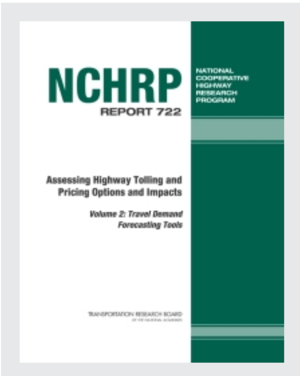

Assessing Highway Tolling and Pricing Options and Impacts: Volume 2: Travel Demand Forecasting Tools

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 722

Assessing Highway Tolling and Pricing Options and Impacts

Volume 2: Travel Demand Forecasting Tools

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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FOREWORD

By Lori L. Sundstrom
Staff Officer
Transportation Research Board

NCHRP Report 722: Assessing Highway Tolling and Pricing Options and Impacts provides state departments of transportation (DOTs) and other transportation agencies that are considering instituting or modifying user-based fees or tolling on segments of their system with a decision-making framework and analytical tools that better describe likely impacts on revenue generation and system performance. This report is presented in two volumes. *Volume 1: Decision-Making Framework* should be of immediate use to staff responsible for structuring the policy-level evaluation of potential tolling and pricing solutions to examine their policy implications, performance expectations, and financial impacts. *Volume 2: Travel Demand Forecasting Tools* will provide staff who develop the forecasts of potential revenue, transportation demand, and congestion and system performance with an in-depth examination of the various analytical tools available for direct or adapted use.

The continued growth in travel demand, worsening congestion, and the significant reduction in transportation funding available from traditional sources has prompted a number of DOTs and other transportation agencies, including toll authorities and metropolitan planning organizations, to turn to tolling and pricing as a method to fund new capacity and to more effectively manage congestion and improve the performance of their systems. A number of agencies have initiated projects that rely on tolling (the assessment of a fixed fee for the use of a roadway) and/or pricing (varying toll rates by time of day or volume of traffic) as an alternative to traditional funding sources. Several states have enacted legislation that requires new capacity to be funded by revenues derived from tolling and/or pricing. Traditional methods and analytical tools used in transportation decision making such as transportation demand forecasting, risk analysis, benefit-cost analysis, financial analysis, market research, and others fall short, however, in addressing the complexities associated with tolling and pricing decision making.

Under NCHRP Project 08-57, Parsons Brinckerhoff, Inc., was asked to develop a decision-making approach for DOTs and other transportation agencies to use to conduct comprehensive, transparent, and technically defensible analyses of a range of likely impacts of potential tolling and pricing solutions. The resulting decision-making framework in Volume 1 can be applied to a variety of scenarios in order to understand the potential impacts of tolling and pricing on the performance of the transportation system, and on the potential to generate revenue to pay for system improvements. Parsons Brinckerhoff conducted a literature review, collected state-of-the-practice information from numerous agencies, and provided five detailed case studies (viewed through the lens of the decision-making framework) that present lessons learned and illustrate a variety of best practices. Volume 2 provides a set of practical recommendations for developing travel models for different pricing studies. The research team also evaluated travel models and network simulation tools used to forecast travel demand and revenue, and identified short-term and long-term improvements and strategic directions to improve the quality of their results and relevance to decision making.

Public and private sector decision makers and practitioners should find *NCHRP Report 722* a valuable resource as they review issues associated with tolling and pricing decisions.

CONTENTS

Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

CHAPTER 1

Summary

NCHRP Report 722: Assessing Highway Tolling and Pricing Options and Impacts, Volume 1 and *Volume 2*, together, constitute the body of the final report. Each volume, however, is a self-contained document that can be independently reviewed and understood by the reader. The purpose of Volume 2 is to survey forecasting tools applied at different stages of pricing projects, synthesize the best practices, provide practical recommendations for possible short-term improvements, identify the main gaps, and outline the major directions for principal long-term improvements. Several of the suggested improvements are further tested in the pilot studies.

1.1 Need for Solid Traffic and Revenue (T&R) Forecasts

Decisions about toll roads involve structural and technical details. The accuracy of T&R forecasts is crucial; in addition to the usual planning aspect there is generally a political aspect involved (intertwined with public relation/intervention), as well as private investors. As a result, T&R forecasts are closely reviewed by many parties and the level of scrutiny of expected performance is much greater than for non-tolled highway projects. In particular, issues that relate to environmental justice will be especially scrutinized during the NEPA process. T&R projections will be scrutinized by the project sponsors and specifically by the rating agencies at the Investment Grade stage.

If the T&R forecasts are not reasonable and if modeling tools that were applied do not satisfy the criteria established in the profession, the project may fail during any stage of development. In addition, even if the project is accepted, financial conditions may be much worse than they could have been under different forecasts as the result of a low credit rating.

Even if the pricing project is successful within the formal terms of the Environmental Impact Analysis and is graded high with respect to the revenue versus cost, computerized travel models and related tools can help tremendously with building consensus among the general public and potential stakeholders, as well as at the political level. Travel model results should be presented in a form that are accessible to and can be convincing for a wide audience of non-technical people. In this regard, the following products of the T&R forecasts can be seen as important:

- Demonstration of the congestion relief and improved highway throughput using visual traffic simulation tools.
- Mapping of travel time savings and showing accessibility improvements [like isochrones of travel time needed to reach the central business district (CBD) area].
- Detailed equity analysis focusing on specific population segments (like low income people in the area directly affected by pricing) to illustrate how each segment is affected, by a proposed pricing action and alternative transportation options.

Pricing affects travel demand in many ways. In general, pricing affects travel demand negatively in the sense that travelers will attempt to avoid pricing by switching to other (free) roads, transit, or other periods of the day, depending on available options. With pricing, however, travel times on the priced facility improve significantly. Thus, toll versus saved time ultimately represents the major trade-off from the perspective of highway users. This trade-off is resolved differently by different population segments and also varies by different geographic segments. As a result, total aggregated user benefits and/or revenue cannot tell the whole story, and structural details are important to assess potential winners and losers of the pricing project.

Ultimate winners are travelers for whom travel time savings (as well as companion travel time reliability improvements) are valued more than the toll. Losers represent travelers for whom travel time savings are valued less than the toll. Some will continue using the facility while others will switch to alternative options (free roads, transit, other time of day, other destination, etc.). The comparison of travel time savings to tolls is embedded in each decision-making process and is generally formalized by value of time (VOT), which represents traveler willingness to pay for one saved hour (and measured in dollars per hour).

From a practical perspective, travel demand models represent tools for modeling traveler responses to pricing and identifying winners and losers, their benefits and costs, with a desired level of accuracy for multiple travel segments comprised of different population groups for different geographic areas. The necessary level of detail requested by the National Environmental Policy Act (NEPA) process, as well as by the rating agencies, includes four to five major travel purposes, three to four income groups, three to four time-of-day periods, and (normally) thousands of zones (trip origins and destinations). All these details are important since they can have large impacts on traveler willingness to pay, calculation of travel time savings, and identification of alternative options available for each traveler. As a result, it is generally impossible to implement all related calculations with the necessary level of detail using simplified spreadsheet-based methods.

1.2 State of the Practice and Challenges in T&R Forecasting

1.2.1 Main Factors Affecting Reasonability of T&R Forecast

A reliable and creditable T&R forecast is a function of many factors. The following major components of the forecasting process can be identified as important:

- Travel forecasting model structure, its soundness from the analytical point of view, and its ability to realistically portray the behavioral response of travelers to congestion and pricing.
- Quality and comprehensiveness of the base year data used for model validation and calibration including a Household Travel Survey and other complementary surveys, traffic counts, etc.
- Reasonableness of the assumptions regarding the future growth of population and employment in the regions, as well as the development of the transportation network. These assumptions represent key inputs to the T&R forecasting procedure and their impact on the final result is as substantial as the quality of the model itself. The reported criticism of T&R forecasts implemented in the past in many regions is, to a large degree, attributable to problems with these input assumptions. Different from the first two factors, where concrete recommendations and well-defined technical procedures can be stated, substantiation of future socio-economic and transportation network scenarios is a very open issue that resides more in the planning domain, rather than in field of modeling. In this regard, the current report only summarizes certain basic rules (like conservatism and comparison of the future scenarios to the observed trends), reporting the most frequent pitfalls and concerns.

1.2.2 State of the Practice and Major Gaps Identified

The extensive analysis done in this research of travel models and network simulation tools applied in practice for T&R studies has revealed a highly diverse picture, with a large proportion of applications with simplified methods as well as a growing number of applications of more advanced modeling tools. The following main conclusions can be made regarding the general tendencies and specific important methods observed, along with the identification of gaps where improvements are needed:

- There is a great deal of variation in approaches. In most cases, the model applied for the highway pricing project was essentially a modification of the existing regional model available for the study. Thus, limitations and deficiencies of the existing regional model were inevitably adopted for the study.
- In most cases, only route itinerary (assignment) and binary route type choice (toll versus non-toll) models were employed for comparison and evaluation of pricing alternatives. This achieves reasonable results under the assumption that pricing would not affect mode choice, time-of-day choice, trip distribution, and trip generation. While this simplification might be acceptable for some analyses of intercity highways, it is more difficult to defend for forecasting most of the metropolitan and urban facilities.
- Pricing effects on trip distribution have been incorporated by using mode choice Logsums as the measure of accessibility in destination choice or gravity-type distribution models. The use of mode choice Logsums in gravity models needs to be tested extensively; unlike destination choice frameworks, where appropriate elasticities to cost are expected when reasonable Logsum parameters are used, it is not clear that doubly-constrained gravity models behave appropriately to changes in level of service (LOS) variables such as the introduction of tolls.
- In some cases there is an inconsistency between the travel times and costs used for the trip distribution and mode choice models, in that the travel times reflect priced conditions while the toll cost itself does not enter the impedance function. This is the case when travel times are fed back from a generalized cost assignment into a distribution model that is a function of travel times only.

- In a few cases utility functions in multinomial or nested logit mode choice models are miss-specified. Undesirable specifications include toll utilities that are a function of the toll alternative travel time and travel time savings with respect to the free alternative. This type of specification may result in counterintuitive results when the LOS attributes on either the toll or the free routes change. Another potentially problematic specification is the use of thresholds, such as making the toll alternative available only if it meets a pre-defined minimum time savings goal.
- There is no consensus on whether road pricing costs should be shared among vehicle occupants and, if so, how. Most models either assume that the full toll cost is either borne by all occupants or that it is equally shared among the occupants.
- In some regional modeling systems that were specifically modified for congestion pricing projects**,** peak-spreading models were applied. Trip-based 4-step models are normally based on time-of-day (peak) factors that are not sensitive to the relative congestion levels at different periods of the day. AMBs can offer a better framework where peak-spreading effects are captured by time-of-day choice sub-model sensitive to the congestion level and pricing.
- Almost all models, including advanced activity-based models (ABM) are characterized by a significant discrepancy between the user segmentation VOT in the demand model compared to network simulation. While at the demand modeling stage, segmentation normally includes several trip purposes, income groups, car occupancy, and time-of-day periods; network simulations are characterized by more limited segmentation. Traffic assignments are implemented by periods of the day and for multiple vehicle classes that typically include vehicle type and occupancy. However, trip purposes and income groups are blended together before assignment, creating strong aggregation biases with respect to VOT.
- Most models break down the network simulation into four broad time periods, typically AM Peak (2 to 4 hours long), Midday, PM Peak (2 to 4 hours long), and Night, and are therefore able to compute LOS differences by time of day only at this level of aggregation. Only one of the regional models reviewed performs the network simulation at a finer time-of-day disaggregation.

