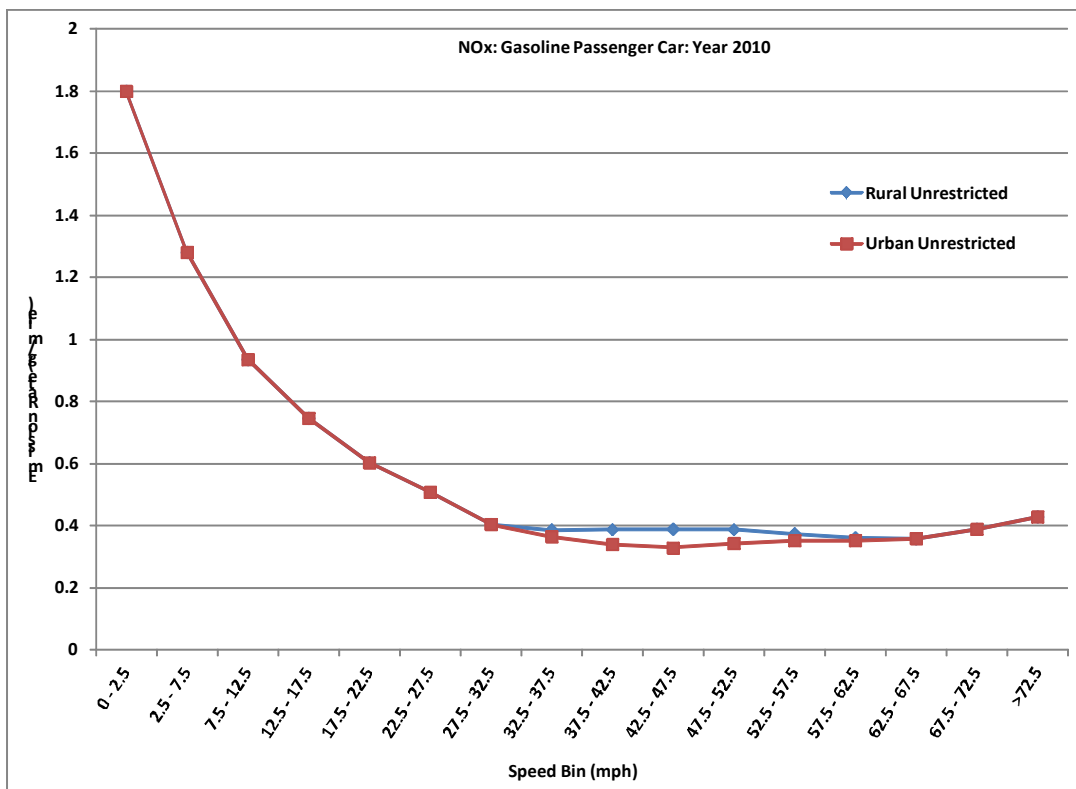


Figure C3: NO<sub>x</sub> emissions rates (g/mile) by speed bin for gasoline passenger cars (model year 2010, relative humidity = 60%, temperature = 90F) for unrestricted rural and urban roads

Given the substantial runtime of MOVES, it was desirable to limit the ranges of input variables wherever reasonable. Based on the road type sensitivity tests summarized here, we generated MOVES output for only urban restricted and urban unrestricted road types to be used for both rural and urban locations.

## Altitude

Altitude must be specified in MOVES as either “Low” or “High.” Altitude is entered for two reasons: (1) older vehicles tend to have higher emissions at high altitude compared to low

altitude, and (2) barometric pressure is required for some MOVES calculations (EPA, 2010b). For all PET simulations, we selected “Low,” which was also used by TTI and is appropriate for all of Texas with the possible exception of small mountainous regions such as the Guadalupe Mountains in far western portions of the state.

### Age and Fuel-Engine Fraction Distributions

For the TTI 2012 MOVES simulations, age distributions (ranging from 0 years [new] to 30 years) and fuel-engine (i.e., diesel) fractions (FEF) were developed using TxDOT mid-2010 county registrations data and MOVES model defaults, as needed. The age distributions were based on vehicle registration aggregations for each TxDOT district consistent with the vehicle registration aggregations used in estimating the SUT/fuel VMT mix. Table C3 summarizes the data sources and aggregations criteria. As an example of results, Figure C4 presents the age distributions for passenger cars and combination long-haul trucks. The 2010 age distributions and FEF data developed by TTI were used in support of all PET simulations.

**Table C3: TTI data sources and aggregations for SUT age distributions and fuel-engine fractions (FEFs)**

MOVES SUT ID	SUT Description	TxDOT category aggregations*	Geographic aggregations for age	Geographic aggregations for FEFs
11	Motorcycle	Motorcycles	TxDOT District	NA – 100% gas, no FEFs
21	Passenger Car	Passenger	TxDOT District	MOVES defaults
31	Passenger Truck	Total Trucks <= 8500	TxDOT District	MOVES defaults
32	Light Commercial Truck	Total Trucks <= 8500	TxDOT District	MOVES defaults
41	Single Unit Short-Haul Truck	>8500+ > 10000+ >14000+ >16000+	TxDOT District	Statewide
42	Single Unit Long-Haul Truck	>8500+ > 10000+ >14000+ >16000+	Statewide	Statewide
43	Refuse Truck	MOVES defaults		
51	Motor Home			
52	Intercity Bus			
53	Transit Bus			
54	School Bus			
61	Combination Short-Haul Truck	>19500+ > 26000+ >33000+ >60000+	TxDOT District	Statewide
62	Combination Long-Haul Truck	>19500+ > 26000+ >33000+ >60000+	Statewide	NA – 100% diesel, no FEFs

\*Numerical values are vehicle weight in pounds.

