# Highway Case Study Investigation and Sensitivity Testing Using the Project Evaluation Toolkit

**by**

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**Thesis**

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# Dedication

This thesis is dedicated to my loving wife Amy, for her unwavering support and boundless affection.

# Acknowledgements

Many individuals contributed to this thesis either directly or through their work in the development of the Project Evaluation Toolkit that is the basis of this document. Dr. Kara Kockelman in particular has served as an excellent mentor, providing guidance, reviewing my work, and stretching my abilities. Her vision has helped guide the Project Evaluation Toolkit to its current state, and I am continually grateful to have access to her insight and wisdom.

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# Abstract

## Highway Case Study Investigation and Sensitivity Testing Using the Project Evaluation Toolkit

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As transportation funding becomes increasingly constrained, it is imperative that decision makers invest precious resources wisely and effectively. Transportation planners need effective tools for anticipating outcomes (or ranges of outcomes) in order to select preferred project alternatives and evaluate funding options for competing projects.

To this end, this thesis work describes multiple applications of a new Project Evaluation Toolkit (PET) for highway project assessment. The PET itself was developed over a two-year period by the thesis author, in conjunction with Dr. Kara Kockelman, Dr. Chi Xie, and some support by others, as described in Kockelman et al. (2010) and the PET Users Guidebook (Fagnant et al. 2011). Using just link-level traffic counts (and other parameter values, if users wish to change defaults), PET quickly estimates how transportation network changes impact traveler welfare (consisting of travel times and operating costs), travel time reliability, crashes, and emissions. Summary measures (such as net present values and benefit-cost ratios) are developed over multi-year/long-term horizons to quantify the relative merit of project scenarios.

This thesis emphasizes three key topics: a background and description of PET, case study evaluations using PET, and sensitivity analysis (under uncertain inputs) using PET. The first section includes a discussion of PET's purpose, operation and theoretical behavior, much of which is taken from Fagnant et al. (2010). The second section offers case studies on capacity expansion, road pricing, demand management, shoulder lane use, speed harmonization, incident management and work zone timing along key links in the Austin, Texas network. The final section conducts extensive sensitivity testing of results for two competing upgrade scenarios (one tolled, the other not); the work examines how input variations impact PET outputs over hundreds of model applications.

Taken together, these investigations highlight PET's capabilities while identifying potential shortcomings. Such findings allow transportation planners to better appreciate the impacts that various projects can have on the traveling public, how project evaluation may best be tackled, and how they may use PET to anticipate impacts of projects they may be considering, before embarking on more detailed analyses and finalizing investment decisions.

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## INTRODUCTION

As a consequence of global recession, governments around the world are trimming budgets (Economist 2011a, 2011b and 2011c). The Highway Trust Fund's surplus has disappeared, and funding for transportation projects has become increasingly constrained. Revenue streams from gasoline taxes have fallen, as federal gas taxes and light-duty-vehicle fuel economies have remained constant (at 18.4 cents per gallon [Jackson 2006] and 20 miles per gallon [EPA 2010], respectively, since 1997). At the same time, construction prices are rising, showing 59% increases between 2000 and 2009 among six representative states (WSDOT 2011). Meanwhile, transportation needs are increasing. Between 1984 and 2009 the United States population grew by 30% (US Census Bureau 2000 and 2009) while VMT rose 71% (FHWA 2009).

These changes have resulted in federal legislation (SAFETEA-LU) calling for transportation agencies to conduct comprehensive project evaluation before funding large scale projects (FHWA 2010b). The U.S. Governmental Accountability Office (GAO) found that "the largest highway, transit and safety grant programs distribute funds through formulas that are typically not linked to performance and, in many cases, have only an indirect relationship to needs" (2008 p. 31). And 34 surveyed state DOTs responded (to a GAO survey) that political support and public opinion are very important when making funding decisions, compared to only 8 that expressed the same level of importance for benefit-cost (B/C) ratios. The GAO notes that these measures are important, by stating "Rigorous economic analysis, applied to benefit-cost studies, is a key tool for targeting investments" (2008 p. 37). In order to accomplish this goal, transportation agencies must develop and apply tools to predict project impacts. In essence, transportation professionals must determine (and then pursue) the most socially beneficial and budget-sensitive projects they can, under tight funding constraints.

This paper details one such toolkit for the analysis of major highway capacity expansion and tolling project applications. Kockelman et al.'s (2010) Project Evaluation Toolkit or PET allows users to quickly and with minimal input ascertain trip tables for abstracted networks (Xie et al. 2010), anticipate demand shifts under different network scenarios, and generate a host of project-evaluation metrics for side-by-side comparison. PET anticipates emissions, crashes, traveler welfare, and network reliability impacts, relative to Base Case network conditions, and relies on user specification of project costs to estimate long-term performance metrics (like internal rates of return, benefit-cost ratios, and net present values).

PET also enables sensitivity testing of project impacts, by allowing users to randomize 28 sets of parameters (including values of travel time, link performance parameters, demand elasticities, and regional growth rates, among others). Sensitivity testing allows basic project assumptions to exhibit a degree of uncertainty and vary over the course of multiple trial runs, producing a distribution for possible outcomes and giving analysts a sense of risks and rewards across project alternatives.

An appreciation of the likely distributions of project outcomes is essential to wise decision making, since actual outcomes can be much different than those expected. Standard & Poor's Bain and Plantagie (2004) describe much of this problem, noting that estimates for some project types have not only been inaccurate, but biased overall. In this light, transportation planners, policymakers and investors may opt for a project with more certain benefits, rather than one with slightly greater predicted benefits, but also a greater degree of uncertainty (with some outcomes which may be particularly bad).

Additionally, agencies may wish to package projects with a significant degree of risk as a public-private partnership (Bain and Plantagie 2007).

This thesis examines the potential impacts for a variety of distinct highway-related projects for Austin, Texas. Projects include link expansion and toll settings, demand management, shoulder lane use, speed harmonization, incident management and construction phasing alternatives. The variance in model outputs is examined in greater detail for two of these projects (expansion and tolling scenarios) by varying 28 sets of model inputs (largely behavioral parameters) – one set at a time and in combination – in order to better understand the impacts of multiple degrees of uncertainty across project scenario alternatives. Simulation results suggest how much uncertainty exists in model predictions, with regression results (for output prediction) identifying key assumptions and inputs.

## BACKGROUND AND LITERATURE REVIEW

### Existing Transportation Project Evaluation Models

Currently, several tools exist for highway project evaluation. Most of these are either limited in scope to single corridor analysis (such as HERS-ST or Cal-BC) or very detailed (such as regional transportation planning models). The Project Evaluation Toolkit described in this paper takes a middle road, using an abstracted network of as many links as analysts wish to include for assessing broad travel pattern changes without the extensive detail required for a fully developed travel demand model. Furthermore, while many existing toolkits analyze certain impacts, none evaluates as many output measures (such as travel time reliability and internal rates of return across random inputs of parameter simulations).

The FHWA's Highway Economic Requirements System – State Version (HERS-ST) evaluates project impacts based on pavement quality, operating costs, safety costs, travel time changes and emissions. Emissions of VOC, NOx, SOx, and PM2.5 are estimated based on vehicle speeds (FHWA 2005). HERS-ST estimates changes in travel demand using elasticities (i.e., the "rebound effect", or latent demand effects, as network travel times fall). HERS-ST estimates simple link-level demand (ignoring link connections) but does not contain an embedded travel demand model to account for shifting traffic patterns on parallel or alternate routes between origin-destination pairs and is therefore more suited for corridor analysis, rather than network analysis.

In association with Cambridge Systematics, System Metrics Group developed the California Life-Cycle Benefit/Cost Analysis Model (Cal-B/C) for the California Department of Transportation (2009). This spreadsheet-based toolkit estimates changes in crashes, emissions, travel time savings and operating costs. Cal-B/C requires users to input before and after traffic link volumes, thus requiring additional analysis outside the tool.

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

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

## Sensitivity Testing and Uncertainty in Transportation Project Evaluation

In 2003 Flyvbjerg et al. published an important cost-overrun study of 258 major public works across 20 nations, emphasizing road projects (167 of the 258 cases) with the rest comprising rail, bridges and tunnels. Two years later, a follow-up study (Flyvbjerg et al. 2005) focused on travel demand forecasts, for 210 major rail and roadway projects. Both studies concluded that cost and traffic estimates are highly uncertain, and regularly much different from actual values. For example, road project costs averaged 20.4% higher than projected costs – with a standard deviation of 29.9%, and half of all road projects had overstated demand by more than 20 percent, with a quarter of estimates overstating demand by at least 40 percent. Rail-related biases were even more dramatic, with 72% of all projects overstating ridership by 70 percent or more. Such results highlight a substantial underlying degree of uncertainty in forecasting traffic flows (as well as bias).

In their review of this literature, Lemp and Kockelman (2009b) noted that predicted traffic volumes exceed actual volumes by over 30% in half of the hundreds of cases examined. Even when correcting for optimism bias, uncertainty of traffic volumes and revenues remains substantial, suggesting that analyst assumptions are far from perfect. To address at least the variance in potential project outcomes, Lemp and Kockelman recommended that project evaluations be conducted using Monte Carlo or related simulations to "provide probability distributions of future traffic and revenue." (2009b, p 1). This is consistent with the practice of many others, including Ševčíková et al.'s (2007) model projecting future households by traffic analysis zone, Gregor's (2007) GreenSTEP emissions model which uses Monte Carlo sampling to generate distributions and Wang's (2008) application estimating uncertainty impacts using a freight mode choice model. While such sampling addresses the variability underlying key sources of project uncertainty, it does not address issues of model misspecification and bias.

The methods employed here use processes similar to those applied by Kockelman and Zhao (2002), Pradhan and Kockelman (2002) and Krishnamurthy and Kockelman (2003) in their investigations of uncertainty propagation through a standard four-step travel demand model and integrated transport-land use models. For example, Krishnamurthy and Kockelman varied 95 parameters and two demographic inputs over 200 simulations. After generating model predictions, they identified key inputs by regressing important outputs on the sets of variable inputs. Results were most strongly impacted by changes in the link performance function parameters, and shares of peak versus off-peak traffic (Krishnamurthy and Kockelman [2003]).

## TOOLKIT DESCRIPTION

The Project Evaluation Toolkit relies on user-entered Base Case and alternative-scenario transportation networks with link-specified traffic volumes or average annual daily traffic (AADT). PET accommodates hundreds of network links plus 141 parameter values which may be modified by the Toolkit user. PET uses this information to estimate future year traffic volumes based on network changes and Base Case origin-destination travel demand growth rates. Impacts are then assessed for traveler welfare (based on cost and travel time changes, using the rule of half (RoH) and/or logsum differences), travel time reliability, crashes, emissions, fuel use and tolling revenues. PET uses project cost and impact results to produce economic summary measures to help transportation planners and policy makers prioritize projects. All impacts are interpolated between the initial-year and the design-life year (using linear or exponential expressions). Finally, PET has sensitivity analysis capabilities that allow users to examine the impacts of uncertain parameter inputs (e.g., values of time and traffic growth rates), in order to generate ranges of potential scenario outcomes.

PET simultaneously serves several needs not currently met by any other single model. For example, its data requirements and run times (less than an hour to evaluate three scenarios, versus the Base Case) are less cumbersome than required by regional planning models. PET allows up to five traveler classes for assignment and infers trip tables from link counts, closely mimicking traffic shifts on a complete network following network changes (Xie et al. 2010). PET holistically evaluates full-network impacts, unlike other sketch-planning tools that lack embedded travel demand models and focus on corridors. However, PET faces network-size limitations (with run times growing exponentially with network links) and neglects land use details (typically used for trip generation and attraction computations). Thus, PET is intended for use upstream of the

NEPA process, allowing planners to quickly evaluate a number of potential project variations before selecting the most appealing candidate(s) for more detailed demand modeling (and more detailed networks).