1.2.3 Recommended Short-Term Improvements

Although the major strategic directions to improve models are strongly associated with a new generation of advanced ABMs and network simulation tools like DTA, there are many practical steps that can be taken to improve 4-step models (and simple ABMs) to better prepare them for T&R forecasting and to ensure reasonable model sensitivities for different pricing projects and policies. The following improvements can be made:

- A travel model that is going to be applied for a highway pricing study should comply with a minimal set of structural requirements. These include a reasonable model sensitivity to toll across all travel dimensions that can be affected by pricing, including route choice, mode (and car occupancy) choice, trip distribution, and time-of-day choice, etc. Across all these choices, a reasonable level of segmentation and correct estimates of VOT (with the necessary aggregations) should be applied.
- The demand model should be segmented by at least 4–5 travel purposes and 3–4 income groups with VOT specific for each combined segment. Additional useful steps that can be taken are to apply differential travel time coefficients by segments in the network assignment step, as well as by congestion levels, representing in part a simple proxy for highway the effect of congestion on reliability.
- A revision of the network procedures to incorporate differential tolls and vehicle categories relevant to the pricing study is necessary. The traffic assignment should incorporate and distinguish relevant vehicle classes (auto, commercial vehicles, trucks, taxis, etc.) with the appropriate average VOT per class. The technique of multi-class assignment is supported in all major transportation software packages (TransCAD, EMME, and Cube) and can be further applied to differentiate between VOT groups within the same vehicle class. If tolls or vehicle eligibility are differentiated by vehicle occupancy (HOV/HOT lanes) the auto vehicle class should be additionally segmented by the relevant occupancy categories (SOV, HOV2, HOV3, etc).
- It is highly recommended (though it is not absolutely essential in the early stages of pricing studies) to incorporate a binary route type choice model (toll versus non-toll facility), either as a lower-level sub-nest in mode choice or as a pre-assignment procedure. This sub-model allows for capturing a toll bias associated with the perception of the generally improved reliability and safety of the toll facility, as well as provides for better (non-linear) specifications of the tradeoffs between travel time savings and extra costs.
- It is essential for congestion pricing studies to include an improved time-of-day choice (peak-spreading) model sensitive to congestion level and pricing. Although the trip-base structure is very limited in addressing time-of-day choice factors, it can incorporate a time-of-day choice model with a fine level of temporal resolution (one hour or less) that would roughly correspond to the outbound and inbound components of the tour-based time-of-day choice model applied separately for each trip segment.
- There are a growing number of applications where mode and/or occupancy choices were included. In several cases,

mode, occupancy, and binary route type choices were combined in one multi-level nested logit choice model structure where occupancy and route type choice served as lower-level sub-choices. These improvements can be implemented and are equally relevant for both 4-step models and ABMs.

- It is essential to equilibrate the demand model (at least mode choice and route type choice) and the highway assignment to ensure that the results correspond to (or at least approximate) a stable equilibrium solution. It is more difficult to include the trip distribution (and other sub-models like time-of-day choice or trip generation) in the global equilibrium, which might require multiple iterations and special averaging algorithms. However, it is essential to eventually ensure a reasonable level of convergence of the entire model system. Recent experience with the New York ABM has shown that effective strategies of equilibration based on a parallel averaging of trip tables and LOS skims can achieve a reasonable level of convergence in three to four global iterations, even in one of the largest and most congested regional networks.
- Network simulations should be carefully validated and calibrated to replicate period-specific traffic volumes, as well as period-specific LOS attributes. In this regard, the prevailing practice of model validation by daily traffic counts has to be replaced with more extensive and elaborate validation or calibration by four to five time-of-day periods.
- There are many reserves for improvements that relate to a better understanding and incorporation of rules of the financial world. Many of them relate to the way a model is used, rather than to its structure. They include more thorough procedures for assessing non-modeled days (weekends and holidays) and time-of-day periods (if the model does not cover an entire weekday), as well as explicit consideration of possible ramp-up dynamics for the first several years of a project. The model structure and output should be made to produce the necessary inputs to the financial plan. Of special importance is the issue of quantification of risk factors. Risk analysis essentially represents an important strategic direction with many aspects that have yet to be explored by travel forecasters. Some simplified procedures, however, based on the possible scenarios for main input factors can be applied even with a simple travel model.

1.2.4 Recommended Long-Term Improvements and Strategic Directions

The main avenues for improvement of modeling tools applied for pricing studies are seen to be associated with the advanced ABM framework on the demand side and DTA on the network simulation side. ABMs provide clear advantages over trip-based models in the analysis of pricing policies. In particular, limitations of trip-based models such as a lack of policy sensitivity and insufficient market segmentation can be overcome with more advanced models. The main advantages of ABM structure for modeling highway pricing scenarios can be categorized according to the following model features:

- **Tour-based structure** that is essential for accounting for tolls applied by direction by time-of-day periods, in a consistent and coherent way. This is, however, conditional upon obtaining a level of temporal resolution that matches the details of pricing schedules. Since variable pricing schemes are frequently in the focus of pricing studies, it is essential to have a large set of period-specific simulations, ideally, hourly assignments (or a full-day DTA) in order to address different pricing schedules.
- **Microsimulation of individuals** that allows for probabilistic variation of individual parameters including VOT, car rationing by license plate, toll discounts associated with different payment types, and/or population groups. In addition to that, a fully disaggregate structure of the model output is extremely convenient for reporting, analysis, and evaluation of the pricing scenarios, in particular for the screening of winners and losers, and for equity analysis across different population groups.
- **Entire day individual activity pattern** that allows for a consistent modeling of non-trip pricing options, such as a daily area pricing fee.

There are, however, a number of issues that remain to be addressed by ABMs in practice. First, most ABMs continue to rely on static equilibrium highway assignment algorithms. It is common knowledge that such techniques fail to adequately address congestion due to their lack of ability to reflect queuing. One of the advantages of priced facilities (particularly dynamically priced facilities) is that they offer more reliable travel times than competing congested facilities where the variability of travel time can be quite onerous. From this perspective, the integration of an ABM and DTA in one coherent modeling framework represents one of the most important strategic directions for the field.

The advanced and flexible microsimulation modeling paradigm embedded in ABM and DTA structures opens a constructive way to include many recent theoretical advances in applied operational models. The following main aspects and directions were identified in this research:

- Heterogeneity of road users with respect to their VOT and willingness to pay. This requires a consistent segmentation throughout all of the demand modeling and network simulation procedures to ensure compatibility of implied VOTs. In addition to an explicit segmentation, random coefficient choice models represent a promising tool for capturing heterogeneity.

- Proper incorporation of toll road choice in the general hierarchy of travel choices in the modeling system. Additional travel dimensions (such as whether to pay a toll, car occupancy, and payment type/technology) and associated choice models should be properly integrated with the other sub-models in the model system. The impacts of pricing on long-term choices, such as vehicle ownership, workplace location, residential location, and firm location, need to be better understood. Most ABMs are based on cross-sectional data and are unable to fully capture long-term behavior associated with the introduction of pricing policies. Hopefully, as more policies become implemented, more longitudinal data will be available to improve this critical aspect of travel demand models.
- Accounting for reliability of travel time associated with toll roads requires the incorporation of travel time reliability in applied models with quantitative measures that can be modeled on both demand and supply sides.
- More comprehensive modeling of time-of-day choice based on the analysis of all constraints associated with changing individual daily schedules.
- More comprehensive modeling of car occupancy-related decisions, including differences in carpool types (planned intra-household, planned inter-household, and casual) and associated VOT impacts.
- Advanced traffic simulation procedures such as DTA and microsimulation, and better ways to integrate them with travel demand models. In this regard, future research needs to systematically incorporate features such as heterogeneous users in response to dynamic tolls and to develop efficient heterogeneous intermodal shortest path algorithms.

Many of these research topics are being addressed in ongoing NCHRP and SHRP 2 projects. Incorporation of the results of these studies in models applied for highway pricing studies in practice represents an important challenge for the transportation modeling profession.

1.3 Model Features Required for Different Pricing Studies

1.3.1 Model Features for Different Pricing Projects

Based on an accumulated modeling experience with various pricing projects, we have first classified the required model features that stem from the range of planning needs associated with different project types. Further on, in the subsection that follows, the same model features are arrayed by the four main stages of decision-making process defined in Volume 1.

As shown in Table 1, there are some model features that are absolutely essential to pricing studies in the very beginning of analysis, while other more advanced features may be reserved for subsequent stages of project development (detailed feasibility and investment grade studies). The more advanced features, however, may become extremely relevant even early on, if a corresponding pricing strategy is included in the range of options included in the scope of the particular study, and a robust and consistent analysis of it is required to compare with other more easily modeled alternatives. Both essential and advanced modeling features may still belong in the category of short-term improvements, however, and are not explicitly distinguished here between 4-step and ABM frameworks in this classification.

1.3.2 Model Features for Different Stages of Decision Making

The model improvement process and its desired features can be arrayed in parallel with the basic general stages of pricing studies. A framework of gradual corresponding improvements is outlined in Figure 1: four major stages of the project development (described in Volume 1, Chapter 4, in detail), and four broad stages of improvement of the forecasting tools. In general, having an advanced model from the very early stage would be an advantage; however, it is not always necessary. A pricing study could begin with a simplified model, while the data and modeling tools are improved in the process, subject to the specific pricing alternatives identified at the earlier stages for further analysis.

In the majority of cases reviewed where decision making about highway pricing was made in a systematic way, supported by forecasting tools, the existing regional model (typically that of the MPO) was employed. The development of a new regional model from scratch is of course a time consuming and costly effort. Also, the timing of a major model improvement effort, often driven by periodic data availability, might not coincide well with the schedule of road pricing study. Consequently, in many cases the best available model, along with some short-term improvements, was applied. There is, however, a growing recognition of the importance of travel model improvements in view of the scrutiny by rating agencies and private investors of T&R forecasts, and many agencies have made substantial efforts to improve their models for pricing studies. In many cases, the RFP issued by the interested agency for a T&R study explicitly included a model improvement task. Additional benefits of this effort, as perceived by MPOs, are that this study also can contribute to the

Table 1. Model features needed for different pricing studies.

Pricing Study Component	Model Features	
	Essential	Advanced
All types of pricing	Toll facilities coded in the highway network with toll incorporated in the volume-delay functions	Toll plazas and access ramps coded with realistic delay functions
	Segmented VOT by travel purpose and income group in demand model	Perceived highway time by congestion levels / reliability
	Segmented VOT by vehicle class in traffic assignment	Additional vehicle class stratification by VOT
		Route type (toll vs. non-toll) sub-choice
	Mode choice and assignment equilibration	Inclusion of trip distribution in equilibration through mode choice logsum
HOV/HOT lanes	Car occupancy (SOV, HOV2, HOV3+) sub-choice in mode choice	Additional vehicle class stratification by occupancy in assignment
Area and other large-scale pricing schemes	Trip generation sensitive to accessibility/generalized cost	Accounting for trends in flexible / compressed work schedules and telecommuting
Highway pricing in parallel with transit improvements	Mode choice with developed transit nest	
	Bus speeds linked to highway congestion	
Congestion pricing	Peak spreading model	Time-of-day choice model Accounting for trends in flexible / compressed work schedules and telecommuting
Dynamic (real-time) pricing		Special network / toll equilibration procedure
Highway pricing in parallel with parking policies	Parking cost inclusion in mode choice	Parking choice model for auto and drive-to-transit trips with parking constraints
Equity analysis	Model segmentation and reporting of user benefits (time savings and extra cost) by 3-4 income groups	

general improvement of the regional model and spur additional useful data collection, model validation, and testing.