Source: Adapted from TTI, 2011a

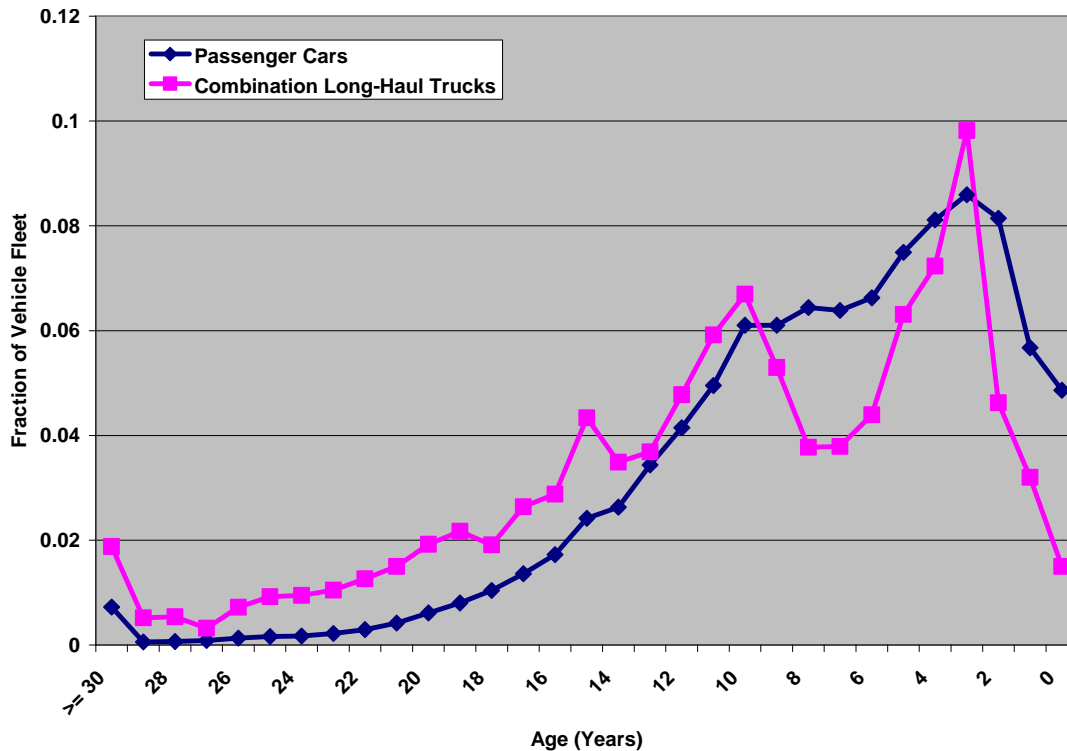


Figure C4: TTI age distributions for the 2012 HGB county group for (1) passenger cars (TxDOT district data), and (2) combination long-haul trucks (statewide data)

## Relative Humidity

Relative humidity affects running exhaust emissions predicted by MOVES for gasoline and diesel vehicles through two mechanisms: (1) directly via a humidity correction factor for NO<sub>x</sub>, and (2) indirectly via an air conditioning adjustment (the temperature and humidity is used to calculate the heat index value, which in turn is used to predict the fraction of the vehicle fleet with in-use air conditioning [EPA, 2010b]).

To analyze the sensitivity of emissions rates to relative humidity, a meteorological MOVES input file was developed that varied temperature in 10°F increments between 20°F and 100°F and relative humidity in 10% increments between 20% and 90%. Each combination of temperature and relative humidity was used to estimate emissions. The ranges of temperature and relative humidity were chosen to be representative of hourly meteorological conditions that occur (above some minimal frequency) during a typical year in Texas. For a given temperature and SUT/fuel/pollutant combination, the minimum and maximum emissions rates across the range of simulated relative humidity values were compared to quantify the amount of variability associated solely with changes in relative humidity at a given simulated temperature.

The vast majority of meteorological scenarios demonstrated that changes in relative humidity had no or little impact on predicted emissions rates and rate differences greater than 10% were limited to CO and NO<sub>x</sub>. Figure C5 presents example CO results for gasoline passenger cars. At temperatures of 70°F and lower emissions are not affected by the choice of relative humidity value. At higher temperatures, CO emissions increase as relative humidity increases due to an assumed increase in the fraction of vehicles with in-use air conditioning. The largest

variation in emissions rates for a single temperature occurred at 90°F, which has a maximum difference in emissions of 23% (minimum: 3.7 g/mile at 20% relative humidity, maximum: 4.5 g/mile at >80% relative humidity).

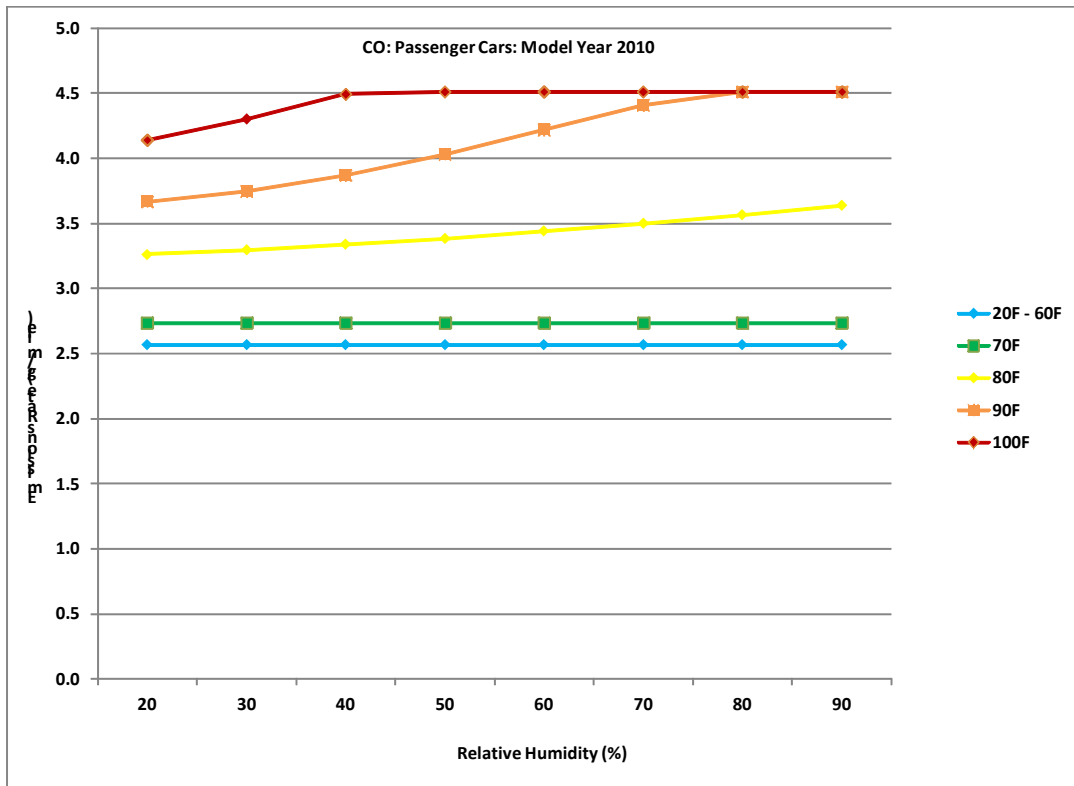


Figure C5: Average CO emission rates (g/mile) versus relative humidity for gasoline passenger cars (model year 2010, restricted urban roads) by constant temperature