## Travel Demand Modeling Process

The fully integrated travel demand model is a key PET component. Developed by Dr. Chi Xie under the guidance of Dr. Kara Kockelman, this crucial component helps set PET apart from essentially all other sketch-planning tools. The travel demand model strives to closely mimic full-network demand estimation results across different roadway facilities, times of day, and changed network conditions, while reducing computing times, data demands, and staff expertise requirements. The effort and input required to run such abstracted models are much lower than for the full-network counterpart. For example, the 194-link Austin network used in this work was developed from scratch in little over 40 hours (and can be used for other projects' evaluations); and the full run time for all alternatives in each case study described below was approximately 30 minutes on a standard desktop PC (with a 2.4GHz processor and 3.0 GB of RAM).

PET's travel demand model uses five major steps (Fagnant et al. 2011) to assign traffic for alternative scenarios and future years. These produce a base trip table estimate, elastic trip table estimates for each scenario, mode split and time of day estimates, and 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 1.

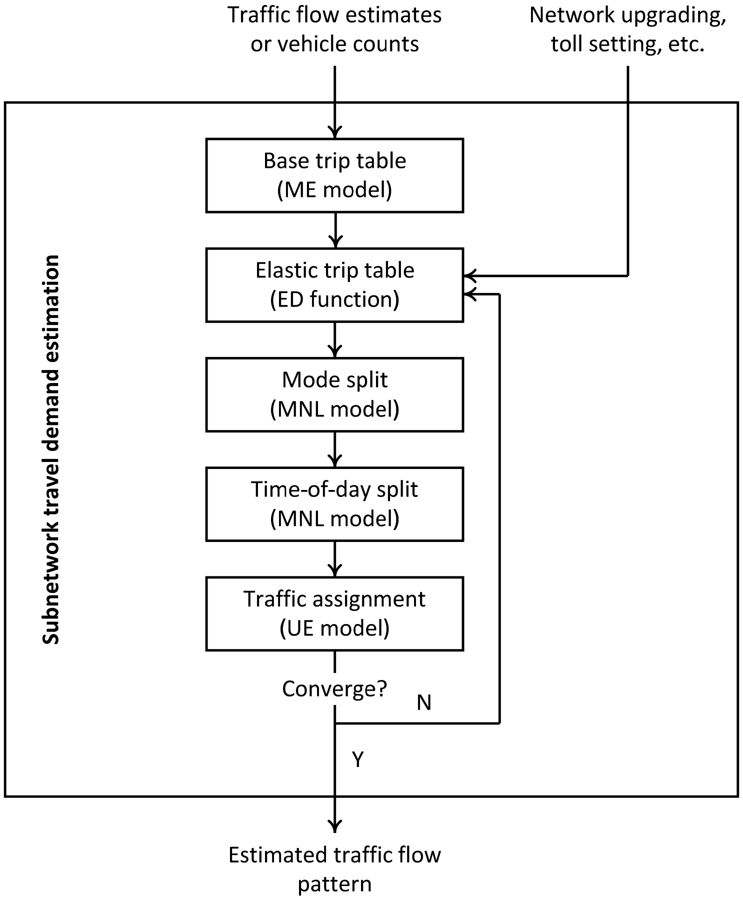

Figure 1: PET's Travel Demand Modeling Process

PET's travel demand model operates by first estimating a base trip table from coded-link volumes using a maximum entropy methodology (Xie et al. 2010). Next, PET performs an iterative process to equilibrate travel times, costs, and flows, beginning with the application of elastic demand functions governing all origin-destination (O-D) pairs:

$$x_{ij,d}^{k} = x_{ij,d}^{b,k} \left( \frac{g_{ij,d}^{k}}{g_{ij,d}^{b,k}} \right)^{\eta} \qquad (1)$$

where $x_{ij,d}^{k}$ is the traffic volume of traveler class $k$ (in vehicles per time period) between origin $i$ and destination $j$ during time-of-day period $d$, $g_{ij,d}^{k}$ represents the generalized cost (linearly combining time and money) of class $k$ individuals traveling between origin $i$ and destination $j$ during time-of-day period $d$, and the superscript $b$ denotes the Base Case scenario traffic volumes or path costs. The $\eta$ term represents the elasticity of trip-making and is set to -0.69 based on weighted elasticities observed from application of regional travel demand models to the complete Austin network (Lemp and Kockelman 2009a). This function estimates changes in trip making for each user class, based on general travel cost changes between each O-D pair.

After application of the elastic demand function, an incremental logit model (Ben-Akiva and Lerman 1985) is used to estimate changes in travel mode (e.g., SOV, HOV2, HOV3 or transit). For the heavy-truck driver class, the probability of choosing the heavy-truck mode is 1.0 so the mode split step is effectively ignored for these users (Fagnant et al. 2011). For other traveler classes, mode-split probabilities depend on user type (work-related [non-commute] travel, commuters and travelers with other non-work purposes), with each user type possessing distinct values of travel time and reliability. Their mode splits take the form:

$$P_{ij,m}^{k}=\frac{P_{ij,m}^{b,k}e^{-\lambda_m \Delta g_{ij,m}^{k}}}{\sum_m P_{ij,m}^{b,k}e^{-\lambda_m \Delta g_{ij,m}^{k}}} \qquad (2)$$

In this model, $P_{ij,m}^{k}$ represents the probability that a traveler of type $k$ originating at origin $i$ and traveling to destination $j$ will choose mode $m$; and $\Delta g_{ij,m}^{k}$ represents changes in generalized travel costs (as defined earlier). The mode-choice model requires a single mode scale parameter ($\lambda_m$)to reflect the generalized cost term's coefficient in the associated systematic utility function (Ben-Akiva and Lerman 1985).

The model then estimates changes in up to five time-of-day splits using a similar incremental logit model (with an associated time of day scale parameter, $\lambda_m$). Finally, the demand model uses a multi-class user-equilibrium traffic assignment model to estimate the network flow pattern. The multi-class user-equilibrium flow pattern can be obtained by solving the optimization problem:

$$\begin{aligned} &\min \textstyle\sum_a \int_0^{v_{a,d}} t_a(\omega)d\omega + \sum_a \ \sum_k \sum_m \frac{v_{a,m,d}^k s_{a,m,d}}{VOT^k} \\ &\text{subject to} \quad \textstyle\sum_p f_{ij,p,m,d}^k = x_{ij,m,d}^k \qquad (3) \\ &\qquad\qquad\quad f_{ij,p,m,d}^k \geq 0 \end{aligned}$$

where $v_{a,d}$ and $v_{a,m,d}^k$ are the total flow rate on link $a$ and the flow rate of traveler class $k$ and transportation mode $m$ on link $a$, respectively, during time-of-day period $p$, $s_{a,m,d}$ is the monetary cost associated with link $a$ for travelers class $m$ in transportation mode $m$ during time-of-day period $d$, and $VOT^k$ is the value of time of traveler class $k$. Link flow rate $v_{a,d}$ is the sum of all path flows going through link $a$:

$$v_{a,d} = \sum_{ij} \sum_p \sum_k \sum_m f_{ij,p,m,d}^k \delta_{ij,p}^a \qquad (4)$$

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

$$v_{a,m,d}^k = \sum_{ij} \sum_p f_{ij,p,m,d}^k \delta_{ij,p}^a \qquad (5)$$

The optimal solution to the above problem ensures that for each traveler class during time of day in which they are traveling, all used paths between each O-D pair have minimum and equal generalized travel cost (including travel time, operating costs, toll and other fixed link costs). This four-step iterative process (of elastic demand, mode and time-of-day choice, and network assignment, across multiple traveler classes) continues until equilibrium is reached using the method of successive averages. For more travel demand modeling details, see Kockelman et al. (2010).

## Traveler Welfare Estimation

Once the demand model reaches convergence, traveler welfare impacts (consisting of changes in monetized travel times and operating costs plus any surplus from new travelers) are estimated for each O-D pair (*ij*), traveler class ($k$), and time of day (*d*) using the rule-of-half (RoH) (Geurs et al. 2010):

$$\Delta CS_{ij,d}^{k} \cong \frac{1}{2}\left(w_{ij}^{b,k} x_{ij,d}^{b,k} + w_{ij}^{k} x_{ij,d}^{k}\right)\left(g_{ij,d}^{b,k} - g_{ij,d}^{k}\right) + w_{ij}^{b,k} x_{ij,d}^{b,k}\left(g_{ij,d}^{b,k} - g_{ij,d}^{k}\right) \qquad (6)$$

where $x$'s represent each O-D pair's flow rate (before and after the network or policy change: $x^b$ and $x$), $g$ is generalized travel cost, and $w$ is vehicle occupancy rate. This formulation accounts for benefits to new travelers who may be adding new trips due to reduced travel costs, as well as benefits to travelers who were already traveling from a given origin to a given destination, and see their travel costs fall. This is graphically depicted in Figure 2, where the benefit to users equals the shaded areas.

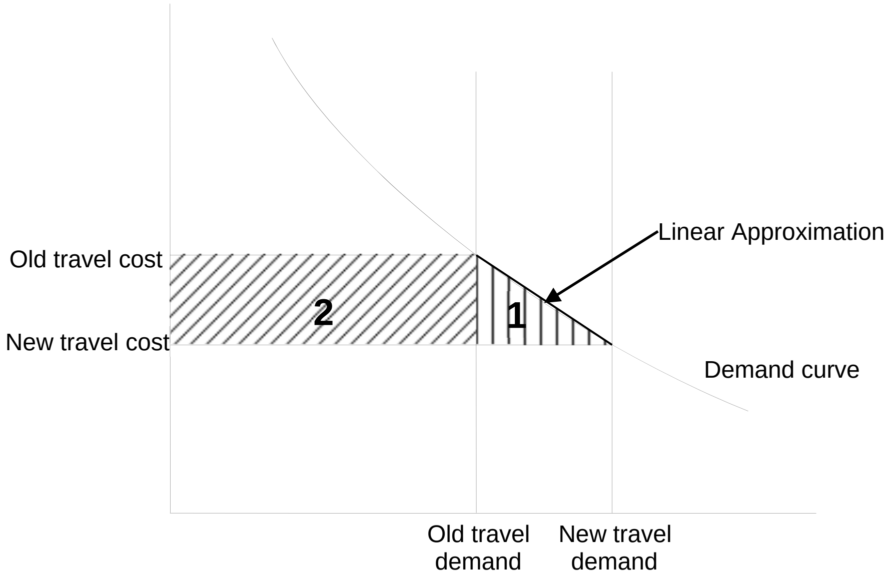

Figure 2: Changes in Consumer Surplus (in Shaded Areas) as Travel Price Falls (and Demand Rises) (Fagnant et al. 2010)

Preliminary testing was conducted based on Lemp and Kockelman's (2009a) demand model specifications to find that the RoH results very closely track (<5%) nested and standard logsums, provided that no major network changes are made or new alternatives are added (such as a subway mode).

## Reliability Estimates

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

$$r_{a,SD} = \sqrt{r^0_{a,VAR}\left(1+\sigma\left(\gamma+\frac{v_a}{c_a}\right)^{\tau}\right)} \tag{7}$$

where $r^0_{a,VAR}$ is the free-flow travel time variance of link, $a$ and, $\sigma$ $\gamma$ and $\tau$ are function parameters. Using nonlinear least-squares, regression parameters were estimated to be $\sigma = 2.3$, $\gamma = 0.7$, and $\tau = 8.4$ (with an $R^2_{adj}$ of 0.408) (Kockelman et al. 2010). More details can be found in PET's documentation (Fagnant et al. 2011).