A wide range of cases was found in this research with respect to the t rigor of the methods and levels of sophistication applied for the modeling in each of the decision-making stages. Notwithstanding possible deviations based on different project development frameworks and varying states of existing regional modeling capabilities, there are several clear patterns that can be generalized and used to characterize both prevailing and best practice. The following correspondence between the stage of decision making and appropriate modeling tools can be recommended.

Stage 1: Exploratory

General strategic go/no-go decisions about highway pricing possibilities are made in this stage. The existing regional model should be applied with at least a set of minimal short-term improvements that would normally include the following common steps (corresponding to the list of general model features essential for all pricing studies identified earlier).

- Coding of highway facilities with the corresponding pricing forms (flat, fixed variation by time-of-day, variable real-time, etc.) converted into travel time equivalents for highway assignments and skimming.
- Incorporation of tolls in the demand models currently developed; most frequently trip distribution and mode choice models are included.
- Proper implementation of network equilibrium and associated feedbacks (at least between the assignment and mode choice models, with a subsequent consideration of the trip distribution model as well).
- Calibration effort (through proper adjustment of model coefficients, mode specific constants, and/or distributional K-factors) in order to reasonably match traffic counts in the base year, approximate travel times and speeds, in the relevant corridor or sub-area.

Stage 2: Preliminary Feasibility Study

Further improvements are recommended at this stage depending on the pricing project nature. These improve-

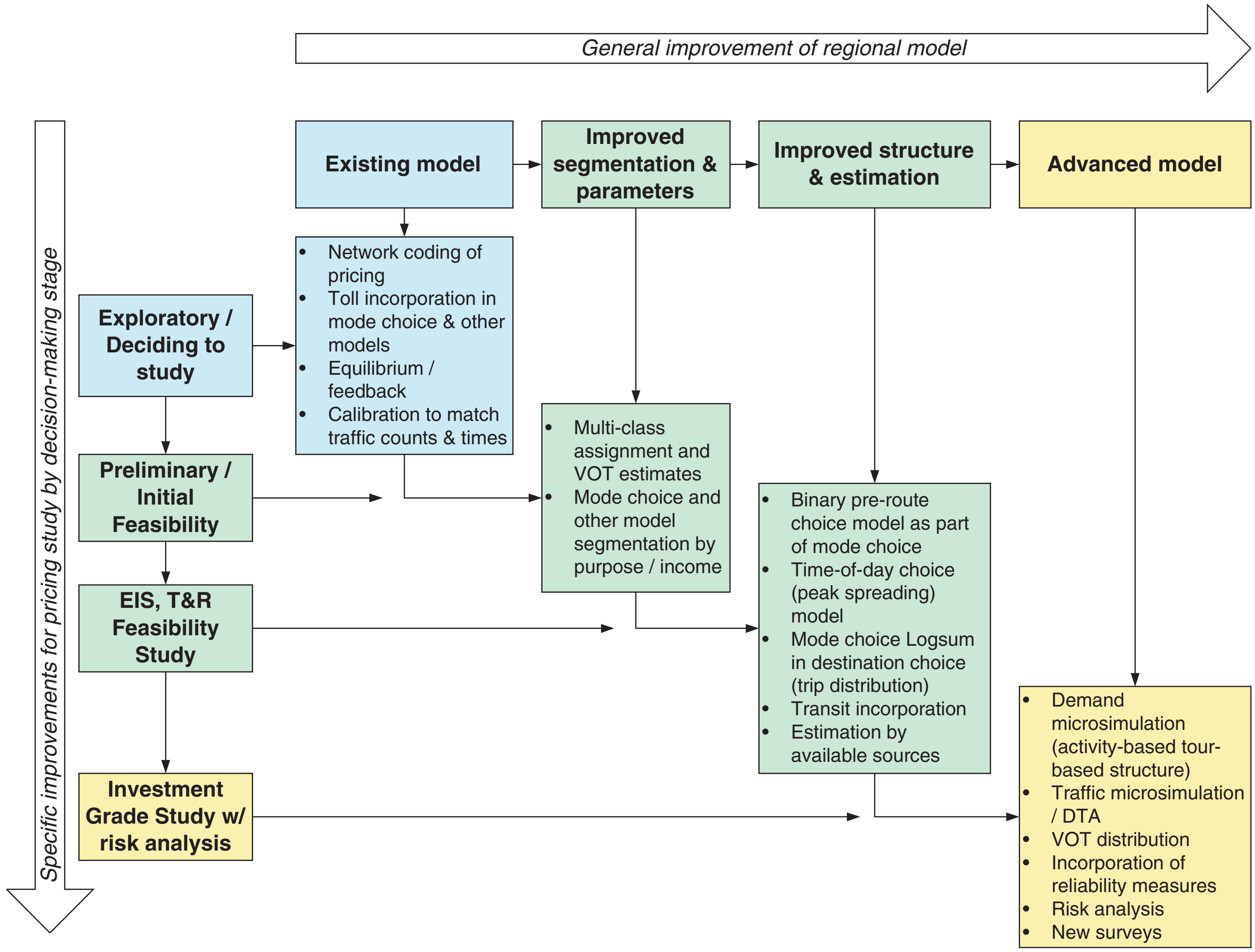

Figure 1. Forecasting tools by stage of project development.

ments would mostly include better model segmentation and differentiation of the model coefficients related to VOT. At least two additional improvements are generally needed:

- Mode choice (and trip distribution if technically possible) segmentation by travel purpose and income group (that have a strong impact on the VOT).
- Multi-class assignment procedure that would distinguish traffic by vehicle types (auto, commercial vehicle, heavy truck, taxi, etc.) and auto occupancy (SOV, HOV2, HOV3+, etc) that directly relate to the pricing policy differentiation and eligibility.

Stage 3: Environment Impact Statement (EIS)

This stage is associated with full T&R studies. The model structure should be improved in order to incorporate additional important sub-models. The following improvements are generally warranted at this stage:

- Introduction of a binary route type (toll versus non-toll) choice model as part of the mode choice model (at the lower level of mode hierarchy). Even in cases where mode choice may not play a significant role, such as intercity highways with perhaps no transit alternatives and a high percentage of trucks, this binary choice model explicitly represents the users' perception of tolls and related decision-making. It is also essential in order to be able to incorporate a sensitivity of demand, beyond just travel time savings, to the additional measures of travel quality and reliability typically associated with toll roads.
- Introduction of a time-of-day choice and/or an incremental peak-spreading model that is essential for urban toll roads and congestion pricing variable pricing analysis.

- Including a proper linkage between mode choice and destination choice (trip distribution) models through the logsum accessibility measure, essential to ensure logical sensitivities of the model when multiple pricing alternatives are compared.
- Implementing this linkage may also require model (re) estimation efforts based on the existing household travel survey and other available sources, or the collection of new survey data in the corridor and possibly with a stated preference component.

Stage 4: Investment Grade Study

The model improvement process will ideally lead to a complete or gradual transition toward an advanced model structure that would fully support specific requirements of the Investment Grade Study, including comprehensive risk analysis across different relevant factors. The following features of such an advanced model are especially relevant for highway pricing projects:

- Individual (household/person) microsimulation of the travel demand choices within an ABM tour-based structure.
- Individual (vehicle) microsimulation of traffic using DTA.
- Detailed analysis of travel markets and associated probabilistic VOT distributions, essential for capturing important factors such as situational variation in VOT.
- Explicit incorporation of travel time reliability measures and willingness to pay for reliability improvements, along with average travel time savings.
- Integration of the T&R forecasting and financial risk analysis stages through a set of well designed sensitivity tests and an analytical representation of risk factors in multivariate simulations.
- Implementation of multiple model runs with different toll values for the purpose of toll optimization, with toll optimization estimated with respect to the revenue, network conditions (measured by minimal speed, maximum V/C ratio, or maximum throughput), or by social welfare (utility) function.
- Conducting and using new RP household travel surveys, with supplementary SP components, designed for and applied in the estimation of advanced models.

1.3.3 Specific Requirements for Forecasting Tools for Investment Grade Studies

Rating agencies put travel forecasting procedures under a high level of scrutiny that is different from the model evaluation/validation criteria applied in the public sector. Investment Grade studies are characterized by more stringent requirements on T&R forecasts, added levels of scrutiny with regard to model structure and calibration, and the need for a number of additional post-modeling steps compared to the preliminary financial feasibility studies.

Analysis of the existing models done to date, as well as the tracking history of model applications and associated (well-published) criticism from the rating agencies, have clearly shown that some principal improvements in modeling tools are needed to ensure credibility of T&R forecasts, as well as to better integrate the transportation modeling culture with the culture of the investment analysis community.

It should be understood that the quality of forecasts can directly affect the project bond rating (i.e., the possibility to obtain the necessary loans and the interest rate associated with them). The three major rating agencies (i.e., Fitch Ratings, Moody's, and Standard & Poor's) have developed demanding tests for T&R forecasts (especially those produced by public agencies) and examine variations in many input parameters, as well as the model structure itself.

For these reasons, investment grade studies require an advanced and well calibrated travel model integrated with network simulation. There are several important technical specifics of an Investment Grade study compared to a T&R forecast produced for feasibility studies that should be addressed that are not necessarily included even in advanced ABMs. These relate to the model structure and calibration, model application, and a number of post-modeling steps that convert the model outputs into the inputs needed for a project financial plan.

Model Structure and Calibration. The following aspects relate to the model structure and calibration:

- Presence of all three major relevant travel choice dimensions (route, mode, and time-of-day) that represent first-order responses of the travelers.
- More elaborate time-of-day choice or peak-spreading model distinguishing between the peak hour and "shoulders" within each broad period.
- Flexible trip generation model sensitive to accessibility improvements.
- Flexible trip distribution model fundamentally linked to the mode and route type choice model by mode-choice inclusive values (Logsums) as impedance measures.
- User segmentation by VOT across travel purposes, income groups, times of day, vehicle type and occupancy.
- Extensive newly collected data and more rigorous model calibration is normally assumed. It should be understood that even a well-calibrated regional model might have certain discrepancies compared to traffic counts and/or speed surveys for a particular corridor or facility. Consequently,

it is essential to recalibrate the model based on the most recently collected data, including traffic counts, special surveys (e.g., users of a particular toll facility), and speed measurements in the relevant corridor.

Model Application. The following aspects relate to the model application:

- Toll rate optimization and multiple sensitivity tests with different toll and toll escalation scenarios.
- Risk analysis and risk mitigation measures. This includes identification and quantification of risk factors. It should be understood that the culture of the investment world is based on a probabilistic view of the model outcome, in contrast to the conventional travel forecasting culture based on a deterministic interpretation of the model outcome. A theoretically consistent incorporation of probabilistic risk analysis in T&R forecasting procedures is an important avenue for bringing these two worlds together and is essential for the current synthesis.

Risk Factors. The following general concepts and risk factors are considered by rating agencies:

- Start-up toll facilities are considered the most risky and are put under a stress test, especially if the forecast was implemented by a public agency.
- Accurate traffic and revenue forecasting in dense urban areas will always lie at the opposite end of a reliability spectrum from, for example, a river crossing with a clear competitive advantage over limited alternatives.
- Traffic patterns associated with well-defined, strong radial corridors appear to be more reliable.
- Forecasts prepared by project sponsors and bidders (interested parties) are generally higher than prepared by investors/bankers; this "optimism bias" is estimated at 20% or more. More aggressive forecasts can be accepted for public private partnerships (PPP) that do not need rating.
- VOT miscalculation and improper aggregation across different income groups/travel markets are problematic (that's why a proper model segmentation is essential).
- Recession/economic downturn (GDP growth is correlated with traffic growth with some lags).
- Slower future-year land-use development along the corridor. Reconsideration of population, employment, and income growth forecasts prepared by the MPO or DOT for the region/corridor is one of the frequent requests.
- Possibility for actual lower time savings than the modeled ones.
- Improvements to competing free roads or other alternatives.
- Considerably lower usage of toll roads and managed lanes by trucks.
- Lower off-peak/weekend traffic (40-50% of weekday) than is normally assumed (70-75% of weekday).
- Specific risk factors for trucking market that are essential if trucks constitute a significant share in the traffic. In particular, less reliability should be placed on forecast if the trucking market is composed of a large number of small, owner-driver general haulers.