Of all pollutants simulated, predicted NO<sub>x</sub> emissions had the most sensitivity to changes in relative humidity. Figure C6 presents the NO<sub>x</sub> emissions rate results for gasoline passenger cars. At temperatures less than 50°F, emissions were minimally affected by changes in relative humidity. For temperatures of 50–80°F, increasing relative humidity is associated with decreasing NO<sub>x</sub>. At higher temperatures, increases in relative humidity from moderate to maximum values are associated with no change (100°F) or increases (90°F) in NO<sub>x</sub> emissions. The largest change in emissions rates across a constant temperature was 32% (minimum: 0.37 g/mile at >70% relative humidity, maximum: 0.48 g/mile at 20% relative humidity) at 70°F. Additional analysis demonstrated that the greatest difference in minimum/maximum NO<sub>x</sub> emissions rates for any combination of SUT/fuel/temperature was 44% for several gasoline SUTs (refuse truck, combination and single unit trucks, motor homes, school buses, motorcycles) at simulated temperatures of 80°F.

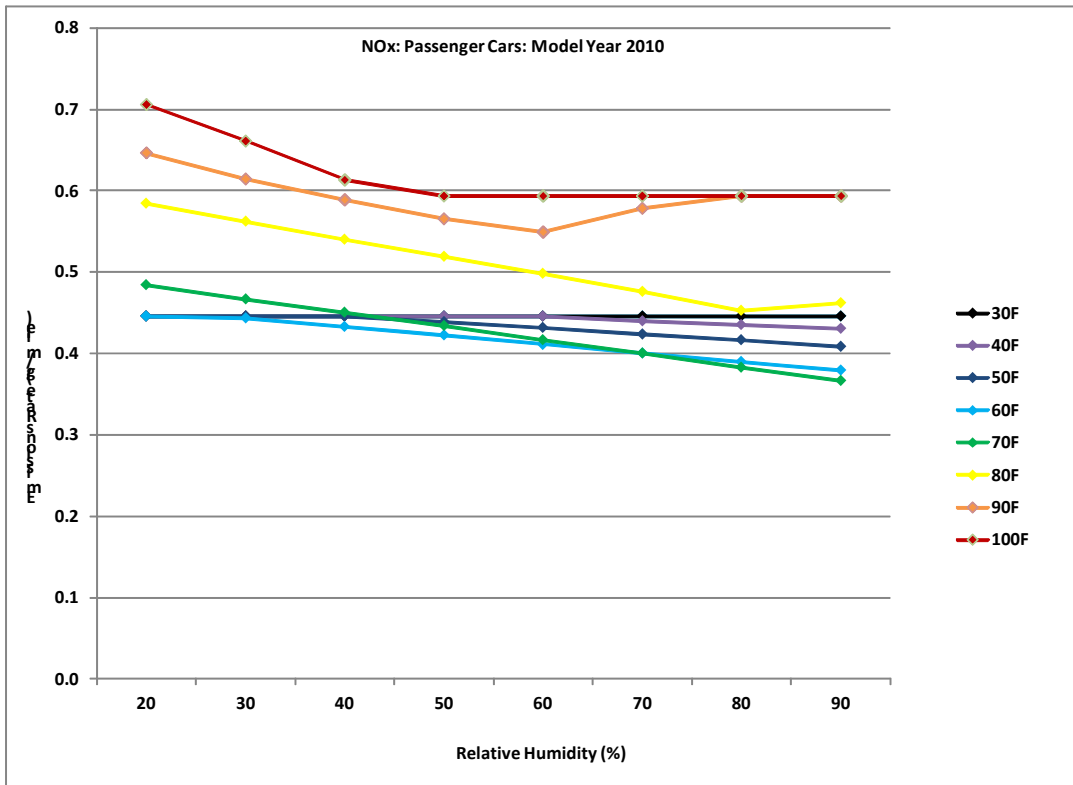


Figure C6: Average NO<sub>x</sub> emission rates (g/mile) versus relative humidity for gasoline passenger cars (model year 2010, unrestricted urban roads) by constant temperature

Based on the MOVES climatological data for all 254 Texas counties, the annual average relative humidity is 62%. For the PET simulations, we originally proposed to use a constant relative humidity value of 60%. Setting the relative humidity at 60% captures an emissions rate for a given temperature that is often (but not always) representative of average conditions across the range of relative humidity values as opposed to the extreme emissions rates that are most often predicted at very dry or very moist conditions. Ultimately (as described in the body text of this memorandum), the PET simulations were limited to summer and winter scenarios; however, given the sometimes significant change in emissions rates associated with varying relative humidity values, future versions of PET could consider the inclusion of additional meteorological scenarios.

## Temperature

Ambient temperature affects running exhaust emissions rates predicted by MOVES for gasoline and diesel vehicles through three mechanisms: (1) directly via a temperature correction factor for NO<sub>x</sub>; (2) indirectly via an air conditioning adjustment (the temperature and humidity is used to calculate the heat index value, which in turn is used to predict the fraction of vehicles with in-use air conditioning); and (3) changes in the rate of VOC emissions processes such as evaporation from fuel leaks, engine block permeation, and vapor venting from fuel tanks. In addition to impacts on both running and off-network evaporative processes, temperature is also important in the calculation of emissions associated with off-network vehicle starts.

The MOVES database includes climatological monthly average diurnal hourly temperature profiles for each US county (thus, a given county has 24 hours \* 12 months = 288 hourly temperatures). Figure C7 shows the annual number of monthly average hourly temperatures within eight temperature ranges for four representative regions of Texas. The selection of Texas areas shown in Figure C7 was somewhat subjective, but covers a wide range of geographic regions ranging from Amarillo in the Texas Panhandle, to the highly populated metropolitan areas of DFW, HGB, and San Antonio.