PET multiplies each link's travel time unreliability by each user's value of reliability[1] and sums over all links to determine the total system reliability costs.

### Crash Estimates

PET uses safety performance functions from Bonneson and Pratt's (2009) Roadway Safety Handbook to predict the total number of fatal plus injurious crashes on each directional link in the PET networks. Fatal and injurious count *shares* or splits, along with extrapolations of property damage only (PDO) crash counts, are then estimated from Texas crash data sets, (TxDOT 2009). Key factors are link functional classification, AADT and number of lanes. Local land use type, median type, and intersection control also have important safety impacts along arterials, while entrance and exit ramp frequencies are important for freeways. Segment (link) crashes are estimated for all Toolkit-coded roadway types, and intersection crashes are estimated for arterials and rural roads.

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

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

## Emissions Estimates

PET predicts emissions rates and totals using the U.S. Environmental Protection Agency's MOBILE 6.2 model's rates. PET's extensive (1.37-million row) lookup tables provide grams per mile for 13 emissions species. These are the standard hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx), carbon dioxide (CO2), particulate matter < 2.5μm (PM2.5), particulate matter < 10μm (PM10), and sulfur dioxide (SO2), along with the following mobile-source air toxics (MSATs): ammonia (NH3), benzene (BENZ), butadiene (BUTA), formaldehyde (FORM), acetaldehyde (ACET), and acrolein (ACRO). While many MSATS are not yet regulated, they are carcinogenic and thus of interest to the public and its policy makers (Health Effects Institute 2007).

Emissions rates depend on facility type (freeway, arterial, local road, or ramp), vehicle speed (14 speed categories – from 2.5 mph and slower to 65 mph and faster), temperature range (four temperature ranges, with 30 degrees at the low end and 105 at the high end), year of analysis (based on analysis year closest to 2010, 2015, 2020, or 2025, and impacting vehicle ages [and thus rates]), vehicle type (28 types), and vehicle age (6 age categories in 5 year increments). 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 normal, exhaust generation of all emissions types. Evaporative emissions are also estimated for HC and BENZ, as are PM2.5 and PM10 from brake wear and tear.

MOBILE6.2 assumes fixed CO2 emissions rates (and essentially constant PM emissions rates) with speed, which is generally found to be unrealistic. Fuel use and CO2 values across different speeds were modified based on fuel economies developed under work by West et al. (1997), as presented in Davis and Diegel (2007). Lower speeds thus significantly impact CO2 and most other species, though not PM or NH3 (which remains unintuitive). Various emissions rates begin to rise slightly for certain species above 40 mph but MOBILE6.2 rates terminate at 65 mph. Figure 3 illustrates per-mile emission rates with respect to vehicle speed on a freeway facility with 10% heavy vehicles at 80 degrees Fahrenheit for HC, CO and NOx.

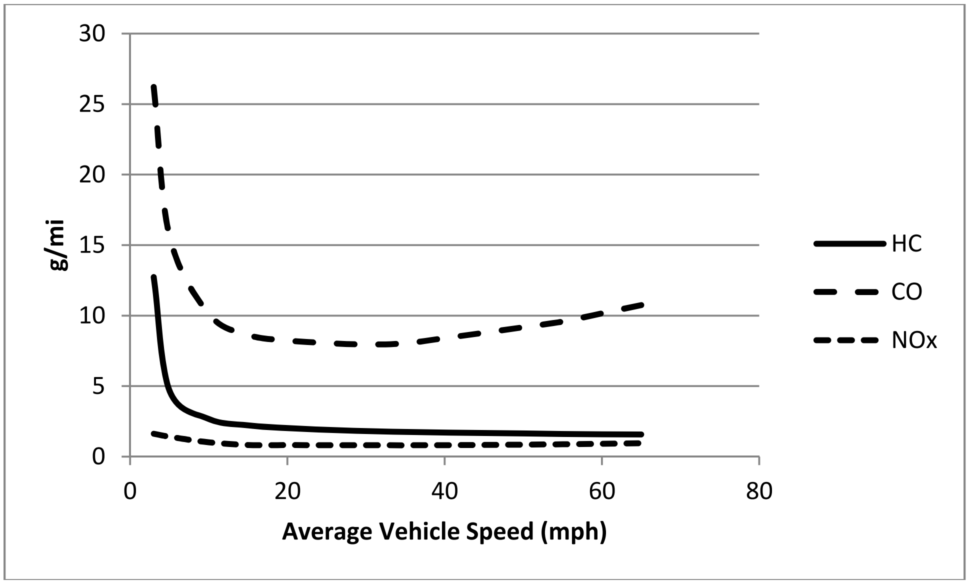

Figure 3: Freeway Emission Rates (2010, 10% HDV, 80°F) (Fagnant et al. 2010)

PET defaults do not monetize emissions, though McCubbin and Delucchi (1996) provide US estimates and Mailbach et al. (2008) present European estimates of emission costs for certain species based on health impacts. These range from \$2900-\$5800 per ton of HC, \$70-\$140 per ton of CO, \$620-\$7600 per ton of NOx, \$620-\$18,000 per ton of SO2 and \$4500-\$830,000 per ton of PM2.5 (all 2010 \$US), depending on area density, country and study.

### Summary Measures

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

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

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

# Chapter 2: Case Study Investigation

To demonstrate PET's capabilities, five case studies were conducted, modeling a variety of potential project types:

1. *Capacity Expansion* – This case study involves conversion of a four-lane arterial segment (along US 290) to a four-lane freeway. Three pricing alternatives were explored: a non-tolled option, pricing by vehicle/mode, and pricing by mode and time of day.
2. *Travel Demand Management* – This set of scenarios attempts to move traffic off a highly congested freeway (IH 35) through pricing and/or capacity reduction.
3. *Shoulder Lane Use* – In this scenario, Loop 1's shoulder is used as a travel lane during peak periods.
4. *Speed Harmonization* – Here, speed limits are reduced as V/C ratios approach 1.0 in order to avoid crashes.
5. *Incident Management* – Roving freeway service patrols are assumed to remove capacity-reducing incidents faster (during congested times of day), thereby moderating delay costs.
6. *Construction Phasing* – This case study examines lane closure alternatives for impacts of closing a single lane over a long period versus closing two lanes over a shorter duration.

All case studies were conducted using PET and a consistent methodology to demonstrate how transportation planners can quantitatively compare capacity expansion projects to projects more focused on operations. While the first five case studies demonstrate new projects that could be introduced to an existing transportation network, the sixth examines the implementation of such a project and the various costs associated with two phasing alternatives. Each case study was modeled separate from the others (e.g., incident management was not modeled in conjunction with shoulder lane use). All case studies were conducted in reference to a common Base Case scenario, which models the Austin Regional network as it currently exists. While PET can also handle other project types (for example, reversible lanes, ramp metering, and automatic traveler information systems), these case studies broadly demonstrate its capabilities. All case studies and all alternative scenarios assume a 5% discount rate, which is lower than the 7% required by the OMB for federal projects, but is on the high end of the 3 to 5% discount rates typically used for state transportation projects, (FHWA 2007). Additionally, a 20-year design life (with the exception of the construction-phasing case study) was assumed, along with a 1% annual growth rate in Base Case trip rates between all O-D pairs, though PET has the ability to account for pair-specific growth rates. The 1% growth rate is lower than the estimated regional population growth (Robinson 2008) but close to or higher than the expected growth rate for zip codes in which the most congested roadways lie. Figure 4 illustrates the case study locations on Austin's 194-link (abstracted) network.

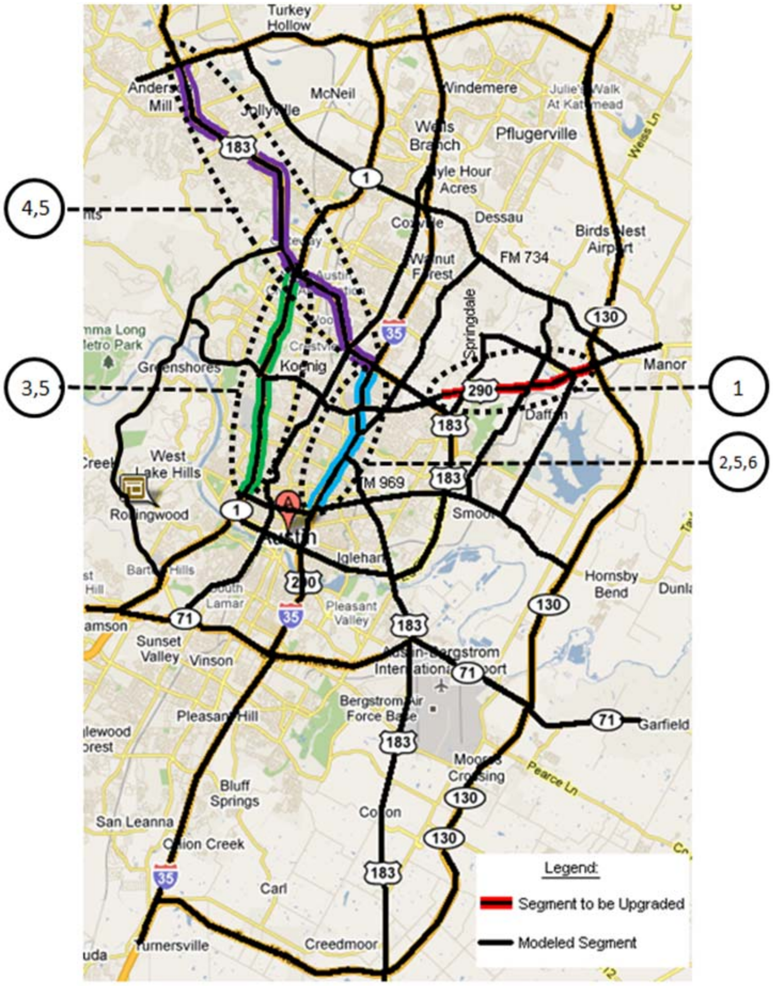

Figure 4: Case Study Locations – (1) Capacity Expansion, (2) Travel Demand Management, (3) Shoulder Lane Use, (4) Speed Harmonization, (5) Incident Management, and (6) Construction Phasing

### HIGHWAY EXPANSION AND TOLLING

The three capacity-expansion scenarios were examined first, all upgrading the existing four-lane segment (two through lanes in each direction) from an arterial to a four-lane grade-separated freeway or tollway. Two-way total capacity was estimated as increasing from 3080 vehicles per hour (vph) to 7640 vph. Grade separation also involved the elimination of seven intersections between US 290 and minor streets in the alternative scenarios. The first scenario (Freeway Upgrade) was modeled as a non-tolled freeway; the second (Tollway Upgrade) as a tollway with fares at \$0.20 per mile for SOVs (similar to Austin's US 130 [TxDOT 2011]), \$0.10 per mile for HOVs (2 or more persons), no toll for transit users, and \$0.60 per mile for heavy-trucks; and the third scenario (Tolling by TOD) using the second scenario's base prices doubled during the PM peak and halved during the off-peak period.

Initial project costs were estimated at \$71.8 million for the Freeway Upgrade and \$80.5 million for the two tolling scenarios, based on an estimated construction cost of \$3.2 million per freeway lane-mile plus another \$760,000 per directional mile for installation of toll collection infrastructure and 10 percent for design costs, as per recent Texas projects (TxDOT 2008). These project costs are probably under-estimated, since these numbers neglect interchange costs at US 183 and SH 130. A \$30 million repaving project was also assumed 10 years after the initial-year in the Base Case scenario. Annual maintenance and operations costs were assumed to be \$410,000 for the Freeway Upgrade scenario plus another \$1.13 million for the two tolling scenarios, based on recent Texas estimates (TxDOT 2008).