Post-Modeling. The following important aspects relate to the post-modeling steps:

- Annualization of revenues including modeling of or assumptions about weekend and holiday revenues, seasonality, within-week variability, etc. The factors may vary from corridor to corridor, and the best way for established facilities is to develop individual factors based on the observed patterns. It is also important to consider that weekend VOTs are generally lower, due to a greater mix of purposes and schedule flexibility than on the modeled typical weekday.
- The yearly T&R stream needed for the Financial Plan is normally calculated by interpolating and extrapolating between and beyond modeled years for long periods (40–50 years and longer). Capacity constraints and adverse effects of congestion when traffic volume approaches capacity should be taken into account for deep forecasts if they are not directly simulated in the model.
- Detailed consideration of a ramp-up period. If it is not modeled as a dynamic behavioral response in the model (which is unfortunately the case with even the most advance AB models), certain assumptions are made based on the past experience with similar projects. Specific ramp-up considerations are associated with electronic toll collection (ETC), especially if no cash payment option is provided. In this case, the ramp-up period is almost none for routine users and commuters, but might be significant for occasional users and visitors.
- Detailed consideration of bulk discounts, person/vehicle type discounts, toll evasion (if any), and other revenue loss factors such as accidents or incidents, extreme weather, or special events, among others.
- Accounting for toll rates escalation (CPI, GDP, floor, ceiling) versus population income (and VOT) growth over a long period of time.
- The model output needs to be processed in formats suitable for the subsequent analysis and preparation of the Financial Plan. It is important to provide a transparency of the results and identify the key factors that have the most significant impact on the forecasts (Origin-Destination pairs with the largest number of trips, core travel markets) for which data and calculations can be demonstrated for practitioners and reviewers.

1.4 Organization of Volume 2

Volume 2 is organized in six subsequent major sections:

- **Chapter 2: State of the Practice in Forecasting Methods** represents a survey of the existing practices. It provides an in-depth analysis of models applied for highway pricing studies, including both 4-step trip-based models and tour-based ABMs. It concludes with a list of identified common features, gaps and critical issues that should be addressed.
- **Chapter 3: Survey Methods to Support Pricing Studies** is devoted to an overview of survey techniques that support the development of models and decision-making regarding pricing options. It includes Revealed Preference and Stated Preference survey types, as well as the ways to integrate them in an effective model estimation process.
- **Chapter 4: Critical Issues and Directions for Short-Term Improvements** covers short-term improvements and associated critical issues; most improvements in this section are those that can be implemented with trip-based, 4-step models. This section also identifies a core list of model features needed for different pricing studies and associated critical issues, relating to demand modeling and network simulation. The model improvements are put in the context of the different phases of the project development, from preliminary feasibility to investment grade studies. Special attention is paid to the issues associated with using a travel model output for evaluation of pricing projects.
- **Chapter 5: Strategic Directions for Improvement** outlines long-term improvements that can expected to yield major breakthroughs. Many of them are oriented toward emerging advanced-practice-age models, such as ABMs on the travel demand side, and DTA and traffic microsimulation tools on the network supply side. Specific model improvements are suggested where technical breakthroughs can be reasonably expected, such as those in the direction of user segmentation by VOT, incorporation of reliability measures, inclusion of additional travel choice dimensions (like acquisition of transponder), time-of-day choice models with fine temporal resolution, accounting for different carpool formation mechanisms, and better integration of demand and dynamic network simulation models. Special attention is paid to a constructive coordination of the current NCHRP project and SHRP 2 Project C04, "Improving Our Understanding of How Highway Congestion and Pricing Affect Travel Demand."
- **Chapter 6: Pilot Studies for Demonstration of Improved Tools** describes four Pilot Studies that demonstrate the advantages of the suggested improvements to travel models applied for highway pricing projects. It includes application of advanced ABMs for various pricing studies in the San Francisco and New York Regions, application of DTA in the Baltimore-Washington, D.C., corridor, and a technical overview of the enhancements for a trip-based 4-step model prepared for pricing studies in the Los Angeles Region.
- **Chapter 7: Conclusions and Recommendations for Future Research** distills the information presented in the previous sections and pilot studies. It summarizes the main conclusions and presents important directions for future research that were identified, but could not be fully addressed as part of the current synthesis.

The report also contains a list of sources and an appendix that provides additional technical details on particular topics.

CHAPTER 2

State of the Practice in Forecasting Methods

2.1 Basics of T&R Forecasting

A travel demand model predicts travel flows between origins and destination by time of day, mode, and route within each mode. In addition, these models produce the necessary information on toll facility patronage, as well as tolling and pricing impacts on all trips in the region. A travel demand model represents a sequence of calculations structured by meaningful travel dimensions. There are two major approaches for structuring a demand model: the traditional trip-based (frequently referred to as 4-step) and an advanced tour-based (frequently referred to as activity-based) with numerous technical variations. Traditional 4-step models were the foremost modeling technique used during the 1980s and 1990s for most MPOs in United States, and they constitute a majority of travel models in practice even today. In recent years, however, advanced ABMs have been applied in practice, currently constituting the majority of newly-developed models for large MPOs (more than 10 such models in practice). The typical model structure and relevant travel dimensions modeled in each type of model are shown in Figure 2.

A demand model represents a computerized travel simulation system where demand generation is integrated with network simulation, and equilibrium travel times and costs are sought. This equilibrium feature, which is technically implemented by means of feedbacks of travel time and cost to the demand generation stages, is essential for pricing studies. Pricing affects travel demand by shifting the equilibrium point to a solution where social/economic welfare is greater than without pricing. This is analytically consistent with the policy objectives of pricing, where pricing is often intended to affect travel choices in such a way that network capacity is utilized in a more optimal way.

The following model features are specifically important for pricing projects:

- Network simulation and associated route choice sensitivity to tolls. Changes in route choice represent first-order response to pricing, and associated trade-offs between travel time savings and tolls are the cornerstone of toll facility traffic forecasts.
- Other first-order responses to pricing include mode choice and time-of-day choice. If pricing is applied and there is a reasonable transit alternative for the given trip, travelers may consider switching to the transit mode. In addition, travelers may consider switching to other time-of-day periods to avoid paying tolls. The first order responses are characterized by the highest elasticity of substitution from an economic perspective and must be included in the model. ABMs have a more detailed structure of choices. In particular, mode choice is modeled first for the entire tour and then for each trip on the tour, conditional upon the chosen entire-tour mode. Pricing impact on mode and time-of-day choice is modeled through the corresponding feedbacks.
- There is a set of additional pricing impacts that can affect almost any travel dimension. For example, as a response to pricing, travelers may choose another destination for a trip or not implement the trip at all, substituting some other activity or linking the trip to another tour as a stop, etc. These impacts are generally considered second-order effects and are associated with a generally lower elasticity to pricing, although the accumulated effects over a longer period of time can still be significant and even affect residential location choices and land-use development (components of the land-use model). The second-order effects are modeled through additional feedbacks where the period-specific mode-choice Logsums are used to inform all upper-level models about the tolls and travel time savings for all affected modes. There are several reasons why pricing impacts on upper-level choices can be better modeled through mode choice Logsums rather than through direct feedback of auto travel times and tolls. First, mode choice Logsums combine all travel time and cost components in a single and theoretically sound measure of accessibility. Secondly, highway pricing and associated congestion relief may

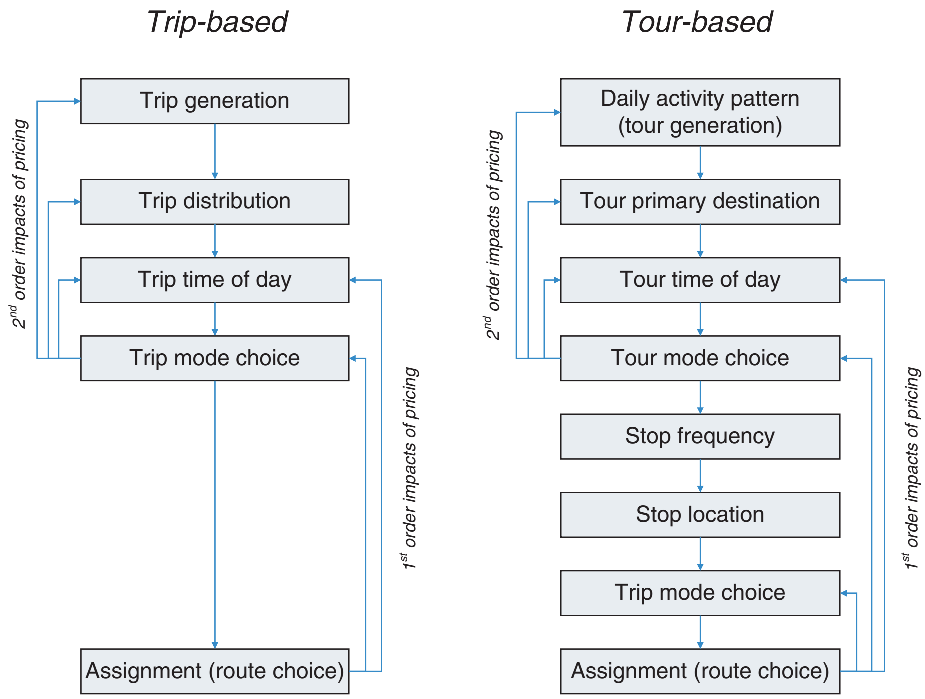

Figure 2. Typical structure of demand model.

affect transit modes as well, such as buses in mixed traffic or using HOV lanes as well as park and ride options.

2.2 Travel Cost Representation in Demand and Network Models

Highway pricings should first be properly incorporated in network assignments and skimming procedures through generalized cost functions. Then, through generated travel time and cost skims, pricing will affect all other choice dimensions, specifically mode choice, time-of-day choice, trip/tour distribution, and other upper level choices. In highway assignments, the generalized cost function is defined for each network link and further calculated for each origin-destination pair. It can be written in the following general way:

$$G_k = a_k \times T_k + b_k \times C_k \qquad \text{(Equation 1)}$$

where:

k = vehicle types and auto occupancy classes,
T_k = travel time,
C_k = travel cost (only toll is normally included for assignment purposes),
a_k = coefficient for travel time,
b_k = coefficient for travel cost, and
a_k/b_k = Value of Time (VOT).

For highway tolling and pricing projects it is essential to separate vehicle types like private auto, light truck, heavy truck, taxi, etc., and auto occupancy classes like SOV, HOV/2, HOV/3, etc., in the traffic assignment for the following reasons:

- Different vehicle types and occupancy classes may have very different VOTs. In this respect, some additional segmentation by VOT (based on trip purpose and/or income group) is also recommended and will be discussed further below.
- Toll rates might be differentiated by vehicle types and/or occupancy classes. A good example of this is an HOT-3 lane where vehicles with three or more passengers do not pay the toll, vehicles with two passengers pay half of the toll, and SOVs pay a full toll.
- General prohibitions and eligibility rules can be applied for certain vehicle types on certain facilities [for example, trucks prohibited on expressways or truck-only toll (TOT) lanes] or auto occupancy classes (for example, HOT lanes).