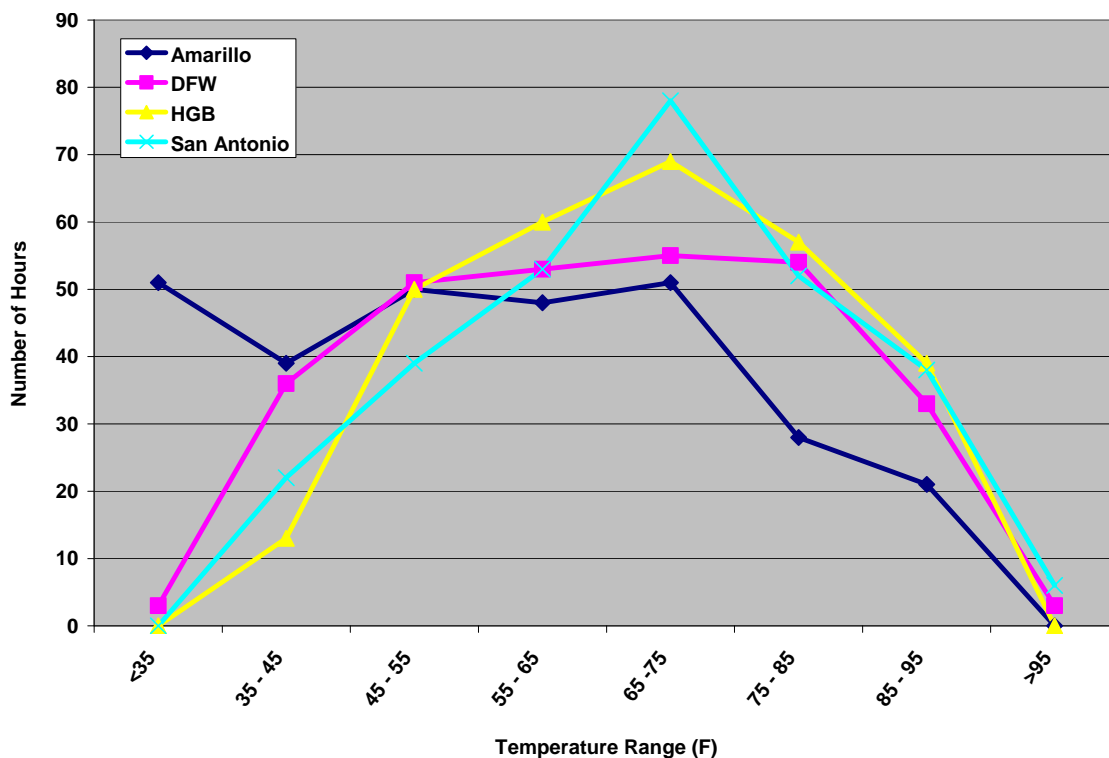


Figure C7: Annual number of hours binned by MOVES climatological temperatures for Potter County (Amarillo), Dallas County (DFW), Harris County (HGB), and Bexar County (San Antonio)

The range of temperatures used for the MOVES sensitivity studies was specified to be representative of the most common conditions that typically occur over the eastern half of Texas, which is characterized by the highest human and vehicle populations. Based on the frequency of occurrence of average monthly hourly temperatures shown in Figure C7, we selected four temperatures for input to the MOVES sensitivity simulations: 40°F, 60°F, 80°F, and 100°F. For PET's purposes, these four temperatures could be characterized as cold, cool, warm, and hot, respectively. Although temperatures as warm as 100°F were uncommon in the MOVES hourly temperature database, we chose to include 100°F in the sensitivity studies to represent especially hot daytime conditions during the summer. The most recent year (2011) was characterized by all-time record dry and hot conditions over most of Texas, and daily maximum temperatures exceeded 100°F on a majority of June–August days over most of the state ([http://atmo.tamu.edu/osc/library/osc\\_pubs/2011\\_drought.pdf](http://atmo.tamu.edu/osc/library/osc_pubs/2011_drought.pdf)). In contrast, we chose not to



simulate temperatures as cold as 20°F because: (1) extremely cold temperatures are uncommon over the most highly populated regions of Texas, and (2) the coldest temperatures typically occur during the nighttime hours when vehicle traffic would be expected to be light, though very cold mornings may overlap with portions of the morning rush hour during winter.

Sensitivity tests demonstrated that ambient temperature has substantial impacts on emissions for some on-road running processes for specific combinations of SUT/fuel/pollutant. As examples, Figures C8 and C9 present exhaust emissions rates from gasoline passenger trucks for NO<sub>x</sub> and PM<sub>2.5</sub>, respectively, binned by vehicle speed. For both pollutants, the largest differences in emissions rates occur at the lowest speeds; the highest emissions of NO<sub>x</sub> and PM<sub>2.5</sub> are associated with the warmest and coldest temperatures, respectively.

For off-network processes, changes in temperature are often associated with relatively large impacts (measured as the percent change between the minimum and maximum emission rates across the simulated range of temperatures) on predicted emissions. Example results for vehicle starts, which are affected by both temperature and hour of day, are shown in Figure C10 for CO from motorcycles and in Figure C11 for PM<sub>2.5</sub> for combination short-haul trucks. For both CO and PM<sub>2.5</sub>, emissions rates increase as temperature decreases.

Some of the largest overall impacts of temperature on emissions are predicted for VOC evaporative processes for gasoline SUTs. Evaporative rates for parked vehicles (i.e., fuel tank venting, engine block permeation, and fuel leaks) depend on both temperature and hour of day since MOVES incorporates a number of assumptions about the vehicle fleet for each hour (e.g., the amount of time since a vehicle was last running as well as the duration of running time). In addition, emissions associated with fuel tank venting are dependent on the daily (e.g., 24-hour) profile of temperatures.

Figure C12 demonstrates the impact of ambient temperature on VOC emissions associated with evaporative permeation from parked gasoline light commercial trucks. The average daily emission rate at 100°F (0.21 g/vehicle) is approximately 10 times larger than the average rate at 40°F (0.02 g/vehicle). Note that the evaporative permeation rates show little variation throughout the day. Sensitivity studies of on-road evaporative emissions (not shown) indicated that fuel leaks and fuel vapor venting were characterized by little temperature or hour of day variability. (Note that the fuel vapor venting studies assumed a flat diurnal temperature profile [e.g., constant temperature].) For on-road running evaporative permeation, the minimum and maximum hourly emissions rates for physically large SUTs (e.g., single unit and combination trucks) varied by up to a factor of two or higher; however, the hourly variability for the most common gasoline vehicles (e.g., passenger cars and trucks) was minimal.

The example results in Figures C8–C12 demonstrate that ambient temperature can substantially impact predicted emissions rates for some SUT/fuel/pollutant combinations for both on-road running and off-network emissions processes. Ultimately (as described in the body of this memorandum), the PET simulations were limited to summer and winter scenarios; however, given the sometimes substantial change in emissions rates associated with variations in ambient temperature, future versions of PET could consider the inclusion of additional meteorological scenarios.