All three alternative scenarios showed favorable benefit-cost ratios. The Freeway Upgrade scenario was most favorable from the public's perspective, with a 14:1 B/C ratio, while the Tollway Upgrade and the Tolling by TOD were still beneficial, having respective B/C ratios of 6.5:1 and 3.9:1. The main reason for the Freeway Upgrade's strong performance lies in its superior traveler welfare impacts, as shown in Table 1.

| | | Freeway Upgrade | Tollway Upgrade | Tolling by TOD |
|---|---|---|---|---|
| Initial-Year | Total Impacts | **$32.0 M** | **$12.4 M** | **-$0.5 M** |
| | Traveler Welfare | $23.8 | $5.0 | -$4.6 |
| | Reliability | $7.0 | $6.3 | $3.3 |
| | Crashes | $0.7 | $0.7 | $0.6 |
| | Emissions | $0.5 | $0.4 | $0.2 |
| Design-Year | Total Impacts | **$132.9 M** | **$99.6 M** | **$82.5 M** |
| | Traveler Welfare | $76.6 | $49.1 | $38.3 |
| | Reliability | $51.8 | $47.2 | $41.4 |
| | Crashes | $1.4 | $1.3 | $1.3 |
| | Emissions | $3.1 | $2.0 | $1.5 |

Table 1: Present Values of Capacity Expansion Scenario Impacts ($ million)

In the Freeway Upgrade scenario, travelers gain a mobility benefit without having to pay an extra fee, as in the other two tolling scenarios. However, this carries an implicit cost since the Freeway Upgrade must be financed through tax revenues. Conversely, the tolling scenarios are not only self-financing, but likely revenue generating with an estimated 23% (Tollway Upgrade) and 29% (Tolling by TOD) internal rates of return (to tolling authorities, rather than to society at large). Transportation planners may therefore prefer the Tollway Upgrade which conveys more public benefits than the Tolling by TOD scenario, but both offer a tolling mechanism to quickly recover invested funds. This project appears much more profitable than existing tollways in Austin, presumably due to its lack of parallel (non-tolled) frontage roads and assumption of no additional right-of-way requirements. Both tolling projects appear much more profitable than existing tollways in Austin, presumably due to its lack of parallel (non-tolled) frontage roads and assumption of no additional right-of-way requirements.

Though traveler welfare and travel time reliability benefits significantly outweigh the monetized benefits of crashes and emissions, the significance of the latter impacts should not be ignored. Over the course of the 20-year design life, the three projects were projected to result in the prevention of 480-530 injurious crashes, 6 or 7 of which were estimated to be fatal. Most emissions types are forecasted to fall in the initial-year and all in the design-year. In particular hydrocarbons, butadiene, formaldehyde and acrolein are lower by 0.9% when comparing the Freeway Upgrade's design-year with the Base Case scenario. This is particularly impressive when considering that the target links handle only 1.45% of total system traffic. For both crashes and emissions, the Freeway Upgrade was the preferred scenario, followed by the Tollway Upgrade. The major reason for this is that some vehicles in the Tolling scenarios chose longer and slower routes along arterials, thus increasing emissions and crash risks.

Average daily speeds on the upgraded segment increased in all three scenarios when compared to the Base Case scenario, showing a 23 mph (55 vs. 32 mph) difference in the initial-year and 31 mph (54 vs. 23 mph) by the design-year. US 290 traffic was lower for the Tolling by TOD scenario than in the Base Case scenario (1200 fewer vehicles per day [vpd] in the initial-year and 400 fewer in the design-year) while positive in the other two scenarios (160-275 more vpd in the first year increasing to 930-1100 more by the design-year). Most of the drop-off occurred in the PM peak, indicating that the steep PM peak tolls were not worth the mobility benefit to a number of travelers.

## TRAVEL DEMAND MANAGEMENT

The second case study sought to reduce I-35 traffic levels by imposing tolls or reducing capacity. The first alternative scenario ($1 Toll) imposed a $1 toll ($0.20 per mile); the second scenario ($2 Toll) imposed a $2 toll (just over $0.40 per mile); and the third scenario (Lane Reduction) removed a travel lane in each direction (reducing capacity from 9200 vph to 6900 vph in each direction). It should be noted that the abstracted network (of 194 links) did not model I-35's frontage roads, and a more complete analysis that included these links may produce different results.

Though all scenarios attempted to reduce network VMT, results are mixed: VMT rises in both the initial and design-years of the two tolling scenarios, but falls in the Lane Reduction scenario's design-year. While all alternative three scenarios predict travel reductions along I-35 (relative to the Base Case), PET's travel demand model predicts that many travelers would shift their routes rather than forego travel altogether. This is despite the model's accounting for the possibility of fewer total travelers through use of travel demand elasticities. Table 2 shows PET-estimated changes in the coded-network's VMT. The 'Surrounding Links' row listed in Table 2 reflects VMT changes along the 22 links closest to the impacted I-35 project area. These links represent the most likely alternative routes that travelers could take instead of I-35, while still reaching the same destinations.

| | Initial-Year | | | Design-Year | | |
|---|---|---|---|---|---|---|
| | $1 Toll | $2 Toll | Lane Reduction | $1 Toll | $2 Toll | Lane Reduction |
| System | 0.32% | 1.32% | 0.06% | 0.28% | 0.94% | -4.99% |
| I-35 | -6.2% | -22.4% | -0.4% | -5.7% | -17.8% | -45.4% |
| Surrounding Links | 21.1% | 40.0% | 1.3% | 18.3% | 30.7% | -11.3% |
| System | 17.0 | 70.5 | 3.1 | 18.7 | 61.5 | -328 |
| I-35 | -27.2 | -98.9 | -1.9 | -31.1 | -96.5 | -246 |
| Surrounding Links | 32.6 | 61.6 | 2.0 | 34.7 | 58.2 | -21.5 |

Table 2: PET-Estimated VMT Changes for I-35 Corridor Changes (as a percentage of the Base Case scenario's VMT and annual million VMT)

Locally, the most striking impacts are shown along one bypass route east of I-35. In the $1 Toll scenario's design-year, Cameron Road's traffic volumes (between I-35 and US 183) rise by 250%, accounting for an additional 27,000 AADT on both links.

Similarly, 27,000 new AADT is added to the US 183 links between 35th Street and Cameron, increasing traffic on those links by 64%. Additional changes in VMT may be attributed to longer-distance trips. The cost increases on I-35 (in either time or money) cause some vehicles to take longer routes around it (thus increasing VMT) and other vehicles to forgo the trip altogether (thus decreasing VMT). Furthermore, a more complete analysis could be run, modeling I-35's frontage roads and other nearby alternative local routes. This may mitigate some of the system VMT increases that are shown in the Lane Reduction alternative.

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Interestingly, the Lane Reduction scenario's traveler welfare impacts shows the least impact for the initial-year (-$90 million) but the most in the design-year (-$3.54 billion). Crashes are predicted to increase in most scenarios (thanks largely to VMT shifts to local roads), with the $2 Toll scenario showing crash cost increases of $7.8 and $8.5 million in the initial and design-years. Other than the Lane Reduction scenario's design-year (where crash costs are predicted to fall by $5 million due to the dramatic network

VMT reductions), predicted crash costs in other instances rise by less than $1 million per year. Reliability worsens in most alternatives, though with very different magnitudes: $270 thousand cost improving to a $3.5 million benefit (in the $1 Toll scenario), $24 million cost decreasing to $14 million ($2 Toll), and $40 cost million increasing to $1.4 billion (Lane Reduction, where 68% of reliability costs come from just 14 links with PM peak V/C ratios > 1.5). Both tolling alternatives show increases in all pollutants, while the Lane Reduction scenario shows mixed results. The $1 Toll scenario shows a near-uniform emissions decrease of 0.3% (± 0.1% across all emissions species in the initial and design-years), while the $2 Toll scenario shows reductions ranging from 1.0% to 1.8% in the initial-year and 0.6% to 1.1% in the design-year, with hydrocarbons showing the greatest reductions. Emissions in the Lane Reduction scenario's initial-year are predicted to rise (with the exception of very small decreases in CO and NOx); however, the design-year shows emissions predictions rising for seven pollutant species (with HC and Acrolein posting the greatest increases, at 10.3%) and decreasing for six others (with NH3 posting the greatest decrease, at -5.9%). Emissions and crash increases are attributable in part to changes in total VMT but also to shifting freeway traffic to arterials (where crash and emission rates are higher due to more stop-and-go behavior and conflicts, caused by signalized intersections and driveways).

### SHOULDER LANE USE

A shoulder lane use case study was conducted to model the impacts of using freeway shoulders as travel lanes on Loop 1 between US 183 and 15th Street. This 6.7-mile section consists of 6 lanes with a bi-directional AADT just over 160 thousand. Two alternative scenarios were evaluated, the first assuming that shoulders would be open for use as a conventional lane between 2 PM and 7 PM (Short Open Shoulders) and the second assuming that shoulders would be open as early as 7AM (Long Open Shoulders). Loop 1 makes a particularly good candidate for shoulder lane use since heavy-truck usage of the facility is currently restricted.

The costs of allowing shoulder lane use were estimated at $1.17 million per centerline mile, based on the installation of overhead gantries with lane use control signal indications at half-mile spacing (FHWA 2010a). An additional 50% in construction cost was added to account for guardrail and other fixed-object relocations, as well as emergency pullouts for a total initial cost of $12 million when accounting for design. Loop 1's existing shoulders are already wide throughout the section (8' to 12'); and, since heavy-trucks would be restricted, the shoulders were assumed to require no initial reinforcement. Additional annual maintenance was assumed to be $31 thousand per centerline mile to account for heavier use of the shoulders (TxDOT 2008), and 5% of construction costs were assumed to be required annually for shoulder lane use operations. Use of the shoulder lane was assumed to increase overall capacity by 1150 vph when active, similar to experiences in Hessen, Germany (Riegelhuth and Pilz 2007).

As may be expected, both scenarios garner very high B/C ratios, with the Short Open Shoulders showing a 19 B/C ratio and the Long Open Shoulders scenario with a 36 B/C ratio. Essentially, these projects added significant capacity to the roadway segments at minimal costs. The Long Open Shoulders scenario shows roughly double traveler welfare and reliability benefits when compared to the Short Open Shoulders scenario in both the initial and design-years.

The greatest reason for the high user benefits is due to increased capacity (and therefore speeds) on the impacted links. During the PM peak speeds were up 9 mph (from 38 mph to 47 mph) in the initial-year and 12 mph (from 22 mph to 34 mph) in the design-year. However, the suitability of implementing these scenarios comes into question. FHWA (2010a) notes that many states with active shoulder lane use limit shoulder speeds to 35 mph or lower. In the initial-year, even the heaviest PM peak period speeds would average this speed. While the model could be refined further to narrow the band for which PM peak speeds are modeled (for example, examining only the three heaviest travel hours), presently shoulder lane use would likely be open for very limited times. However, future shoulder lane use should be strongly considered, as traffic continues to grow and speeds fall.

Traffic is also estimated to increase on the case study lanes, though the increase is minimal. In the initial-year traffic is projected to be up versus the Base Case scenario by only 200 AADT in the Long Open Shoulders scenario and 45 AADT in the Short Open Shoulders scenario. While these figures increase to 1,500 and 1,000 AADT by the design-year, the increased traffic still accounts for less than 0.8% of total traffic in the Base Case scenario.

The results of this case study indicate that a shoulder lane use project should be strongly pursued, though the times when the shoulder lane is open should remain flexible. The high B/C ratios indicate that even if limited shoulder openings are allowed, travelers should reap substantial benefits well beyond the costs of construction, maintenance and operation. Transportation operations personnel should continue to monitor congestion levels and widen the shoulder lane use period as traffic grows.