In order to satisfy all these conditions, traffic assignment should be implemented as a multi-class procedure (available in all major transportation software packages) with 6–12 or even more trip tables depending on the model structure. While this is a certain complication, it is essential for proper modeling of all related choices. If different vehicle types and auto occupancy classes are mixed together (with some average VOT), it is not only a source of bias in route choice, but since assignment procedures serve as the source for skimming LOS variables used in mode choice, time-of-day choice, and all other choices, the distortions in route choice will affect all these models as well.

Equation 1 corresponds to the general expression of highway utility in its most common form. This expression constitutes a key component in all travel choice models. In the context of traffic assignment when choice is modeled between alternative routes, the travel time coefficient is normally set to 1.0. This arbitrary setting does not affect All-or-Nothing choice applied in the conventional Static User Equilibrium assignment (however, more advanced stochastic route choice models would be sensitive to this setting and should be calibrated in a special way). With this simplification, the highway generalized cost function can be written in the following way:

$$G_k = T_k + b_k \times C_k = T_k + \frac{1}{VOT_k} \times C_k \qquad \text{(Equation 2)}$$

While All-or-Nothing route choice embedded in the conventional assignment procedure is frequently applied in practice to distinguish between free and tolled routes, it has been recognized that this is not an adequate tool in itself, since the traveler choice route is not a simple linear combination of time and cost. In particular, toll roads (or managed lanes) can represent a more attractive option because of enhanced reliability and other considerations that are not directly measured by average time and cost. An explicit inclusion of travel time reliability in the highway generalized cost function represents a technical challenge that will be discussed.

A simpler, but still useful, approach that has been applied in many models in practice is to estimate an additional bias constant associated with priced facilities. This bias can be most effectively incorporated in a binary choice model frequently referred to as pre-route choice that is placed between mode choice and route choice. Technically, it can be included as the lower-level sub-nest in the mode choice nested structure. In addition, such models allow for probabilistic choice between free and toll options, helping to avoid the "lumpiness" of the All-or-Nothing assignment that yields unstable routes.

With this enhancement, the highway generalized cost function can be written in the following way:

$$G_k = \begin{cases} a_k \times T_k^{free}, & \text{if } C_k = 0 \\ \gamma_k + a_k \times T_k^{toll} + b_k \times C_k, & \text{if } C_k > 0 \end{cases} \qquad \text{(Equation 3)}$$

where γ_k represents the toll bias.

Since the difference between utilities is all that matters in this choice framework, the expressions in Equation 3 can be rewritten in equivalent terms of relative travel time savings, where the free route generalized cost is set to zero as the reference point:

$$G_k = \begin{cases} 0 & \text{if } C_k = 0 \\ \gamma_k + a_k \times \left(T_k^{toll} - T_k^{free}\right) + b_k \times C_k, & \text{if } C_k > 0 \end{cases} \qquad \text{(Equation 4)}$$

Equation 4 constitutes the essence of many models applied for T&R forecasting in practice. It also has many possible technical modifications. One such modification (which was adopted for many pricing studies in Texas and Colorado) represents a non-linear transformation of the following form (WSA 2001; CSI 2005; Vollmer 2001):

$$G_k = \begin{cases} 0 & \text{if } C_k = 0 \\ \gamma_k + a_k \times \ln\left(1 + T_k^{free} - T_k^{toll}\right) + b_k \times (C_k)^2, & \text{if } C_k > 0 \end{cases} \qquad \text{(Equation 5)}$$

The model form in Equation 5, however, still only corresponds to route choice, and should be further generalized to include other relevant choice dimensions (possible traveler responses) like mode choice, time-of-day choice, destination choice, and others. The corresponding generalization to incorporate mode choice is done by the inclusion of the generalized highway cost, as part of the mode choice utility for highway modes in the following form:

$$U_m^p = \gamma_m^p + a_m^p \times T_m + b_m^p \times C_m + \sum_v \lambda_{vm}^p S_v \qquad \text{(Equation 6)}$$

where:

m = set of modes including auto occupancy classes,
p = travel purpose and other possible segments,
v = person, household, and zonal variables,
T_m = travel time by mode,
C_m = travel cost by mode,
S_v = values of the person, household, and zonal variables,
γ_m^p = mode-specific constant for each purpose/segment,
a_m^p = coefficient for travel time by mode and purpose/segment,
b_m^p = coefficient for travel cost by mode and purpose/segment,
a_m^p/b_m^p = VOT, and
λ_{vm}^p = coefficients for person, household, and zonal variables for each mode by purpose.

The most frequently used person, household, and zonal variables in 4-step models include income, car ownership, and urban density. In research works and ABM, the set of explanatory variables and possible dimensions for segmentation have been significantly extended and will be discussed in more detail in Chapter 5. Travel time and cost variables in themselves include many components. In particular, for auto modes, travel time can include parking search and parking time as well as additional time for picking-up and dropping-off passengers (for HOV) while travel cost can include toll, parking cost, and vehicle operating cost (fuel and some fraction of maintenance cost that depends on the mileage).

Examples of mode choice models incorporating pre-route choice developed for T&R studies in Montreal and San Francisco

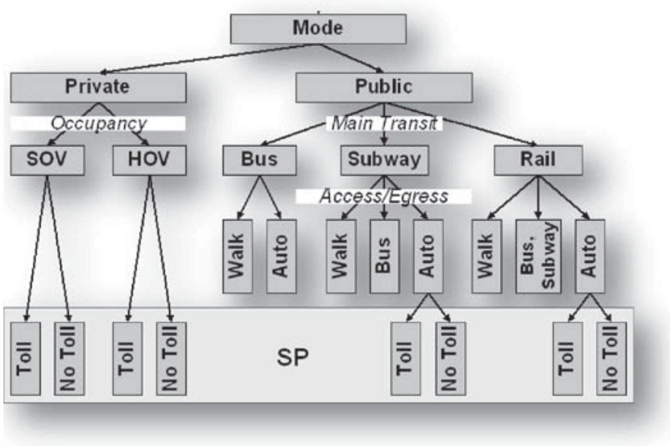

Figure 3. Montreal mode choice model—nested structure incorporating free vs. toll route choice.

are shown in Figure 3 and Figure 4. These models are discussed in detail in Appendix A (Section A.1.2).

Mode utility functions that include travel time savings and additional cost associated with highway pricing (Equation 6) represent the basis for the most theoretically consistent formation of the impedance functions used for destination choice (trip distribution) and/or time-of-day choice by using Logsums of the lower-level choices as components of the utility functions in the upper-level choices. However, in addition to using mode choice log-sums, there is a simplified option available (and frequently used in practice) to employ the highway generalized cost itself (Equation 1) in the utility function of destination choice or time-of-day choice. This simplified option, however, is not recommended unless transit shares are very low.

The details of these models depend on how the destination choice, mode choice, and time-of-day choice are sequenced in either the 4-step or ABM. We will illustrate the basic principles following the typical model structures shown in Figure 2. The time-of-day choice utility can be formed using mode choice Logsums in the following way:

$$V_t^p = \mu \times \ln\left[\sum_m \exp\left(U_{mt}^p\right)\right] + \sum_v \lambda_{vt}^p S_v \qquad \text{(Equation 7)}$$

where:

t = time of day periods (TOD),

$0 < \mu \le 1$ = scaling coefficient that should be in the unit interval, and

λ_{vt}^p = coefficients for person, household, and zonal variables for each TOD.

In aggregate 4-step model systems, TOD choice models normally operate with broad 3- or 4-hour peak periods, and longer off-peak periods. This might require additional peak spreading or peak-hour factoring sub-model. In disaggregate AB model systems, TOD choice models operate with a finer temporal resolution of 1 hour or even less (Vovsha and Bradley 2005). In addition to mode choice Logsums, such person, household, and zonal variables as income and density (especially at the destination end) prove to be significant. The TOD choice utility is sensitive to tolls and associated travel time savings through the mode choice utilities included in the Logsum calculation.

The destination choice utility (or trip distribution impedance functions) can be formed using a Logsum over all TOD periods. While it is possible to calculate this Logsum, which

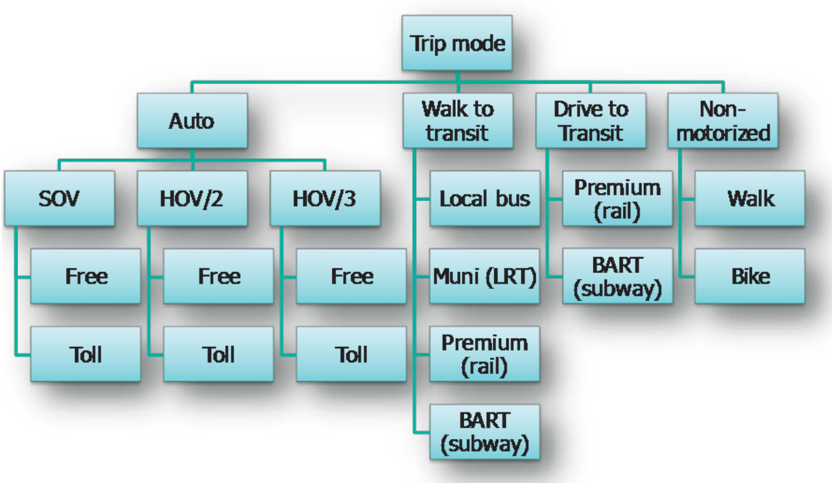

Figure 4. San-Francisco mode choice model—nested structure incorporating free vs. toll route choice.

t would represent the most consistent impedance measure, it is computationally very intensive to do so since it should be implemented for each origin-destination pair. The usual practical approach taken with a 4-step model (as well as adopted for some ABMs) is to use representative TOD periods for each travel purpose to economize on calculations. For example, for trips/tours to work, a combination of AM period (for the journey to work) and PM period (for the journey home) is normally applied; while for non-work trips, the midday (off-peak) period is assumed. Multiple representative periods can be applied or a weighted linear combination of LOS variables between several periods can be used if necessary. In any case, the destination choice utility (and impedance function as part of it) can be generalized in the following way:

$$W_{od}^{p} = \eta \times \ln\left[\sum_{m} \exp\left(U_{od,m,t(p)}^{p}\right)\right] + \ln\left(A_{d}^{p}\right) \qquad \text{(Equation 8)}$$

where:

o, d = origin and destination zones,
$0 < \eta \le 1$ = scaling coefficient that should be in the unit interval,
$t(p)$ = representative TOD period for each purpose, and
A_d^p = destination zone attraction (size variable) for each purpose.

The size variables represent destination zone attractions for each purpose. The most frequently used attraction size variables are total employment for work purpose, enrollment for school purpose, and retail employment for non-work purposes. Many ABMs include more complicated size variables that mix several employment and population variables and can be segmented by urban type and density. Size variables are not added to the impedance function in doubly-constrained gravity models of trip distribution since they are applied directly as constraints on the destination side. The destination choice utility is sensitive to tolls and associated travel time savings through mode choice utilities included in the Logsum calculation.

By using the destination choice utilities sensitive to highway pricing and travel time savings, zonal accessibility indices can be calculated and used as an explanatory variable for trip generation, activity pattern, car ownership, and land-use development models.

Accessibility indices essentially represent mode/destination choice Logsums calculated by trip purpose in the following way:

$$Z_{o}^{p} = \ln\left[\sum_{d} \exp\left(W_{od}^{p}\right)\right] \qquad \text{(Equation 9)}$$

If Equation 9 is directly applied in combination with Equation 8 it may result in very intensive calculations. For this reason, in most model systems, the destination choice utilities used in accessibility calculations are simplified in such a way that they can be pre-calculated based on a limited number of origin-destination skims and for a limited number of modes, travel purposes, and population segments. Even with these simplifications, accessibility measures represent useful explanatory variables sensitive to highway pricing and travel time savings.