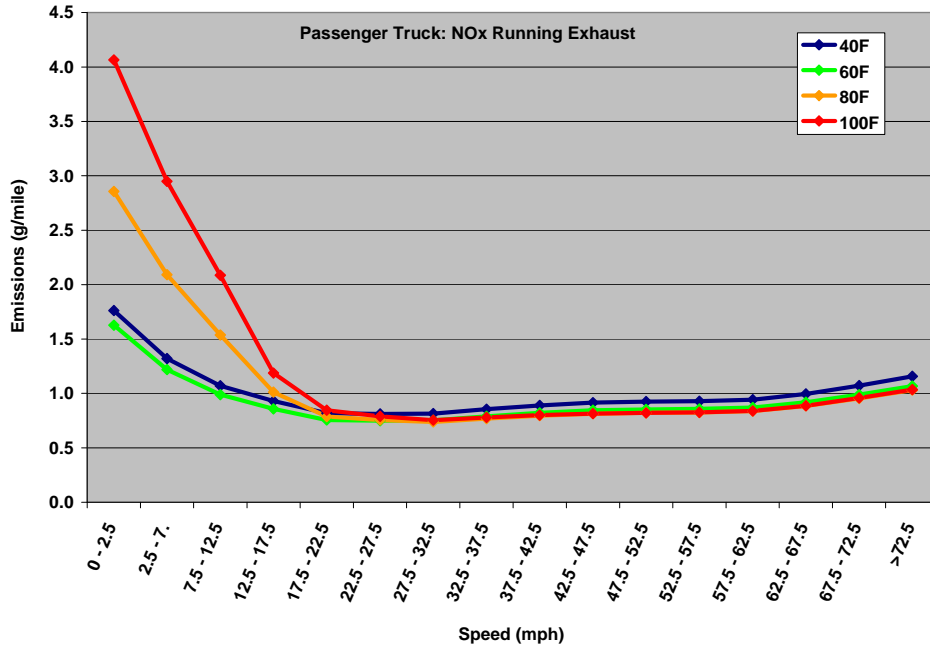


Figure C8: Average running exhaust NO<sub>x</sub> emission rates (g/mile) for ambient temperatures of 40°F, 60°F, 80°F, and 100°F for gasoline passenger trucks (model year 2010, restricted urban roads) binned by vehicle speed

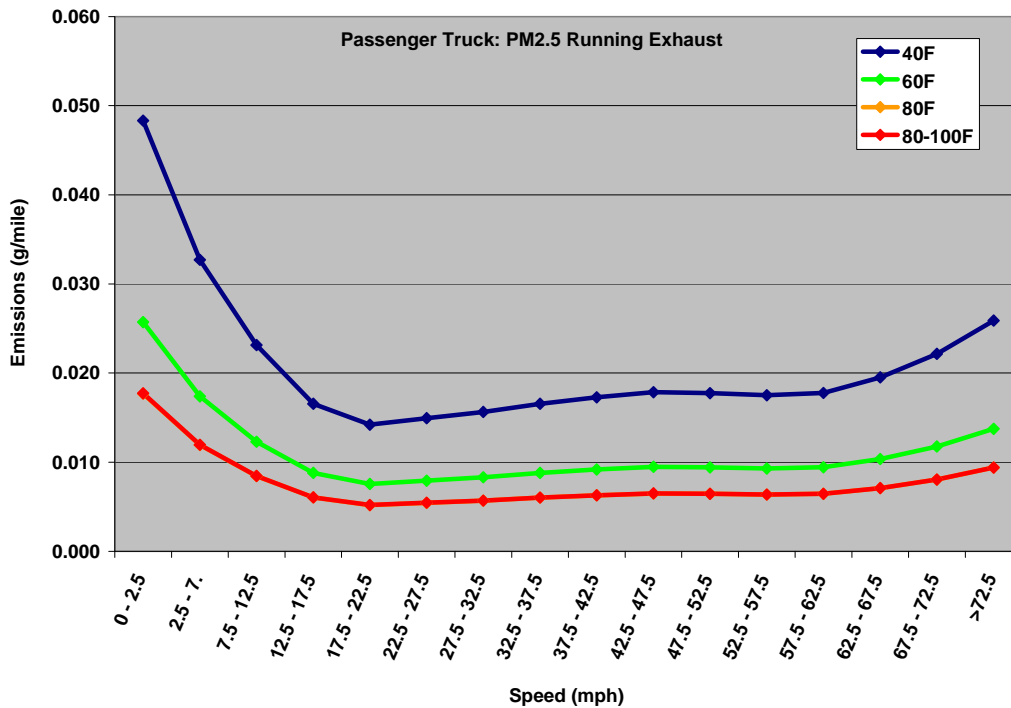


Figure C9: Average running exhaust PM<sub>2.5</sub> emission rates (g/mile) for ambient temperatures of 40°F, 60°F, 80°F, and 100°F for gasoline passenger trucks (model year 2010, restricted urban roads) binned by vehicle speed

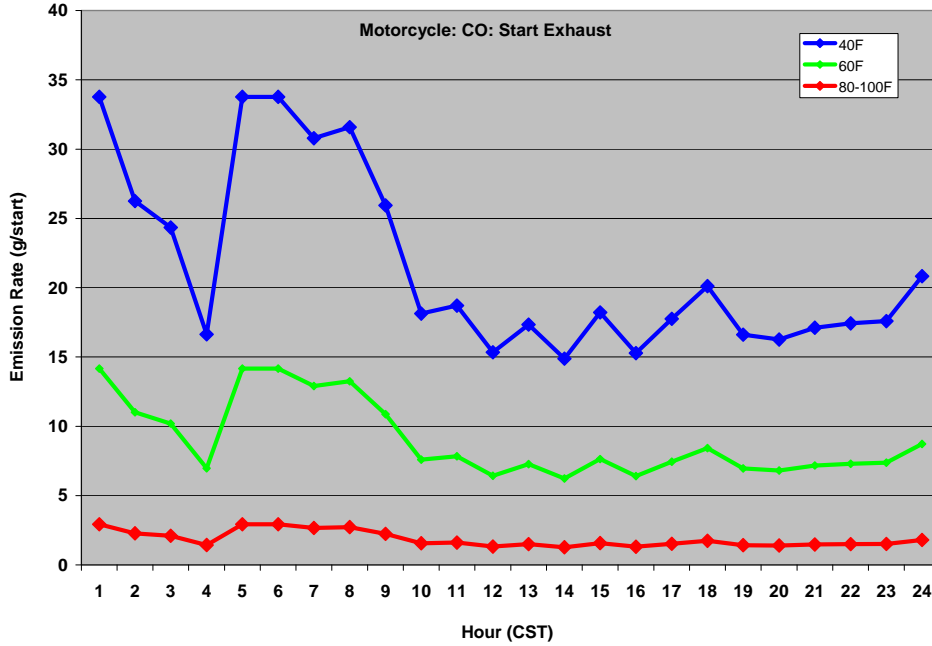


Figure C10: Average starting exhaust CO emission rates (g/start/vehicle) at ambient temperatures of 40°F, 60°F, 80°F, and 100°F for motorcycles (model year 2010, restricted urban roads) by hour of day