### SPEED HARMONIZATION

The speed harmonization case study was modeled on an 11.7 mile segment on US 183 between Texas Toll Road 45 and I-35. This case study assumed that speed harmonization would be active from 7 AM to 10 AM during the morning peak and from

2 PM to 7 PM during the afternoon peak. Bi-directional traffic on this segment was estimated to average over 146 thousand AADT.

Like the shoulder lane use case study, construction costs were estimated at $1.17 million per mile to account for construction of overhead gantries and installation of variable speed limit signs for a total cost of $15 million, including design. It should be noted that speed harmonization may be paired in combination with shoulder lane use, utilizing the same infrastructure to save on costs as noted by FHWA (2010a) though the strategies were evaluated independently in this investigation.

PET estimates speed harmonization impacts via a crash reduction factor that is applied to initial-year and design-year predicted crashes. When speed harmonization is active, PET assumes a 10% to 30% crash reduction factor for crashes that are expected to occur during active times of day on the targeted segment (Fagnant et al. 2011). This case study assumed a 20% median crash reduction factor and crash distributions (by time of day) that follow national trends (NHTSA 2010). No significant speed or capacity changes were assumed, consistent with Waller et al. (2009) and Van den Hoogan and Smulders (1994).

The case study results suggest that 13 fatal and injury crashes may be prevented in the first year, increasing to 17 fatal and injury crashes by the design-year. Moreover, if congestion grows on the segment such that speed harmonization is active from 7 AM to 7 PM, the estimated (annual) number of fatal and injury crashes prevented grows to 25 crashes by the design-year. Over the entire 20-year period, approximately 5 lives are expected to be saved.

Nevertheless, the overall benefit-cost ratio remains low, at just 0.6. This figure assumes economic costs of crashes only (such as productivity loss, property damage, medical costs, etc. [NSC 2009]) and not softer costs such as pain and suffering and the value of life. If willingness-to-pay measures are included (in addition to assuming 1.49 injuries per injury crash [Caltrans 2010] and 1.15 fatalities per fatal crash), the PET-estimated B/C ratio rises to a respectable 1.92. It should also be noted that the benefits of this scenario could be improved by utilizing the overhead gantry and electrical infrastructure to simultaneously implement a shoulder lane use strategy.

### INCIDENT MANAGEMENT

The incident management case study examined the implications of utilizing a freeway service patrol on three of the freeway segments analyzed in the other scenarios: Loop 1 from US 183 to 15th St., US 183 from Texas Toll 45 to I-35, and I-35 from US 183 to FM 969. In all, the freeway towing service was modeled to cover a highway length of 23 miles and be operational from 6 AM to 7 PM.

Recently, Chou et al. (2009) estimated a $50-per-truck-hour cost of such a service with an average of two vehicles required to be on duty per ten miles of service area. Assuming these figures, annual costs of such a program should cost $1.09 million, rounded up to $1.3 million to account for administration and overhead.

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 are estimated, assuming an average of 2.07 incidents per crash (Bertini et al. 2005). This acknowledges the fact that, while crashes are the most common reason for a lane loss, other types of incidents may also cause a lane loss (e.g., spilled truck contents, vehicle breakdowns, and downed tree limbs). PET then uses measures of before and after incident clearance times to estimate total upstream delay, using Wirasinghe's (1978) delay equation:

$$d = \frac{1}{2} t^2 \frac{(q_a - q_l)(q_c - q_l)}{(q_c - q_a)} \tag{8}$$

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. Essentially, Wirasinghe's estimate (based on a triangular area between arrival and departure curves) assumes that when a lane loss occurs, demand will exceed capacity and a queue will begin to form (with departure rate equaling the new link-capacity). Once the incident is cleared, original capacity restored and the queue begins to dissipate. Initial average incident duration was estimated at 65 minutes, falling to 50 minutes with active incident management (Corbin 2006).

Total travel time savings was estimated at 218,000 person-hours in the initial-year, increasing to 925,000 person-hours by the design-year. With an aggregate $10.75-per-person-hour assumed value of travel time (accounting for different types of travelers with different purposes [Fagnant et al. 2011]) the program should more than pay for itself, with a resulting B/C ratio of 3.9. Even in the initial-year, the monetized travel time benefits should outweigh the costs.

Emissions benefits should also result from this project. Projected impacts include a reduction in hydrocarbons from 2590 tons in the initial-year to 4690 tons in the design-year, and carbon monoxide reductions of 2290 tons in the initial-year to 25,600 tons in the design-year. Nitrous oxide emissions are estimated to actually increase in the initial-year by 53 tons, but posted annual reductions of 94 tons in the final year. Other emissions showed positive impacts; for example, benzene, butadiene, formaldehyde, and acetylene showed reductions in the 4- to 19-ton range initially, widening to a 6-27 ton range by the design-year.

## WORK ZONE PHASING

The work-zone-phasing case study estimated the impacts of closing one lane on I-35 between US 183 and FM 969 (a 4.6-mile, eight-lane freeway segment with 250 thousand AADT). Two alternative scenarios were examined: the first assumes a Single-Lane Closure in each direction for a full year, and the second assumes a Two-Lane Closure in each direction for six months. In this case-study examination, both scenarios' project costs were assumed equal, so results focus on impacts to the traveling public.

The impacts between the two scenarios are substantial, with the six-month closure faring far worse. Monthly traveler welfare and reliability costs are estimated at $11.8 million in the Single-Lane Closure (or approximately $1.60 per I-35 traveler per day) over the 12-month period, while monthly costs for the Two-Lane Closure are estimated at an astounding $730 million (for each of the six months). Readers should note that PET's travel demand model (with standard, static assignment) allows demand to exceed capacity without limit, resulting in some extraordinary travel times (e.g., 29 hours to travel a 0.6 mile link) and correspondingly unreasonable traveler welfare estimations. Nevertheless, the broad implications remain that the Two-Lane Closure will result in serious negative consequences for travelers while the Single-Lane Closure should be uncomfortable but manageable. Additionally, this calls for further investigation into the PET travel demand model's assignment and elasticity estimations. This dramatic travel cost increase should quash demand through the elasticity measures or cause travelers to take more circuitous but quicker routes.

Another significant difference between the two phasing scenarios is the re-routing of traffic that occurs in the Two-Lane Closure scenario. In this scenario, much traffic on I-35 opts to take alternate routes, resulting in a system-wide 22 million VMT increase per month, or 4.7%. of the Base Case total. In contrast, the Single-Lane Closure results in a system-wide monthly traffic increase of only 72 thousand VMT, indicating that the constrained I-35 route was still preferable to taking a more circuitous path. The implications of increased VMT are clear in both crash and emissions increases. For example, 2350 monthly additional tons of hydrocarbons, 3100 tons of carbon monoxide, 130 tons of nitrous oxide, and 1.3 tons of particulate matter are emitted per month in the Two-Lane Closure compared to respective Single-Lane Closure emissions increases of 28 tons, -12 tons (decrease), -1.5 tons (decrease) and 0.013 tons.

As also noted earlier, crashes too should experience an increase in frequency with the additional exposure. In the Single-Lane Closure, an estimated 18 additional injury crashes are expected to occur over the 12-month period. While this is definitely not a desirable outcome, it is likely acceptable given the massive impact of the construction project on so many travelers. Conversely, the Two-Lane Closure is estimated to result in an additional 430 injury crashes over six months, increasing the total system-wide number of crashes by 4.9%. This is a highly undesirable outcome that should be avoided, as feasible.

In summary, the longer Single-Lane Closure construction phasing scenario is anticipated to be very strongly preferred to the shorter Two-Lane Closure. While at times a two-lane closure may be unavoidable, managing engineers and policy makers should ensure that these more significant closures come at night and off-peak hours, when impacts will be minimized. The shortcomings of this case study should also be recognized, particularly on two fronts. The network that was used in this case study omits many side streets that are not critical routes under normal circumstances, but would show dramatic jumps in travel when the segment is under construction. Also, the maximum-entropy routine used to develop a trip table often estimates shorter trips rather than longer ones. Many travelers journeying between more distant locations than estimated by PET would likely alter their path upstream and avoid the work zone.

## CASE STUDY CONCLUSIONS

These six case studies described above demonstrate PET's major capabilities. They show how analysts can compare disparate projects and network policies, from capacity expansion and tolling projects, to operational strategies such as shoulder lane use, speed harmonization, and incident management. In each instance, alternative substitute scenarios can be compared to select a preferred project alternative. These preferred alternatives may later compete for funding against one another. The use of a consistent methodology across project types and scenarios means that all projects are evaluated on a level field, helping ensure that the best projects rise to the top while allowing analysts to evaluate a number of distinct opportunities systematically and rapidly.

# Chapter 3: Sensitivity Testing

While Chapter 2 investigated various applications and manners in which the Project Evaluation Toolkit (PET) may be used, this chapter focuses on more detailed analyses that can be conducted using PET. Specifically, this chapter focuses on the impacts of parameter uncertainty on project outcomes. To this end, two alternative scenarios from the US 290 capacity expansion case study were examined under a variety of random inputs. These are the Freeway Upgrade alternative scenario and the Tollway Upgrade alternative scenario (with pricing by mode).

## METHODOLOGY

Twenty-eight parameter sets were then varied during sensitivity analysis in order to determine the impact of parameter variation on outcomes. All random draws originate from a lognormal distributions centered at one, with variance governed by a user-specified coefficient of variation, or CoV (where CoV equals the distribution's standard deviation divided by the absolute value of its mean). Variations were conducted by drawing an independent random value for each parameter set. (For example, all user classes' values of travel time would have a single shared draw for a given iteration, so all move up or down together, to economize on the sampling space and to ensure some expected correlation.) This random draw was then applied to the Base Case and all alternative scenarios for that iteration, and to the initial and design-life years (with interpolation of project impacts in intermediate years, to moderate computational burdens). Hundreds of iterations were run, for hundreds of evaluations across all scenarios (each versus the corresponding Base Case).

Two sets of runs were conducted with three hundred iterations each, the first run containing a low degree of uncertainty (10% CoVfor all parameter sets) and the second a higher degree of uncertainty for most parameters (10% CoV for three parameter sets with a relatively strong degree of certainty, 30% CoV for most parameters, and 50% CoV for four parameter sets with a high degree of uncertainty).

Table 3 shows which parameters were varied and the CoV for each set of runs, as well as the default average parameter values. For a full listing of these and other default-parameter value sources, please see the PET Guidebook (Fagnant et al. 2011).

| Parameter | Low CoV | High CoV | Values Used |
|---|---|---|---|
| Value of Travel Time | 10% | 30% | \$5 to \$50 per hour |
| Value of Reliability | 10% | 30% | \$5 to \$50 / hour of travel-time std. dev. |
| Vehicle Operating Costs | 10% | 30% | \$0.20 to \$0.50 per mile |
| Crash Costs | 10% | 30% | \$7500 (PDO) to \$1.13M (Fatal) |
| Emissions Values | 10% | 50% | For 5 species, varies widely |
| Link Capacities | 10% | 10% | Varies based on indiv. hwy link |
| Link Performance Params. (α & β) for BPR Formula | 10% | 10% | Varies based on link class |
| Free-flow Speeds | 10% | 10% | Varies based on link class |
| Reliability Parameters (σ & τ) | 10% | 50% | 2.3, 8.4 |
| Local Crash Rate Calibration Factor | 10% | 30% | 1 |
| Emissions Rate Calibration Factor | 10% | 30% | 1 |
| Mode Scale Parameter | 10% | 50% | 1 |
| Time-of-day Scale Parameter | 10% | 50% | 0.1 |
| Ambient Temperatures | 10% | 30% | 76 (April-Oct), 56 (Nov-March) degrees Fahrenheit |
| Average Vehicle Occupancies | 10% | 30% | Averages 1.6 across all modes |
| User Class Share: Heavy-Truck Driver (very high VOT) | 10% | 30% | 5% |
| User Class Share: Work Related (high VOT) | 10% | 30% | 10% |
| User Class Share: Commuter (high VOT) | 10% | 30% | 20% |
| User Class Share: Non-Work Related (low VOT) | 10% | 30% | 65% |
| Mode Probability: SOV | 10% | 30% | 35.90% |
| Mode Probability: HOV2 | 10% | 30% | 33.30% |
| Mode Probability: HOV3 | 10% | 30% | 29.60% |
| Mode Probability: Transit | 10% | 30% | 0.12% |
| Annual Trip Growth Rates (over time) | 10% | 30% | 1% Annually |
| Demand Elasticity (for O-D pairs) | 10% | 30% | -0.69 |
| Initial Project Costs | 10% | 30% | \$71.8M - \$80.5M |
| Maint. & Operat. Costs | 10% | 30% | \$409,000 - \$1.13M |

Table 3: Parameter Values and Variation for Sensitivity Testing[2]

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[2] Note: User class shares and mode split shares must sum to one, so sets of drawn values were normalized (after mean-one draws were multiplied by base shares, and heavy-truck shares were removed from consideration).