Further extensions of the formulas for highway utilities that include travel time reliability measures are discussed in Appendix A (Section A.3).

2.3 Models Included in the Synthesis

For this research, documentation was obtained and analyzed in detail. Table 2 shows the list of transportation models and their applications for highway pricing studies.

This review has revealed that there is a great variety of travel models and analytic approaches currently applied in practice by different agencies. In order to constructively analyze and synthesize them, we have developed a template that includes their most important features. Each model has been analyzed in this format based on the available model documentation. This approach makes it possible to meaningfully compare different models, and also helps to identify their commonalities, as well as gaps in particular model structures. The following main model features were included in the template (Table 3).

The details of the selected transportation models applied for pricing studies in the template format are presented in Appendix A (Section A.1). The models are grouped into the following two major classes: 1 = trip-based 4-step models, and 2 = tour-based ABMs.

2.4 Conclusions from the Review of Existing Models

The most important findings and conclusions are summarized below:

- There is a great deal of variation in approaches. In most cases, the model applied for the highway pricing project was essentially a modification of the existing regional model available for the study. Thus, limitations and deficiencies of the existing regional model were inevitably adopted for the study. There was not a single practical case uncovered yet of a regional model specially designed and developed for highway pricing studies or at least having these specific requirements in mind.

Table 2. Forecasting models applied for highway pricing projects.

City / Area	Agency developed the model	Pricing study
Corridor and Sample-Enumeration models:		
New York, NY	PANYNJ	Congestion Management for New York – New Jersey Crossings
Minneapolis-St. Paul, MN	MNDOT, FHWA's STEAM model	Pricing Study
Washington, D.C.	FHWA's SMITE-ML model	Value Pricing Study of the Capital Beltway in Northern Virginia
Regional Trip-Based 4-Step models:		
Alameda County, CA	MTC	I-580/I-680 Corridor Value Pricing Study
Atlanta, GA	ARC	Managed, HOV, and Truck Toll Lanes Study
Austin, TX	CTRMA	Central Texas Turnpike Project
Dallas – FW, TX	NCTCOG	Regional Value Pricing Corridor Evaluation & Feasibility Study
Denver, CO	DRCOG	Northwest Parkway Traffic & Revenue Study
Denver, CO	DRCOG	I-25/SR-36 Value Express Lane Feasibility Study
Colorado Tolling Enterprise	DRCOG, etc	Preliminary Statewide Traffic & Revenue Study
Houston – Galveston, TX	HGAC	Road Pricing Study (QuickRide System), I-10 Katy MIS
Montgomery County, MD		Road Pricing Study
Oakland, Bay Area (MTC)	MTC	HOT Lanes Study
Orange County, CA	OCTA	SR-91 Value-Priced Express Lanes
Orlando / Tampa Bay, FL	FDOT	Turnpike Enterprise
San Diego, CA	SANDAG	I-15 FasTrak and SR-125 South Tollway
Salt Lake City, UT	UDOT	Mountain View Corridor Pricing Study
Sonoma County, CA	SCTA	US-101 Variable Pricing HOV/HOT Lane Study
Phoenix, AZ	MAG	Managed Lanes Study
Pittsburgh, PA	PENNDOT	HOV & HOT Lanes Study
Sacramento, CA	SACOG	Managed Lanes Study
Twin Cities, St. Paul, MN	MC	I-394 HOT Lanes
Washington, D.C.	MWCOG	Managed Lanes Study, HOT Lane in Northern Virginia
Seattle, WA	WSDOT/PSRC	SR-520 Toll/HOV Feasibility Study
Toronto, ON	MTO	Highway 407 Traffic & Revenue Study
Regional Activity-Based Tour-Based models:		
Montreal, QC	MTQ	A-25 and A-30 Traffic & Revenue Study
New York, NY	NYMTC	Manhattan Area Pricing Study
San Francisco, CA	SFCTA	Congestion Pricing Feasibility Study
Portland, OR	METRO	Traffic Relief Options Study

- In most cases, only route itinerary (assignment) and binary route type choice (toll versus non-toll) models were employed for comparison and evaluation of pricing alternatives. This achieves reasonable results under the assumption that pricing would not affect mode choice, time-of-day choice, trip distribution, and trip generation. While this simplification might be somewhat acceptable for intercity highways, it is more difficult to defend for most of the metropolitan/urban facilities.
- Pricing effects on trip distribution have been incorporated by using mode choice Logsums as the measure of accessibility in destination choice or gravity-type distribution models. The use of mode choice Logsums in doubly-constrained gravity models needs to be tested extensively; unlike destination choice frameworks, where appropriate elasticities with respect to cost are expected when reasonable Logsum parameters are used, it is not clear that gravity models behave appropriately to changes in LOS variables, such as the introduction of tolls.
- In some cases there is an inconsistency between the travel times and costs used for the trip distribution and mode choice models, in that the travel times reflect priced conditions, while the toll cost itself does not enter the impedance function. This is the case when travel times are fed back from a generalized cost assignment into a distribution model that is a function of travel times only.
- There are a growing number of applications where mode and/or occupancy choices were included. In several cases, mode, occupancy, and binary pre-route choices were combined in one multi-level nested logit choice model structure.
- In a few cases utility functions in multinomial or nested logit mode choice models are miss-specified. Undesirable

Table 3. Template for transportation model analysis.

Major model feature	Detailed feature / sub-model	Possible characteristics
Spatial scale		Regional
		Corridor / sub-area
		Facility
Coverage of time periods	Regular weekday	AM peak & shoulders
		PM peak & shoulders
		Midday
		Other off-peak (night, early)
		Daily traffic
	Annualization factors	Weekend traffic (assumptions)
		Holidays
		Seasonal variation
Demand model structure	Sample enumeration	
	Aggregate trip-based 4-step	
	Microsimualtion activity-based	
Network simulation tool	Static user equilibrium assignment	
	Dynamic traffic assignment / microsimulation	
	Representation of priced highway facilities	Link tolls & toll equivalents in generalized cost / time functions
		Toll plazas / payment types / delays
Modeled pricing impacts (traveler responses), sub-model structure, form of utility function, incorporation of pricing	Trip-level decisions	Route itinerary in highway network
		Principal decision to take a toll route vs. non-toll route (pre-route choice)
	Tour & trip-level decisions	Auto occupancy
		Mode choice
		Time-of-day choice (including peak spreading effects)
		Destination choice (spatial distribution)
	Day-level decisions	Trip/tour/activity frequency
		Activity re-sequencing as result of time-of-day shifts
	Mid-term mobility decisions and household / person attributes	Transponder acquisition
		Transit pass acquisition
		Long-term parking arrangement
		Free parking eligibility at workplace/school
		Household car ownership
	Long-term location choices	Residential location and dwelling type
		Usual workplace location
		Firm / businesses location
Willingness to pay / VOT and user segmentation	Vehicle classes (in the demand model and network simulation)	Auto
		Commercial vehicle / light truck
		Heavy truck
		Taxi
	Vehicle occupancy categories (in the demand model and network simulation)	SOV
		HOV/2
		HOV/3+
	Trip purpose segmentation (in the demand model)	Work
		Work/business-related
		School
		University
		Shopping
		Escorting children
		Other household maintenance
		Discretionary / leisure / sport
		Trip to airport / rail station / port for long-distance travel
		Intercity business travel
		Intercity non-business travel

(continued on next page)

Table 3. (Continued).

Major model feature	Detailed feature / sub-model	Possible characteristics
	Time of day (in the demand model and network simulation)	AM period
		PM period
		Midday period
		Night period
	Household / person characteristics (in the demand model and network simulation)	Household income group
		Person work status
		Gender
Demand-network equilibrium	Application flowchart with feedbacks	
	Feedback implementation	Number of iterations
		Averaging rules
		Convergence criteria / statistics
Surveys and other data sources for model estimation / calibration / validation	Household travel survey	Size / sample, year, structure / questionnaire
	Survey of existing toll road users	Size / sample, year, structure / questionnaire
	Stated Preference survey	Size / sample, year, structure / questionnaire
Model validation for the base year	General validation targets / reported measures of fit	AADT
		Traffic counts by time of day / vehicle type
	Project-specific calibration	Traffic counts
		Travel time / speed data

specifications include toll utilities that are a function of both the toll alternative travel time and travel time savings with respect to the free alternative. This type of specification may result in counter-intuitive results when the LOS attributes on either the toll or the free routes change. Another potentially problematic specification is the use of thresholds, such as making the toll alternative available only if it meets a pre-defined minimum time savings goal. The nesting coefficients on these models sometimes result in models with unreasonably high elasticities to toll or time differences when the toll diversion is examined at the root level of the model (where they are comparable with the elasticity of route type binary choice models).

- There is no consensus on whether road pricing costs should be shared among vehicle occupants, and if so how. Most models either assume that the full toll cost is either borne by all occupants, or that it is equally shared among the occupants. Some models differentiate between cost sharing for HBW trips and cost sharing for other purposes. Sharing road pricing costs among vehicle occupants makes carpools less cost-sensitive, an assumption that may be acceptable for work trips, but is questionable for other purposes, where the majority of carpools are among members of the same household and often times include minors.
- In some models willingness-to-pay differences between cash-payment users and ETC users are explicitly made (by specifying different values of time or different toll constants). Other models simply use the average toll cost per transaction.
- In some regional model systems that were specifically modified for congestion pricing projects, peak-spreading models were applied. Conventional 4-step models are normally based on time-of-day (peak) factors that are not sensitive to relative congestion levels at different periods of the day. Thus, 4-step models require a post-model peak-spreading sub-model that is difficult to incorporate in the overall equilibrium framework. Activity-based tour-based models can offer a better framework where peak-spreading effects are captured by time-of-day choice sub-model.
- Peak-spreading or time-of-day models are sensitive to differences in travel times by time of day, but not to differences in toll costs by time of day. This may be simply a result of the limited number of localities where road pricing costs vary by time of day combined with observed data insufficient to estimate appropriate model parameters.
- Very few models to date have incorporated all trip and tour-level dimensions in a consistent way, and there have not yet been any practical examples of the incorporation of pricing impacts on the day-level, mid-term, and long-term choices, even with the activity-based models now that have recently come into use.
- Almost all models, including activity-based tour-based models are characterized by a significant discrepancy between the user segmentation by (VOT) in the demand model compared to network simulation. While at the demand modeling stage, segmentation normally includes several trip purposes, income groups, car occupancy, and time-of-day periods; network simulations are characterized by a limited segmentation. Traffic assignments are

implemented by periods of the day and for multiple vehicle classes that typically include vehicle type and occupancy. However, trip purposes and income groups are blended together before assignment, creating strong aggregation biases with respect to VOT.

- There are also discrepancies in the cost functions used to build best paths between the network simulations used to build travel time and cost matrices for the demand models, and the network simulations used to assign trips to the highway network. Best paths for the demand model may be built on the basis of travel time only, while the assignment is performed on the basis of generalized cost, or vice-versa.
- In almost all modeling efforts where pre-route choice (toll versus non-toll) was involved, a problem of inconsistency between the generated trip tables for toll-users and their assignment onto the highway network was reported. This leakage of toll users in the network simulation can be significant and constitutes a non-trivial analytical problem that requires special modeling efforts to resolve.
- Most models attempt to equilibrate supply and demand by feeding back travel times and cost from the assignment step to the trip distribution or mode choice steps. In most cases feedback is executed for a fixed number of iterations, so convergence is not necessarily guaranteed. This may be problematic when forecasting under conditions of high population growth, where congestion effects may be far more pronounced than for the calibration year.
- Most models break down the network simulation into four broad time periods, typically AM Peak (2 to 4 hours long), Midday, PM Peak (2 to 4 hours long) and Night, and are therefore able to compute LOS differences by time of day only at this level of aggregation. Only one of the regional models performs the network simulation at a finer time of day disaggregation.
- With few exceptions, network simulations are validated to 24 hour traffic volumes, even when highway assignments by time periods are available. It is not clear that the models are adequately reproducing LOS attributes and demand for the different times of the day used in the simulation.