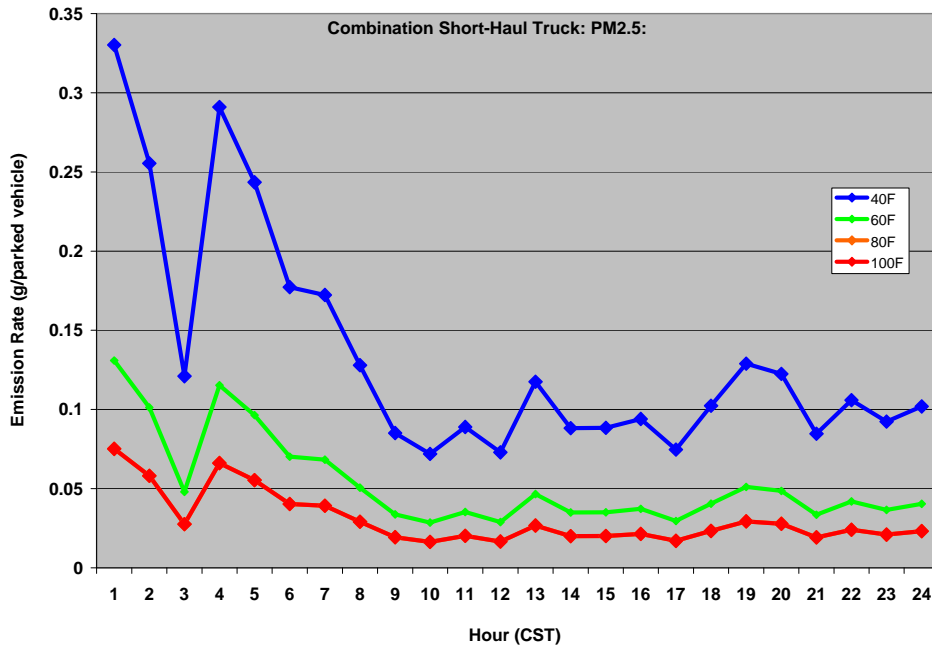


Figure C11: Average starting exhaust PM<sub>2.5</sub> emission rates (g/start/vehicle) at ambient temperatures of 40°F, 60°F, 80°F, and 100°F for gasoline combination short-haul trucks (model year 2010, restricted urban roads) by hour of day

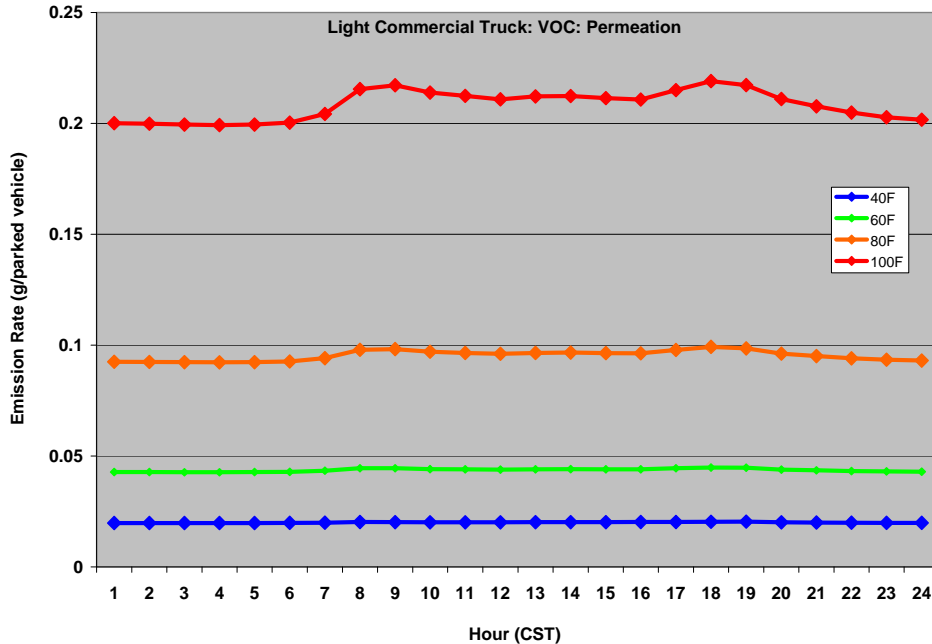


Figure C12: Average evaporative VOC emission rates (g/vehicle) associated with engine permeation at ambient temperatures of 40°F, 60°F, 80°F, and 100°F for gasoline light combination trucks (model year 2010, restricted urban roads) by hour of day

## Off-Network Emissions

MOVES automatically generates off-network emissions rates that are intended to be applied to the total vehicle population. For example, hourly evaporative emissions for each combination of SUT/fuel would be estimated as the total vehicle population (regardless of the percentage of vehicles operating for any given hour) multiplied by the grams per vehicle emissions rate. For PET, we converted the per vehicle emissions rates to per activity rates (e.g., convert emissions from grams per vehicle to grams per vehicle start) via additional post-processing and merging of information among multiple MOVES output tables.

The CPU requirements for the calculation of evaporative and off-network emissions are substantially greater than those for on-road processes. The selection of MOVES inputs (and sensitivity runs) to estimate off-network emissions was informed by the relative contributions of emissions processes to the overall mobile source emissions inventory. As previously discussed, TTI (2010c) estimated summer (June 1–August 31) emissions for on-road and off-network vehicles for the years 2006, 2008, 2012, and 2018 for each of 254 Texas counties. Table C4 presents a summary of the TTI 2012 mobile source emissions inventory for selected pollutants for Harris County, categorized by MOVES emissions process.