## BENEFIT-COST RATIOS

Since benefit-cost (B/C) ratios drive many projects decisions, this output was examined first. B/C variations were dramatic, suggesting that input uncertainty can easily make or break a project. 15% of the 600 runs had B/C ratios below -100, and 17% had B/C ratios greater than 100 in both scenarios. However, B/C output distribution of was very similar for both sets of sensitivity test parameters (i.e., both high and low CoV values), likely due to the invariance of CoV (held at 10 percent) in the BPR link-performance parameters ($\alpha$, $\beta$, and link capacities, $c$). These sets of parameters are found to be key to impact assessment, since they regulate the estimated traffic speed on each traveled link ($s_a$) via the Bureau of Public Roads link performance function (TRB 2000), as follows:

$$s_a = \frac{s_a^0}{1+\alpha\left(\frac{v_a}{c_a}\right)^{\beta}} \tag{9}$$

where $s_a^0$ is the link's free-flow speed (obtained from Cambridge Systematics [2008]), is $v_a/c_a$ is the link's volume-capacity ratio, and $\alpha$ and $\beta$ are behavioral parameters.

Given their similar results, the low and high variation (CoV) sets of runs were combined for further evaluation. A histogram of the combined B/C ratios shows a very wide distribution of values, with a compact center, as shown in Figure 5.

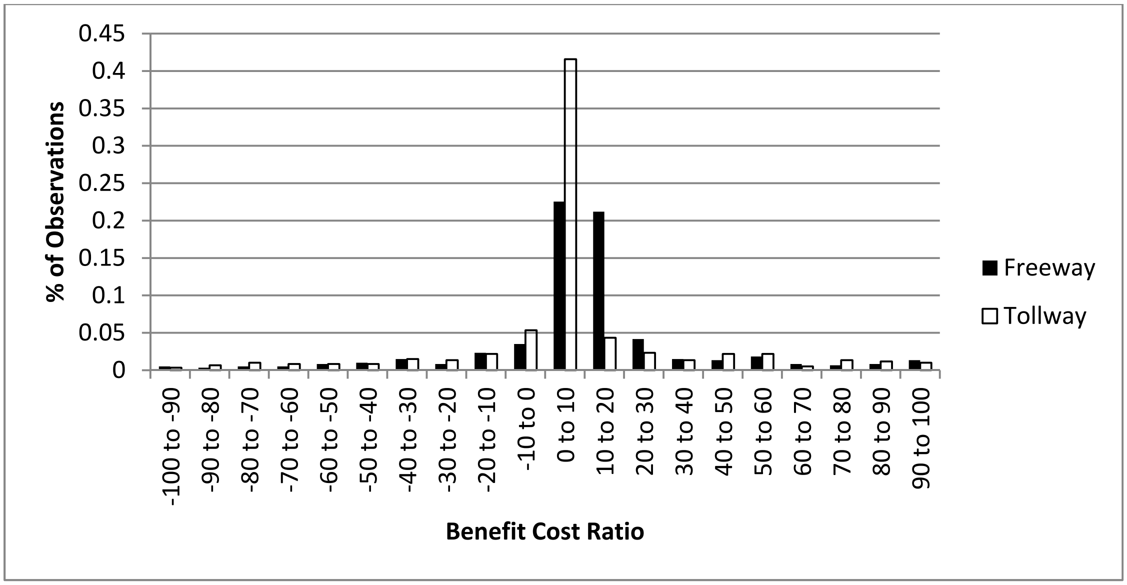

Figure 5: Histogram of B/C Ratios (with values beyond +/- 100 not shown)

Shares of B/C ratios were similar across both scenarios, with 54% (Freeway Upgrade) and 56% (Tollway Upgrade) of outcomes falling in the -20 to +30 band of reasonable B/C ratios, 21% (Freeway Upgrade) and 19% (Tollway Upgrade) falling below -20 and 25% (both scenarios) lying above +30. In other words, there was much more variation in performance measures across test runs than across project alternatives, suggesting that there may be no clear winning alternative, in terms of delivering robust outcomes across modeling uncertainties. Nevertheless, important differences across project alternatives can be observed near the median values. The median B/C value for the Freeway Upgrade scenario was 10.3, compared to 4.0 for the Tollway Upgrade scenario, as apparent in Figure 5's distribution spikes. In fact, in 63 percent of alternative comparisons, the Freeway scenario bested its competitors (Base Case and Tollway Upgrade scenarios) while the Tollway Upgrade scenario was preferred in just 22 percent of trials. In the remaining instances, both alternatives showed negative B/C ratios, indicating a Base Case (no-build) preference. This shows how complex transportation networks can have unpredictable consequences (similar to Braess' Paradox), and how improving travel for some travelers (even at zero cost) may negatively impact others, particularly when modeling elastic demand under congested conditions.

Also of note, the *median* B/C ratios across both alternative scenarios were less than the B/C ratios estimated at mean parameter values. When PET was run without parameter variation, the scenarios yielded favorable B/C ratios of 14.1 and 6.2 for the Freeway Upgrade and Tollway Upgrade scenarios, respectively. In both instances, the 14.1 and 6.2 values fell around the 62nd percentile of the sensitivity-test outcomes, suggesting that false certainty in model parameter values can mask potential project downsides.

One clear factor in extreme B/C cases is a dramatic increase (or decrease) in total VMT versus the Base Case scenario. In instances with B/C ratios lower than -100, VMT averaged a 24% design-year decrease vs. the Base Case scenario, compared to a 51% VMT increase in instances where the V/C ratio was greater than 100 and an average VMT decrease of 1.7% for all other instances. Initial-year comparisons show similar patterns, though to a much smaller degree (1.4% average decrease vs. 4.8% average increase). Alternative scenarios' design-year VMTs grew in almost all sampled runs, though sometimes at a lower rate than the corresponding Base Case scenario. Large VMT changes also coincided with dramatic changes in traveler welfare and reliability. More VMT ties to higher welfare estimates for induced travelers (thanks to the Rule of Half), but can congest roadways, resulting in negative reliability impacts and often resulting in negative welfare impacts for existing travelers. Therefore, depending on the specific nature of the VMT increase, it can quickly lead to either much higher or lower overall welfare values.

While VMT changes rather directly impact B/C ratios, VMT is not a variable input to the model; like B/C ratios, VMT values are outputs of the PET model. In order to determine the primary sources of extreme variation in B/C ratios, two multinomial-response models were developed, one for each alternative scenario, using parameter values (across the 600 test runs) as covariates, and categorizing B/C outcomes as less than -100, between -100 and +100, and above +100. The middle case served as the base/reference category, and covariates were interacted with indicator variables for the Low, High, and "either low or high" (referred to here as "Extreme") B/C-outcome categories. Such categorization allows one to focus on the general nature of the outcome, without allowing extreme values to dominate the regression. Since each scenario is distinct (e.g., some are weak proposals and others strong), there is no guarantee inputs will impact outputs similarly across scenarios. Therefore, regression analyses were conducted separately for each scenario.

The output-regression model specifications were developed by beginning with all variable parameters as explanatory variables, including a high and a low indicator for each explanatory variable, much like an alternative-specific constant. (Thus, for example, the model began with a high_VOTT coefficient, which corresponds to outcomes with B/C ratios above 100, and a low_VOTT coefficient for outcomes with B/C ratios below -100). Parameters were selected using stepwise deletion and addition of input values as covariates, with a p-value cutoff of 0.05. Null hypothesis tests were conducted at the 5% level to determine if a single "extreme" value could be applied to both the high and low coefficients, as a merged parameter. For example, the capacity variation coefficient value was -32.5 for the high indicator and -33.6 for the low indicator, with standard deviations of 3.4 and 3.5, respectively. These coefficient values were combined to a single extreme coefficient value, indicating the impact of capacity variation on the probability that a given scenario's B/C ratio would be either very high or very low. Table 4 shows the results of this analysis, with the parenthetical values noting the corresponding outcome indicator (less than -100 for Low, above +100 for High, and either of these outcomes as Extreme).

|  | Scenario |  |
|---|---|---|
| **Name** | **Freeway Upgrade** | **Tollway Upgrade** |
| High Category Constant | -4.32 (High) | -9.82 (High) |
| Low Category Constant | -4.42 (Low) | -9.38 (Low) |
| Value of Travel Time | 5.65 (Extreme) | 3.68 (Extreme) |
| Value of Reliability | 1.98 (Extreme) |  |
| Crash Costs | -1.63 (Extreme) |  |
| Emissions Values | 1.01 (Extreme) | 0.659 (Extreme) |
| ***Link Capacities*** | ***-32.5 (Extreme)*** | ***-31.9 (Extreme)*** |
| ***Link Performance Params.*** | ***13.5 (Extreme)*** | ***19.7 (Extreme)*** |
| Local Crash Rate Calibration Factor | 1.07 (High) |  |
| Ambient Temperatures |  | 1.57 (Low) |
| Average Vehicle Occupancies |  | -1.63 (Extreme) |
| User Class Share: Heavy-Truck Drivers (very high VOT) | 3.62 (Extreme) | 3.32 (Extreme) |
| User Class Share: Non-work related (low VOT) | -2.78 (Extreme) |  |
| Mode Probability: SOV |  | 0.993 (High) |
| Mode Probability: HOV2 | 1.27 (Extreme) |  |
| Mode Probability: HOV 3+ | 1.41 (Extreme) | 1.31 (High) |
| Annual Trip Growth Rates (over time) | 5.5 (Extreme) | 5.88 (Extreme) |
| Demand Elasticity (for O-D pairs) | 4.59 (High) & 5.63 (Low) | 6.17 (Extreme) |
| Initial Project Costs | -1.65 (Extreme) | -2.38 (Extreme) |
| $N_{obs}$ | 600 | 600 |
| Likelihood Ratio Index | 0.568 | 0.626 |

Table 4: Parameter Estimates for Multinomial Models Predicting Extreme B/C Ratios

Several significant findings emerge from Table 4's parameter estimates. First, substantial decreases in assumed link capacity values or increases in the two link performance parameters regularly cause the extreme outcomes, by creating a very congested network in early years (not just the design-life year, after base trip volumes have grown by over 22 percent). In the most extreme cases, low capacity and high α and β values resulted in instances where system VMT was nearly 8 times larger or smaller in the two expanded-capacity scenarios than in the same-iteration Base Case scenario, thereby generating the unlikely results.