CHAPTER 3

Survey Methods to Support Pricing Studies

3.1 Overview of Survey Methods to Support Pricing Studies

One of the major factors affecting model accuracy relates to the quality of the data used in model estimation, calibration, and validation. Tremendous progress has been made in recent years with respect to data collection technology and new types of surveys, to the point that it is cost-effective to consider such data collection efforts. This chapter discusses the advantages of complementing traditional data sources (home interview surveys and annual average daily traffic counts) with sources that better target potential toll customers. This includes GPS-assisted surveys, processing information available from electronic toll collection systems, combined revealed and state preference surveys, and traffic choices experiments (like the one implemented in Seattle). Techniques that significantly improve the quality and comprehensiveness of the data would also improve the accuracy of the travel model.

The following major types of surveys are applied to support pricing studies (and models developed for these studies):

- Travel Pattern Surveys ("Revealed Preferences") including:
  - Household-Based Travel/Activity Surveys
  - Origin-Destination Surveys on specific facilities and existing toll roads
- Stated Preference Surveys that vary significantly across the following dimensions:
  - Choice Dimensions and Scenario Design
  - Trip Attributes Relevant for Pricing Studies
  - Choice Context
  - Instrument Design
  - Sampling
- Special Survey Types including:
  - Surveys of Commercial Vehicles
  - Behavioral Experiments and Follow-up Surveys
  - Attitudinal / Public Opinion Surveys

A comprehensive Household Travel Survey which is generally needed to develop a regional transportation model can also serve as the source for VOT and other model parameter estimates relevant to modeling road pricing. There is, however, a growing recognition that for pricing analysis the household survey data has to be supported by complementary project-specific revealed preference (RP) and/or stated preference (SP) surveys. This is especially crucial for start-up projects in regions with no prior experience with highway pricing where the RP survey cannot provide direct information about responses to unobserved choices and SP surveys are typically designed to address willingness-to-pay factors relevant for road pricing (value of time savings, value of reliability). Survey data collection can also support other model development data needs, including HOV/HOT lane usage and payment media choice. GPS-based supplements are included with some household surveys and these provide detailed route information for all recorded trips. Either vehicle or person-based GPS data collection can be used but vehicle-based GPS data collection is generally more useful for collecting route information, assuming that tracking routes for transit and pedestrian/bicycle alternatives is not necessary.

Intercept surveys that collect information about the origins and destinations (OD) and other details have been widely used to determine the characteristics of trips that are observed at selected locations (Hagen et al. 2006). These types of surveys are particularly useful for characterizing the trips that currently utilize specific corridors that are, or might be, served by a toll facility and the trips that cross into or out from a cordon that might be subjected to area pricing. This type of focused information is especially useful in estimating the numbers and types of trips that might be affected by the toll facility or area pricing. Although regional travel forecasting models can also be used to synthetically provide this information, these models are typically not sufficiently calibrated to estimate these details as accurately as can be done with an OD survey. Also, as OD surveys have shown, ETC registration lists can allow access to the current toll facility users. This greatly facilitates sampling strategy, questionnaire distribution, and post-survey development of expansion factors.

There are several objective limitations associated with RP surveys for modeling pricing effects:

- First and foremost, they are not applicable for model estimation/calibration in new corridors located in regions where there are no current toll facilities.
- Another associated problem is that with the survey of existing toll facility users, a very specific choice-based sample is created since it can be difficult to define and access non-toll users.
- It is difficult to collect data associated with time-of-day choice since generally only a single trip is observed and surveyed; otherwise the OD survey would need to be extended into a Household/Person Interview Survey.
- It is also difficult to support data types that are necessary for measurement of travel time reliability and estimation of its impact on travelers' choices.
- RP surveys are also not extremely helpful for understanding and modeling mid-term choice, such as transponder acquisition.

For more than 20 years, SP surveys have been used to estimate values of travel time and other parameters related to the effects of tolls and road pricing [see Adler and Schaevitz (1989)]. SP surveys include a set of hypothetical scenarios in which conditions (e.g., travel times, tolls) are varied and respondents are asked to indicate what they would most likely choose under those specified conditions. The conditions are varied according to an experimental plan that optimizes the information about the respondents' preferences that each scenario provides.

SP surveys are especially useful in applications where an alternative such as a toll facility does not currently exist but is being planned for the future. In those types of applications, RP surveys are not useful for estimating price effects because road prices, which are variables of interest, do not vary across trips within the region. While other cost elements such as operating costs do vary across trips, those variations are highly correlated with trip lengths and travel times, and thus generally do not provide reliable indications of the effects of price on travel choices.

With respect to choice dimensions, the SP surveys conducted to support road pricing projects have most often focused on the choice between tolled and toll-free routes. For conventional toll facility studies, these surveys would typically present two alternatives: a toll-free route with a given travel time and an alternative tolled route with a lower travel time and a toll at some level. However, many road pricing projects involve more complex effects beyond simply influencing route choice. Some projects, such as HOT lanes, affect occupancy and mode and so the stated preference scenarios would include other modes and occupancy levels as available choice alternatives. For projects that have time-varying prices, different travel periods should be included among the stated preference alternatives. For area pricing projects, the scenarios could allow alternative destinations. In some special cases, effects on trip frequency may also be included in the stated preference experiments.

Travel times and toll prices are the primary attributes in most road pricing stated preference experiments. The trade-offs between travel time savings and extra cost associated with tolls, are expressed in VOT. However, there are other attributes that may also be significant in travelers' choices in the presence of road pricing. Some of the other attributes or features that have been tested in stated preference experiments for road pricing projects include:

- Travel time components—time in free flow conditions and time in congested traffic,
- Travel time reliability,
- Occupancy-based toll levels,
- FAIR (Fast AND Intertwined Regular) lanes policy,
- Commercial vehicle restrictions,
- ETC discounts,
- Travel time variability,
- Driving distance along the route, and
- Non-toll "running" costs.

In an SP survey, it is extremely important to set a realistic choice context. A common approach is to ask respondents if they have made a recent trip in the relevant corridor, and, if so, to ask for details on the most recent trip and use the information to customize the SP choice context. The use of the most recent trip rather than the most typical one is meant to avoid bias and replicate a random sample, just as household survey respondents are asked to complete a diary for a specific day and not necessarily a typical day. A design issue that commonly arises is the limit on how long in the past the most recent trip can be to qualify for the survey. A typical strategy is to set the limit at 1 or 2 weeks prior to the interview, while a retrospective limit of longer than 1 month is rarely used in practice.

SP surveys have been conducted using several different types of instruments. One important challenge is that multiple SP experiments are needed from each respondent, generally involving a series of trade-offs among several variables that vary across two or more travel alternatives. It can be difficult for respondents to process all of this information unless it is presented visually and, for this reason, telephone-based instruments are rarely used. However, hybrid instruments can be used where trip context information is collected over the phone and the stated preference experiments are provided separately by mail or over the web. In addition, simplified experiments can be designed that are more amenable to phone-based administration.

Sampling for stated preference surveys can also be conducted in several ways. For facility-based studies, some type of intercept sampling is often the only viable alternative. This can be because the population using the facility or corridor is widely dispersed geographically and may, for example, include significant numbers of trips made by individuals who live well outside the region where the facility is located. Intercept sampling can be conducted using the methods described earlier for OD surveys, but it can also be accomplished using intercepts at activity centers in the corridor of interest. For area pricing or cordon pricing, it may be most efficient to intercept people within the potential priced area. For studying corridor-specific projects, it is often effective to use Random Digit Dialing (RDD) or address-based sampling within the residential areas that would be served by the project. For broader regional studies, the options are wider and include more standard phone, mail or web/email recruiting. SP surveys have also been administered along with conventional household travel/activity surveys, usually as an add-on to some fraction of those surveys.

Recent advances in SP survey design and technology have made this tool significantly more attractive and practical, particularly in the following respects:

- Computer-based SP surveys customize choice experiments around specific contexts (choice of toll road/lanes versus non-toll road/lanes, choice between road and transit, switching to other time-of-day periods in presence of congestion pricing, etc).
- The SP framework is extremely convenient for multiple/repeated experiments with the same person and can be effectively employed for screening inherent randomness in travelers' preferences that can be captured through estimation of probabilistic VOT distributions with models like mixed (random coefficients) logit.
- The SP framework is convenient for estimation of Value of Reliability along with VOT and other possible impacts.
- Additionally, SP allows for more efficient experimental design with multiple alternatives, while the RP sample structure is bound to the observed frequencies of different alternatives.
- SP survey can be designed to include transponder acquisition in the model's choice hierarchy.
- SP survey is an effective tool in capturing different price perceptions, for example ETC users versus cash users.

SP surveys do have their own limitations. Incorporating all relevant choices leads to complex designs which may confuse respondents. Thus, SP surveys are only effective as a focused tool. SP surveys also have inherent strategic biases. For these reasons, the most promising direction for model estimation is to use a combination of SP and RP surveys that allows for elimination of strategic biases by statistical scaling procedures.

A more detailed analysis of travel survey techniques for road pricing with numerous examples can be found in Appendix A (Section A.2).

3.2 Summary and Proposed Practice Guidelines

The implemented extensive analysis of specific pricing RP and SP surveys used to support existing applied models has revealed the following general patterns, with the following conclusions offered and possible directions for further research identified:

- At the stage of exploratory/preliminary analysis, data collection is often limited to secondary data (traffic counts, land-use changes). The demand functions and utility expressions for choice models, as well as the coefficient values themselves, are frequently borrowed from other areas and adjusted using household income and other socio-economic data.
- If a project is determined to be feasible, primary data collection is conducted. Investment grade studies typically include extensive data collection, with special OD surveys conducted for most major toll projects.
- In some cases (where toll facilities already exist) OD surveys can be used for RP modeling. In many cases, where a facility is in a "new" corridor without current tolling, models are "borrowed" if the extensions of local model cannot be supported with the conduct of new RP and/or SP surveys.

Currently there is a large and growing opportunity for RP surveys in a wide variety of the existing toll corridors due to a number of reasons:

- Pricing analysis can strongly benefit from a systematic statistical analysis of observed VOT and other behavioral parameters would be possible if the data could be made available. This is one of the major directions of the SHRP 2 C04 project closely coordinated with the current NCHRP 8-57 project.
- In some corridors, along with the demand pattern, accurate travel time estimates can be provided. Otherwise travel times and travel time savings for statistical analysis are calculated in the network simulation model, although it should be taken into account that travel time estimates on congested facilities from network simulation models are inaccurate approximations.
- Also, as the experience of recent OD surveys has shown, ETC registration lists can allow access to the current toll

facility users. This greatly facilitates sampling strategy, questionnaire distribution, and post-survey development of expansion factors.

There are several objective limitations associated with RP surveys:

- They are not applicable for model estimation/calibration in new corridors located in regions where there are no current toll facilities.
- With the survey of existing toll facility users, a very specific choice-based sample is created since it can be difficult to define and access non-toll users.
- It is difficult to collect data associated with time-of-day choice since generally only a single trip is observed and surveyed; otherwise the OD survey would need to be extended into a Household/Person Interview Survey.
- It is also difficult to support data that is necessary for measurement of travel time reliability and estimation of its impact on traveler's choices.
- RP surveys are also not extremely helpful for understanding and modeling long-term choice, such as transponder acquisition.