**Table C4: Summer weekday emissions (tons) estimated by MOVES for gasoline and diesel vehicles in Harris County for 2012**

	CO	NO <sub>x</sub>	SO <sub>2</sub>	CO <sub>2</sub>	PM <sub>10</sub>	PM <sub>2.5</sub>	VOC
Total Emissions in Tons	524.4	104.1	1.0	58189.6	5.2	3.4	45.4
<b>On-Road Running Processes (as a percent of total emissions)</b>							
Running Exhaust	68.7%	79.8%	96.1%	97.7%	46.8%	67.3%	24.2%
Crankcase Exhaust	0.0%	0.0%	1.6%	0.0%	7.2%	10.5%	0.4%
Brakewear					30.3%	11.9%	
Tirewear					11.2%	4.0%	
Evaporative Permeation							0.5%
Evaporative Vapor Venting							5.4%
Evaporative Fuel Leaks							2.2%
Total On-Road Running	68.8%	79.8%	97.6%	97.7%	95.6%	93.8%	32.7%
<b>Off-Network Processes (as a percent of total emissions)</b>							
Start Exhaust	30.8%	17.0%	2.2%	2.0%	3.3%	4.6%	40.2%
Crankcase Start	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.5%
Idle Exhaust	0.4%	3.3%	0.1%	0.4%	0.8%	1.2%	1.9%
Idle Crankcase	0.0%	0.0%	0.0%	0.0%	0.2%	0.2%	0.0%
Evaporative Permeation							12.4%
Evaporative Vapor Venting							7.9%
Evaporative Fuel Leaks							4.4%
Total Off-Network	31.2%	20.2%	2.4%	2.3%	4.4%	6.2%	67.3%

Source: Developed from TTI, 2011a

Based on the summary shown in Table C4, emissions of CO and NO<sub>x</sub> are dominated by on-road running exhaust with significant contributions from off-network starting exhaust, while the vast majority of SO<sub>2</sub> and CO<sub>2</sub> emissions are associated with on-road running exhaust only. For PM<sub>10</sub> and PM<sub>2.5</sub>, emissions from running exhaust are most important, but emissions from crankcase exhaust, brake wear, tire wear, and starting exhaust activities have important contributions as well. In contrast to the other pollutants shown in Table C4, VOC emissions are dominated by off-network processes. The majority of VOC emissions are associated with off-network starts (40.2%), followed by off-network evaporative processes (24.7%), running exhaust (24.2%), and on-road running evaporative processes (8.1%).

Examples of the variation in hourly emissions rates for vehicle starts at ambient temperatures of 40°F, 60°F, 80°F, and 100°F are shown in Figures C13 and C14. For gasoline passenger cars, Figure C13 shows that VOC starting exhaust emissions are highest at the coldest temperatures and during the morning hours, which suggests that the percent cold starts in the parked vehicle fleet dominates the changes in emissions for a given temperature. As shown in Figure C14, there is extremely large variability in hourly emissions of PM<sub>2.5</sub> starting exhaust from diesel single unit short haul trucks, ranging from 0.0008 g/start for hour 14 to 0.0579 for hour 5. Also note that emissions rates are not calculated for the late night and early morning (i.e.,

hours 21–4) because the MOVES default activity data for this particular SUT/fuel combination assumes zero hourly vehicle starts during this time period.

As shown in Figure C15, evaporative VOC permeation emissions from parked gasoline school buses increase substantially as ambient temperature increases. Also note the assumed lack of school bus activity by MOVES during the late night and early morning hours. For gasoline passenger cars (Figure C16), VOC fuel vapor venting emissions from parked vehicles increase as ambient temperature increases and the hourly emissions rates are associated with substantial hour-to-hour variability. At 100°F, the minimum and maximum emissions rates are 0.002 g/vehicle (hour 4) and 0.12 (hour 19) g/vehicle, respectively.

The example off-network results shown in Figures C13–C16 demonstrate that emissions rates often show substantial hour-to-hour variability as well as sensitivity to ambient temperature. Since PET does not explicitly simulate the entire vehicle fleet, off-network processes were limited to vehicle starts and evaporative processes were not simulated for parked vehicles. The omission of evaporative emissions from parked vehicles means PET will under-predict area-wide emissions of VOC and benzene compared to a full MOVES simulation. Based on TTI’s previous Harris County work for summer 2012 (Table C4), evaporative emissions from on-road running and parked vehicles accounted for approximately 8% and 25%, respectively, of county-wide total VOC emissions from mobile sources. The contribution from evaporative processes will be somewhat smaller for other (cooler) seasons of the year. For PET’s purposes, the impact of assumptions used in the estimation of evaporative emissions should be mitigated since PET is designed to quantify differences between a base case and an alternative scenario as opposed to predicting absolute emissions rates; however, it is recommended that any future enhancements to PET revisit the treatment of evaporative emissions.

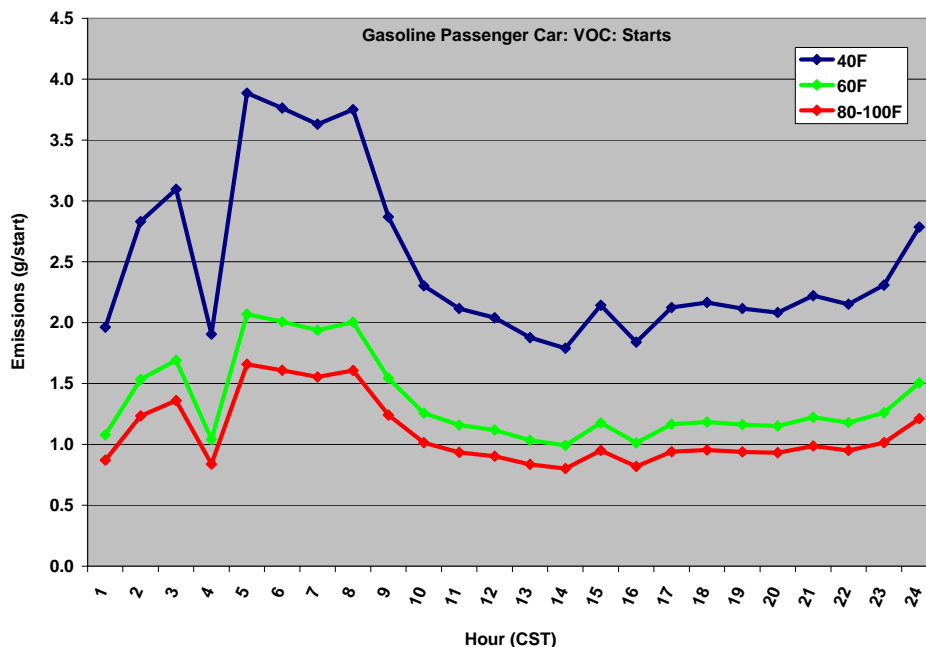


Figure C13: Hourly VOC starting exhaust emissions (g/start/vehicle) for gasoline passenger cars at ambient temperatures of 40°F, 60°F, 80°F, and 100°F (model year 2010, restricted urban roads) by hour of day