As noted earlier, the importance of these parameters also explains why the B/C distributions for the high- and low-variation (Table 3) sets of runs were so similar. Capacity values and the other two link performance parameters (α and β) were modeled with a single 10% CoV in both sets of sensitivity testing runs. While other parameters were allowed to vary more (in the high-variation runs), capacity and link performance parameters remain the driving force behind B/C outcomes. They clearly dominate results, suggesting that link-performance assumptions deserve careful generation and treatment.

Though their Table 4 coefficient values are not quite as large, sizable increases in travel growth rate assumptions, demand elasticity, values of travel time, and truck shares also increase the likelihood of extreme B/C ratios, while increases in the share of non-work related (i.e., low VOT) travel decreased the probability of extreme B/C outcomes. All parameters with Table 4 coefficients exceeding the project-cost variable's coefficient are practically most important. Initial project costs comprise 90% or more of these two scenarios' project lifecycle costs and so serve as a useful reference point: essentially, a doubling of initial costs should reduce the B/C ratio's magnitude by about 50 percent.

Interestingly, when different coefficient values were applied to the High and Low outcomes, the difference never exceeded 1.6, or about 5% of the impact of a similar change in link capacity. This suggests that as Table 4's parameters grow (or shrink if possessing a negative coefficient), the B/C outcome will become increasingly unstable, rather than strictly positive or negative. Therefore, the results highlight substantial potential project performance instabilities caused by key parameters, rather than any clear bias toward (or away from) the build scenarios based on certain inputs.

A second investigation was also conducted to look at the magnitudes of B/C ratios (to complement the multinomial choice model predicting outliers), using an ordinary least squares (OLS) regression model. The best fits were found using the natural log of the absolute value of the simulated B/C ratios. Other specifications were investigated, using B/C ratios directly or attaching a sign to their logarithm (to reflect the original ratio's sign), but these performed poorly (with $R^2$ values less than 0.11). This is likely due to extreme B/C values or outliers (causing non-linear impacts for extreme outcomes) and common factors that contribute to both positive and negative outliers, as shown in Table 4.

One important limitation of using $Y = \ln|B/C|$ is that it fails to predict whether a particular, random setting will result in a win ($B/C > 1$) or a loss ($B/C < 1$). In the presence of extreme (and unlikely) outcomes, it remains important to determine which input factors influence the direction and sign of project impacts, in addition to magnitude. Beyond B/C values, outputs of crash counts, emissions estimates, link volumes, toll revenues and other PET predictions exhibited similar outlying values, with most outliers emerging in the design-year (rather than in the initial-year, which is unaffected by the trip growth rate factor). To address the question of outcome sign, standard linear regressions were performed (using untransformed outputs, like $Y = B/C$) on the middle 50% of initial-year values (in the B/C case) and middle 90% of initial-year outcomes (for other outputs). This was conducted by simply discarding the top and bottom 25% or 5% of points, in order to eliminate the disproportionate impact of outliers. Such results are also shown in the final columns of Table 5 (for the B/C values) and in Tables 6 and 7 (for other PET outputs). In each of these tables, the coefficient values indicate the impact to the Y-value that should be caused by a one-hundred percentage point change in the X-value; for example, among the mid-50% truncated sample, a 10% (or 0.1) capacity increase is estimated to cause the Freeway Upgrade's B/C ratio to fall by -3.12, on average.

| | $y = \ln\lvert B/C\rvert$ | | $y = B/C$ (50 % truncated sample) | |
|---|---|---|---|---|
| | Freeway Upgrade | Tollway Upgrade | Freeway Upgrade | Tollway Upgrade |
| Constant | 2.408 | 1.879 | 38.522 | 20.889 |
| ***Value of Travel Time*** | ***2.881*** | ***2.552*** | ***7.39*** | ***8.408*** |
| Value of Reliability | 0.665 | | | |
| Vehicle Operating Costs | -1.436 | -0.938 | -5.737 | |
| Emissions Values | | | 1.904 | 1.294 |
| ***Link Capacities*** | ***-14.946*** | ***-17.95*** | ***-31.156*** | ***-39.275*** |
| ***Link Performance Params.*** | ***7.914*** | ***10.13*** | ***10.508*** | ***18.561*** |
| Free-Flow Speeds | | | | -7.278 |
| Reliability Parameters | | | 3.749 | 1.62 |
| Emissions Rate Calibration Factor | -0.596 | | | |
| Time of Day Scale Parameter | 0.435 | 0.886 | -1.599 | |
| ***User Class Share: Heavy-Truck Driver (High VOT)*** | ***2.346*** | ***2.089*** | ***5.198*** | |
| User Class Share: Work Related (High VOT) | | | | 2.487 |
| User Class Share: Non-Work Related (Low VOT) | -1.311 | -1.02 | -3.739 | |
| Mode Probability: SOV | | -0.576 | | |
| Mode Probability: HOV2 | 0.761 | | | |
| Mode Probability: Transit | | | -3.338 | -3.169 |
| ***Annual Trip Growth Rate*** | ***3.207*** | ***3.853*** | | 5.994 |
| ***Demand Elasticity*** | ***2.741*** | ***3.137*** | | |
| ***Initial Project Costs*** | -1.306 | -1.027 | **-8.351** | **-1.752** |
| $N_{obs}$ | 600 | 600 | 300 | 300 |
| $R^2$ | 0.655 | 0.732 | 0.403 | 0.438 |
| $R^2_{Adj}$ | 0.647 | 0.727 | 0.38 | 0.419 |

Table 5: B/C Ratios Regression Model Estimates for Freeway Upgrade and Tollway Upgrade Scenarios (X values = Scale factors on underlying variables, such that X = 1.3 = 30% increase in variable value)

Several significant findings emerge from Table 5's parameter estimates. First, the signs on estimated parameters are the same using transformed and untransformed B/C values, in the two datasets (n=600 vs. n=300). Similarly, the most important factors in the first model are also key in the second. The results suggest that, while networks that congest more quickly (due to link-performance parameter value shifts), lower initial costs, and higher values of travel time, trip growth and demand elasticity tend to produce more extreme B/C values, most lead to positive B/C results, on average.

Such results are mostly intuitive, and encouraging. In less extreme input-set cases, link-performance parameter ($\alpha$ and $\beta$) increases and reductions in system capacity appear to greatly enhance the value of capacity increases through new construction projects. Capacity reductions make travel speeds more responsive to demand levels, so the addition of new capacity to a congested network will benefit travelers more than if capacity is added to a network that already has excess capacity. The importance of these parameters is consistent with Krishnamurthy and Kockelman's (2003) propagation of uncertainty tests (in land use-transportation model applications for Austin). Additionally, when the outcome results in a high negative cost, it makes sense that further restricting system capacity and increasing $\alpha$ and $\beta$ can make a bad situation worse. In the most extreme cases, low capacity and high $\alpha$ and $\beta$ values resulted in instances where system VMT was nearly 8 times larger or smaller in the two expanded-capacity scenarios than in the same-iteration Base Case scenario, thereby generating the unlikely results. These unlikely results occurred even though all parameter changes were consistently applied to the Base Case and all alternative scenarios (e.g., a 10% demand elasticity increase would be consistently applied to the Base Case and both alternative scenarios for a given iteration).

Though their parameter values are not quite as large, sizable increases in VOTTs and the share of heavy trucks (which effectively diminishes link capacities) also improved B/C ratios (Table 3). Interestingly, the values of traffic growth and demand elasticity appear to have greater impact on the size – rather than sign – of the B/C outcomes. All parameters with Table 3 coefficients exceeding the project-cost coefficient are practically most important. Initial project costs comprise 90% or more of these two scenario's project lifecycle costs and so serve as a useful reference point: essentially, a doubling of initial costs should reduce the B/C ratio's magnitude by about 50 percent.

Capacity, the link performance parameters and free-flow speeds were estimated as being more important for the Tollway Upgrade than for the Freeway Upgrade scenario, while initial project costs were estimated to have substantial impact on the Freeway Upgrade scenario, but little impact on the Tollway Upgrade's results. This is likely because the Tollway Upgrade scenario charges users for using the upgraded links, so their perceived benefit must be worth their individual costs. Thus, factors that influence their direct benefit become more meaningful, and other factors (such as initial project cost) become less influential to overall project merit.

## CRASHES AND EMISSIONS

The impact of parameter variation on other key impacts was also evaluated. These assessed impacts crash counts, emissions levels, and traffic volumes on the impacted segment, as well as system-wide tolling revenues. Even with a benefit-cost ratio in hand, each of these key measures remains important to decision makers attempting to discern which project alternatives to fund, if any. Crashes in this evaluation were monetized, using Blincoe et al.'s (2002) values and inflating to 2010 values. However, non-economic "soft" crash components (such as the value of life and pain and suffering) were not monetized and should therefore be independently evaluated. Changes in five emissions species (Hydrocarbons, Nitrous Oxides, Carbon Monoxide, Particulate Matter < 2.5 μm, and Particulate Matter < 10 μm) were also monetized, using EU data (Mailbach et al. 2008). These emissions values may be important to cities seeking to meet air quality attainment goals, and PET's "monetary emissions benefits" output provides a framework for users to collectively quantify broad impacts across all five species. Table 6 details the initial-year regression outputs for crash counts and emissions costs.

|  | Initial-Year Crash Counts |  | Initial-Year Emissions ($M) |  |
|---|---|---|---|---|
|  | Freeway Upgrade | Tollway Upgrade | Freeway Upgrade | Tollway Upgrade |
| Constant | -5.63 | -7.23 | -4.99 | -3.93 |
| Value of Travel Time | -1.94 | -3.63 |  | -0.25 |
| Vehicle Operating Costs |  |  | 0.20 |  |
| Emissions Values |  |  | -0.40 | -0.39 |
| ***Link Capacities*** | ***10.97*** | ***11.92*** | ***4.90*** | ***4.59*** |
| ***Link Performance Params.*** | ***-4.94*** | ***-4.83*** | ***-1.30*** | ***-1.15*** |
| ***Free-Flow Speeds*** |  |  | ***1.35*** | ***1.11*** |
| ***Local Crash Calibration Factor*** | ***-16.86*** | ***-15.11*** |  |  |
| Emissions Rate Calibration Factor |  |  | -0.54 | -0.39 |
| User Class Share: Heavy-Truck Driver (High VOT) |  | -2.01 | -0.23 | -0.24 |
| User Class Share: Non-Work Related (Low VOT) | 1.82 | 1.74 |  |  |
| Mode Probability: HOV 3+ |  | 1.91 | 0.22 |  |
| $N_{obs}$ | 540 | 540 | 540 | 540 |
| $R^2$ | 0.563 | 0.479 | 0.522 | 0.451 |
| $R^2_{Adj}$ | 0.558 | 0.473 | 0.515 | 0.443 |

Table 6: Parameter Variation Impacts on Initial-Year Crashes and Emissions Costs vs. Base Case Scenario (mid-90% of data) (X values = Scale factors on underlying variables, such that X = 1.3 = 30% increase in variable value)

Several fundamental inferences may be made from Table 6. As with the B/C ratio results, capacity and the link performance parameters were influential in predicting crash and emissions changes vs. the Base Case scenario. VMT is typically lower in the alternative scenarios than in the Base Case scenario. As system-wide capacity increases across all scenarios, the differences in VMT between the alternative and Base Case scenarios falls, even though overall VMT typically increases. This results in lower crash reductions and lower emissions savings (or higher costs). For example, if initial-year crash counts are estimated to fall by 10 by constructing the Freeway Upgrade, a 10% increase in network capacities (for both the Freeway Upgrade and the Base Case scenario) results in an expected crash reduction of only 8.90. Similarly, if initial-year Tollway Upgrade emissions savings are estimated at $5 million, a 10% increase in capacity is predicted to result in only $4.41 million in emissions savings.

One major difference between the crash and emissions models is that the local crash calibration factor is more influential in predicting crashes than is the emissions rate calibration factor for predicting emissions costs. A 10% calibration factor increase should result in a 10% increase in the associated output (either crashes or emissions), by this factor's definition (a 1.1 crash calibration factor indicates a 10 percent crash increase from the default 1.0 value, suggesting an additional 1.5 initial-year crashes). As expected, the crash calibration factor coefficients are larger than those on other variable inputs (indicating that a change in other parameters will cause less than a roughly 10% change in crashes). Interestingly, the emissions calibration factor is much smaller than the link capacity coefficient and approximately the same value as the link-performance parameters' coefficients, $\alpha$ and $\beta$, thus indicating that a 10% change in capacity will have a much greater than 10% change in emissions and that a 10% change in the link-performance parameters can result in a roughly 10% emissions change. This suggests that crash predictions are much more stable than emissions costs, and less responsive to capacity and link-performance parameter changes.

## TRAFFIC VOLUMES AND TOLL COLLECTION

In addition to reviewing crash and emissions impacts, traffic volumes and toll revenues were also analyzed. Transportation agencies spending money to improve a facility inevitably want to know how much it will be used. Furthermore, toll revenues were not included in the overall benefit-cost ratio, since collected tolls are a benefit-neutral transfer payment from individual travelers to "society" via a public agency's collections (Kockelman et al. 2010). However, transportation agencies (or private enterprise) using PET will undoubtedly be interested in revenues since tolling may be the mechanism to cover project costs. Additionally, PET's tolling output is structured such that system revenues are reported rather than just for the improved links. This is particularly key in this case study since the project could impact collected tolls on an adjacent priced facility (SH 130).

As with crashes and emissions, linear regression models were run for initial-year upgraded-segment traffic volumes in both scenarios, though only for the changes in tolling revenues for the Tollway Upgrade scenario, as shown in Table 7.

|  | Initial-Year US 290 AADT (vehicles per day) |  | Initial-Year Tolls ($M) |
|---|---|---|---|
|  | Freeway Upgrade | Tollway Upgrade | Tollway Upgrade |
| Constant | 1039 | 716 | 8.06 |
| ***Value of Travel Time*** | 72 | ***1118*** | ***1.43*** |
| ***Vehicle Operating Costs*** | -51 | ***1638*** | ***2.03*** |
| ***Link Capacities*** | ***-1591*** | ***-2488*** | ***-1.44*** |
| ***Link Performance Params.*** | ***722*** | ***662*** |  |
| ***Free-Flow Speeds*** |  | ***-1396*** |  |
| Mode Scale Parameter | 23 | -195 | 0.56 |
| Time of Day Scale Parameter |  |  | 0.4 |
| Average Vehicle Occupancy | 56 |  | 0.6 |
| ***User Class Share: Heavy-truck Driver (High VOT)*** | 84 | 246 | ***2.93*** |
| User Class Share: Work Related (High VOT) | 32 |  |  |
| User Class Share: Commuter (Mid VOTT) | -34 |  |  |
| User Class Share: Non-Work Related (Low VOT) | -62 | -505 | -0.71 |
| Mode Probability: SOV |  | -253 | 0.76 |
| Mode Probability: HOV 2 | 44 |  |  |
| Mode Probability: Transit |  | 196 | 0.76 |
| Demand Elasticity | -34 |  |  |
| $N_{obs}$ | 540 | 540 | 540 |
| $R^2$ | 0.811 | 0.540 | 0.284 |
| $R^2_{Adj}$ | 0.806 | 0.531 | 0.271 |

Table 7: Parameter Variation Impacts vs. Base Case Scenario on Traffic Volumes and Tolling Revenues (mid-90% of data) (X values = Scale factors on underlying variables, such that X = 1.3 = 30% change in variable value)

Again, capacity and the link performance parameters were found to be highly influential in estimating traffic volumes. As capacity increases, travelers have less incentive to use the improved link, as opposed to other routes. However, for the Tollway Upgrade scenario, numerous other inputs had substantial impact. Values of travel time (VOTTs) and operating costs appear critical in determining traveler route choices and revenues. When either falls, travelers choose alternative, non-tolled routes. Also, user shares substantially impacted revenues and traffic volumes on the Tollway. The Heavy-Truck Driver user class has the highest VOTT (and pays the highest fare), while the Non-Work-Related user class has the lowest VOTT. Therefore, any increases in the proportion of the Heavy-Truck Driver user class or decreases in the Non-Work-Related user class resulted in more travelers on US 290 and more tolling revenues.

### DESIGN-YEAR IMPACTS

Finally, a series of regression estimates were conducted on the ln|y| transformed values of *design-year* crashes, emissions, traffic volumes and tolling revenues, as shown in Table 8.

|  | ln(Crashes) | ln(Emissions) | ln(US 290 AADT) | ln(US 290 Tolls) |
|---|---|---|---|---|
|  | Freeway & Tollway | Freeway & Tollway | Freeway & Tollway | Tollway |
| Constant | 0.84 | 13.24 | 6.33 | 16.209 |
| Value of Travel Time | 0.74 | 1.49 | 0.65 |  |
| Vehicle Operating Costs | -0.72 | -1.2 | -0.78 (Tollway) |  |
| ***Link Capacities*** | ***-7.34*** | ***-15.58*** | ***-9.33*** | ***-2.158*** |
| ***Link Performance Params.*** | ***4.95*** | ***9.82*** | ***5.2*** | ***0.821*** |
| Local Crash Calibration Factor | 0.84 |  |  |  |
| Emissions Rate Calibration Factor |  | 1.03 |  |  |
| Mode Scale Parameter |  |  |  | 0.156 |
| Time of Day Scale Parameter |  | 0.53 | 0.26 (Tollway) |  |
| Ambient Temperatures |  | -0.55 |  |  |
| Average Vehicle Occupancy | 0.43 (Tollway) |  |  | 0.297 |
| User Class Share: Heavy-Truck Driver (High VOT) | 1.08 (Freeway)<br>0.65 (Tollway) | 1.68 | 0.85 |  |
| User Class Share: Work Related (High VOT) |  |  | 0.49 |  |
| User Class Share: Non-Work Related (Low VOT) | -0.45 | -1.01 | -0.62 (Freeway) |  |
| Mode Probability: HOV 2 | 0.33 | 0.9 | 0.3 |  |
| Mode Probability: HOV 3+ |  |  | 0.35 |  |
| ***Annual Trip Growth Rate*** | ***2.01*** | ***3.52*** | ***1.89*** | ***0.713*** |
| ***Demand Elasticity*** | ***2.36*** | ***2.82*** | ***1.44*** | ***0.86*** |
| $N_{obs}$ | 1200 | 1200 | 1200 | 600 |
| $R^2$ | 0.511 | 0.640 | 0.511 | 0.192 |
| $R^2_{Adj}$ | 0.506 | 0.636 | 0.506 | 0.183 |

Table 8: Design-year Parameter Variation Impacts vs. Base Case Scenario for Natural Log of Crash Counts, Emissions Costs, US 290 AADT, and Toll Revenues (X values = Scale factors on underlying variables, such that X = 1.3 = 30% change in variable value)

Unsurprisingly, capacity and the link performance parameters dominated the outcomes' magnitude in all design-year cases, with outputs (changes in crashes, emissions, volumes and tolls vs. the Base Case scenario) rising as capacity becomes constrained. As noted earlier, this occurs largely because the constriction of system capacity (or increase in link-performance parameters) causes bigger VMT differentials between the Base Case and alternative scenarios. This then magnifies the Upgrade scenarios' impacts. The other parameter sets exhibiting practically significant impacts are annual trip growth rate and demand elasticity. These also have consistent impacts across all four regression models. Next to the capacity and link-performance factors, these two parameters had a greater impact than any other. This makes sense, since growth-rate impacts will be compounded over time, and demand elasticity will regulate the additional number of trips that occur as travel costs change, both crucial elements in the Freeway Upgrade and Tollway Upgrade scenarios.

# Chapter 4: Conclusion

The Project Evaluation Toolkit described in this thesis was developed to provide transportation planners and policy makers with the ability to quickly predict and compare project impacts among a variety of alternative scenarios. PET's application complexity falls between a regional travel demand model and a stand-alone corridor analysis, while providing a host of new and increasingly critical outputs and costs. In this way, PET users should be able to obtain a preliminary estimate of system-wide project impacts before conducting a more detailed analysis of demand patterns using a full-network demand model.

PET estimates changes in traveler welfare (accounting for changes in travel times and operating costs) as well as travel time reliability, crashes, emissions, fuel use and tolling revenues, relative to a base case (e.g., no-build) scenario. It summarizes individual component impacts while providing economic summary measures for inter-project comparisons. Such outputs allow users to comprehensively evaluate and compare scenario alternatives in a robust and consistent framework, as illustrated by the case studies described in Chapter 2.

Case study findings show how traveler welfare impacts dominate all other measures, in the case of capacity expansion projects. Importantly, reliability also plays a significant role, comprising up to 40% of total monetized impacts. If monetized, changes in crash counts and emissions are found to play a rather small role in overall project impacts, accounting for no more than a combined 10% of benefits, as found in the US290 Tollway Upgrade scenario's initial-year impacts (using higher willingness-to-pay [full-cost] measures to avoid crashes). Travel demand management case study results show how attempts to reduce travel demand through congestion pricing or limiting capacity can have unintended results, such as shifting traffic to alternative routes that may be far less suited to handling the added traffic. Meanwhile, operational strategies such as speed harmonization, shoulder lane use, and incident management show promise – with particularly high benefit-cost ratios for the shoulder lane use strategy. Finally, the work zone case study demonstrates that on highly congested facilities it may be better to sacrifice small amounts of capacity for longer periods of time, rather than significantly constraining capacity for a shorter period.

Beyond model development and case study applications, this thesis work involved a thorough investigation into the impacts of parameter uncertainty on highway project outcomes. Twenty-eight parameter variations and their effects on benefit-cost ratios, crashes, emissions, traffic volumes, and tolling revenues were examined in detail. From this evaluation it quickly became clear that, if analysts underestimate capacity or overestimate link performance parameters, benefit-cost ratios and other predictions may quickly become unreasonable. Another crucial finding showed how the median of simulated B/C ratios was significantly lower than the point-estimate B/C ratio (evaluated at input means) when no variation was assumed. This is particularly important since the single-point estimates – very typical of practice –would lead analysts to expect higher benefits from these project scenarios than the uncertainty-in-inputs approach would suggest.

Additionally, even when omitting extreme outcome variations, capacity and the link performance parameters had greater impact on B/C ratios, crashes, emissions, traffic volumes, and tolling revenues than any other examined inputs. B/C ratios strongly depended on VOTTs in both scenarios, though the value of time (and operating costs) impacted the actual use and collected revenues of the improved facility for the Tollway Upgrade much more heavily than in the Freeway Upgrade scenario. As expected, crash counts (and costs) were found insensitive to congestion relative to emissions costs, though both were impacted. Finally, the magnitudes of design-year outcomes were strongly influenced by travel growth rate assumptions and demand elasticity parameters.

In summary, this thesis work offers a new model for travel demand modeling and project evaluations on abstracted networks. The body of the thesis illustrates potential applications of PET and provides detailed analysis of PET outputs using sensitivity testing under input variation. Transportation planners, engineers, and policymakers may employ similar methods, using PET to produce a range of likely outcomes, rather than a single point estimate. This paper details which parameter variations tend to cause the greatest variations in impacts under two scenarios, though ultimate results will depend on the nature of any future project under consideration. These methods and findings should enhance the ability of decision makers to allocate limited transportation funding resources while providing the most beneficial outcomes for society at large.

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