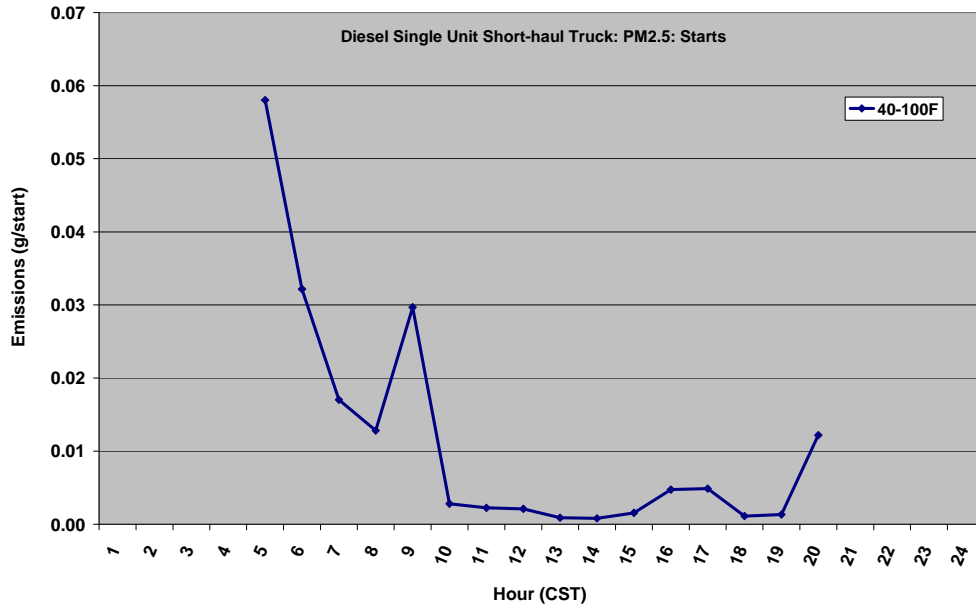


Figure C14: Temperature-independent hourly PM<sub>2.5</sub> starting exhaust emissions (g/start/vehicle) for diesel short haul trucks (model year 2010, restricted urban roads) by hour of day

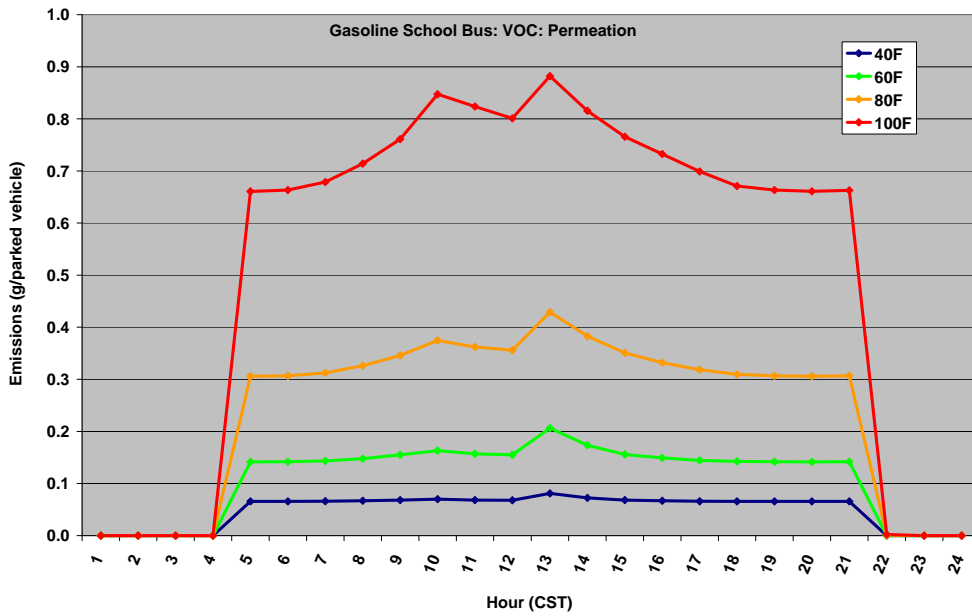


Figure C15: Hourly VOC emissions (g/vehicle) associated with evaporative permeation for parked gasoline school buses at ambient temperatures of 40°F, 60°F, 80°F, and 100°F (model year 2010, restricted urban roads) by hour of day

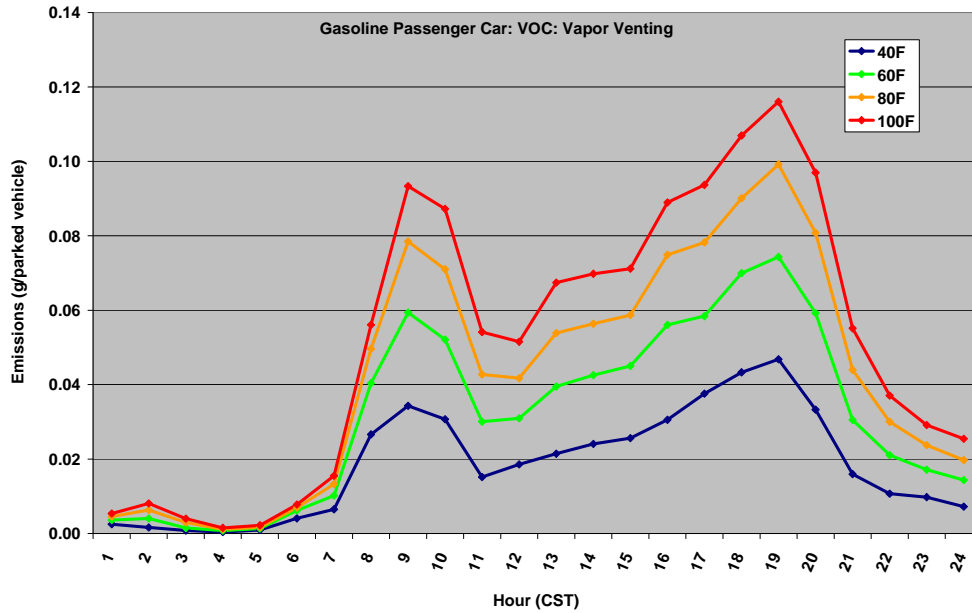


Figure C16: Hourly VOC emissions (g/vehicle) associated with evaporative vapor venting for parked gasoline passenger cars at ambient temperatures of 40°F, 60°F, 80°F, and 100°F (model year 2010, restricted urban roads) by hour of day