Recent advances in SP survey design and technology have made this tool significantly more attractive and practical, particularly in the following respects:

- Computer-based SP surveys customize choice experiments around specific contexts (choice of toll road/lanes versus non-toll road/lanes, choice between road and transit, switching to other time-of-day periods in presence of congestion pricing, etc).
- The SP framework is extremely convenient for multiple/repeated experiments with the same person and can be effectively employed for screening inherent randomness in travelers' preferences that can be captured through estimation of probabilistic VOT distributions with models like mixed (random coefficients) logit.
- The SP framework is convenient for estimation of Value of Reliability along with VOT and other possible impacts.
- Additionally, SP allows for more efficient experimental design with multiple alternatives, while the RP sample structure is bound to the observed frequencies of different alternatives.
- SP survey can be designed to include transponder acquisition in the model's choice hierarchy.
- SP survey is an effective tool in capturing different price perceptions, for example ETC users versus cash users.
- SP surveys have their own limitations. Incorporating all relevant choices leads to complex designs that may confuse respondents. Thus, SP survey is only effective as a focused tool. SP surveys also have inherent strategic biases. For these reasons, the most promising direction for model estimation is to use a combination and SP and RP surveys that allows for elimination of strategic biases by statistical scaling procedures.

These survey and data collection methods constitute a suite of options that can be used to support the analysis of road pricing programs. The decision about which of these methods to employ depends on several factors, including the stage of decision making that the analysis and modeling must support, the types of data and models available for use and, of course, the schedule and budget for the work. Table 4 below provides some general guidelines for the types of data that might be used to support the different stages of project development. In this table, X represents items that are generally required in some form to support the stage and O represents items that may be appropriate depending on the project importance and complexity.

Table 4. Highway pricing survey and data collection needs.

Project Stage	Survey type					
	Household Interview	**Origin-Destination**	**Stated Preference**	**Opinion**	**Highway Speed**	**Traffic Counts**
Exploratory screening	X					X
Preliminary feasibility	X	O	O	O		X
Feasibility evaluation	X	X	O	O	X	X
Investment Grade	X	X	X	O	X	X

CHAPTER 4

Critical Issues and Directions for Short-Term Improvements

All features discussed in the this chapter are short-term improvements in the sense that either they have been already successfully incorporated in some applied models or can be incorporated without principal difficulties that would require a substantial research effort. All the model features discussed are available within either the 4-step or ABM framework, although the 4-step structure requires a significant simplification of some of the recommended features. The classification scheme adopted is essentially a systematic reflection of the State of the Practice in the modeling of road pricing projects, rather than an accounting of all the possibilities offered by the most advanced modeling practices. More fundamental long-term improvements that would represent the state of the art in the modeling of road pricing are discussed in Chapter 5 that follows.

4.1 Classification of Model Features Required for Pricing Studies

4.1.1 Model Features for Different Pricing Projects

Based on the accumulated modeling experience with various pricing projects described in Chapter 2, as well as taking into account the possible data collection techniques described in Chapter 3, the required model features that stem from the planning needs associated with different project types are classified. These same model features will also be arrayed by their correspondence to the four main stages of the pricing project decision-making process defined in Volume 1.

As shown in Table 5, some model features are absolutely essential from the very beginning of any pricing study, while other more advanced desirable features may be reserved for subsequent stages of project development (detailed feasibility and investment grade studies). The more advanced features, however, may become extremely relevant even early on, if a corresponding pricing strategy is included in the range of options of the particular study, and a robust analysis is required, consistent with other more easily modeled alternatives. Both essential and advanced modeling features still belong to the category of short-term improvements and are not explicitly distinguish between 4-step and ABM frameworks classification.

The following features are essential for practically all pricing studies, and their inclusion in the modeling system to be used for a pricing study should be assessed at the outset.

- Toll facilities must be properly coded in the highway network with appropriate toll value equivalents (e.g., minutes, based on VOT) incorporated in volume-delay functions. The subsequent refinement of this component for more advanced stages should include a detailed coding of toll plazas and access ramps in order to realistically represent delays associated with these facilities. In over-congested areas, where toll facilities and their access point are associated with queuing, the most promising tool to realistically portray the traffic conditions is DTA and microsimulation (discussed in Section 5.3).
- The demand model should be segmented by at least 4-5 travel purposes and 3-4 income groups with VOT specific for each combined segment. An additional step is to apply differential travel time coefficients by segments and consequently VOT estimates by congestion levels that would represent a simple proxy for highway reliability (discussed in Section 5.2).
- The traffic assignment should incorporate and distinguish relevant vehicle classes (auto, commercial vehicles, trucks, taxis, etc.) with the average VOT per class. The technique of multi-class assignment is supported in all major transportation software packages (TransCAD, EMME, and Cube) and can be further applied to differentiate between VOT groups within the same vehicle class.
- It is highly recommended (although not an absolute requirement in the early stages of pricing studies) to incorporate a

Table 5. Model features for different pricing studies.

Pricing Study	Model Features	
	Essential	Advanced
All types of pricing	Toll facilities coded in the highway network with toll incorporated in the volume-delay functions	Toll plazas and access ramps coded with realistic delay functions
	Segmented VOT by travel purpose and income group in demand model	Perceived highway time by congestion levels / reliability
	Segmented VOT by vehicle class in traffic assignment	Additional vehicle class stratification by VOT
		Pre-route (toll vs. non toll) sub-choice
	Mode choice and assignment equilibration	Inclusion of trip distribution in equilibration through mode choice logsum
HOV/HOT lanes	Car occupancy (SOV, HOV2, HOV3+) sub-choice in mode choice	Additional vehicle class stratification by occupancy in assignment
Area and other large-scale pricing schemes	Trip generation sensitive to accessibility/generalized cost	Accounting for trends in flexible / compressed work schedules and telecommuting
Highway pricing in parallel with transit improvements	Mode choice with developed transit nest	
	Bus speeds linked to highway congestion	
Congestion pricing	Peak spreading model	Time-of-day choice model Accounting for trends in flexible / compressed work schedules and telecommuting
Dynamic (real-time) pricing		Special network / toll equilibration procedure
Highway pricing in parallel with parking policies	Parking cost inclusion in mode choice	Parking choice model for auto and drive-to-transit trips with parking constraints
Equity analysis	Model segmentation and reporting of user benefits (time savings and extra cost) by 3-4 income groups	

binary route type choice model (toll versus non-toll facility), either as a lower-level sub-nest in mode choice, or as a pre-assignment procedure. This sub-model allows for capturing a toll bias associated with the perception of the generally improved reliability and safety of the toll facility, as well as provides for better (non-linear) specifications of the trade-offs between travel time savings and extra costs.

- It is essential to equilibrate the demand model (at least mode choice and pre-route choice) and the highway assignment to ensure that the results correspond to (or at least approximate) a stable equilibrium solution. It is more difficult to include the trip distribution (and other sub-models like time-of-day choice and/or trip generation) in the global equilibrium, which might require multiple iterations and special averaging algorithms. However, it is essential to eventually ensure a reasonable level of convergence of the entire model system. Recent experiences with the New York activity-based model has shown that effective strategies of equilibration based on a parallel averaging of trip tables and LOS skims can achieve a reasonable level of convergence in 3–4 global iterations, even in one of the largest and most congested regional networks (Vovsha et al. 2008).

Other important model features are associated with particular pricing projects and forms:

- If the pricing forms to be studied include vehicle eligibility and/or toll differentiation by car occupancy, the corresponding sub-choice (SOV, HOV2, HOV3, HOV4+) should be included in the auto sub-nest of mode choice model. So far in practice, an HOV4+ lane has been the maximum considered (HOT lane Atlanta Study in Volume 1). Further on in the modeling, the same car occupancy categories should be separated in the assignment procedure.
- If area pricing or other large-scale pricing schemes are considered, it is reasonable to expect a global effect on trip generation rates (activity patterns), in addition to mode, route, time-of-day, and destination shifts. This requires a flexible trip generation (activity pattern) model that is appropriately sensitive to accessibility measures. A specific but important issue that can be addressed with ABMs is the possible shift in usual work schedules, in particular, to a greater prevalence of compressed work weeks and telecommuting. In most cases, this type of response can only

be estimated with models based on SP surveys (discussed in Chapter 3).

- Highway pricing decisions may be considered in tandem with transit improvements. These include direct transit integration in the highway pricing project: bus rapid transit (BRT) on the HOV/HOT lane, or indirectly through improvements of bus speeds in mixed traffic on congested links, and augmented transit services funded by the road pricing actions and aimed at providing improved transit choices for drivers who could change mode. In order to model these types of effects, the model choice should include a transit nest that adequately portrays the transit options competing with highway options (toll and non-toll). On the network side, bus speed functions should be integrated with highway speed (volume-delay) functions to properly describe the mixed traffic conditions.
- Congestion pricing (i.e., toll differentiation by time-of-day periods and hours) specifically targets departure time of trips. In addition to route and mode shifts, congestion pricing results in departure time shifts within the peak periods (from the peak hour to so-called "shoulders"), as well as between periods (for example, from the AM peak to midday off-peak period). The corresponding choice model components, referred to as "peak spreading" and "time of day choice" should be added to the model system. So far, inclusion of these sub-models in the standard travel demand model system has been problematic, revealing one of the 4-step model's weakest aspects. The ABM framework offers significant advantages in this respect, allowing for the estimation of the impact of time of day charging on all travel over the course of the full day (discussed in Section 5.2.6).
- Real-time dynamic pricing, widely recognized as one of the most advanced and promising pricing forms, represents a special challenge to modeling because it requires a special toll equilibration procedure (discussed later in this chapter).
- Highway pricing (especially area/cordon pricing forms) can be effectively combined with parking pricing and supply policies. If parking is included in the study, the travel model (specifically mode choice) should include parking cost in the auto utility functions. If parking policies become a major policy focus of the study, it is suggested that a more advanced model component be included—an explicit choice of parking location (that can be different from the zone of the person trip destination). This component can be effectively and consistently incorporated in the activity-based model framework only.
- One of the important aspects of any pricing study is equity analysis across income groups and geographic areas. From this perspective, it is essential to segment all sub-models by income groups and ensure that summaries of travel time savings and extra costs that constitute User Benefits could be produced and reported by income group.

4.1.2 Model Features for Different Stages of Decision Making

The model improvement process and desired features can be arrayed in parallel with the basic generalized stages of pricing studies. A framework of gradual corresponding improvements is outlined in Figure 5. Four major stages of the project development (described in Volume 1, Chapter 4) and four broad stages of improvement of the forecasting tools were examined. This is an approximate framework, since many details are dependent on the specifics of pricing study scope and the alternatives that need to be compared. In general, having an advanced model from the very early stage will only be an advantage; however, this is certainly not always necessary. A pricing study could begin with a simplified model while the data and modeling tools are improved in the process, subject to the specific pricing alternatives identified at the earlier stages for further analysis. The timeline of the pricing study and the implementation of the model improvements to support it should be established in a realistic way. In particular, it should be understood that the final stage of Investment Grade study will require at least a year to implement and as much as $1,000,000 or more, of which a large share of the costs will be for model improvements. Consequently, it is recommended to advance, rather than delay, the model improvement steps vis-à-vis the project development stages whenever possible.

In a majority of cases where decision making about highway pricing was done in a systematic way, supported by forecasting tools, the existing regional model (typically that of the MPO) was employed in some manner. The development of a new regional model from scratch is a time consuming and costly effort. Also, the timing of a major model improvement effort, driven by periodic data availability, might not coincide well with the road pricing study. Consequently, in many cases the best available model, along with some short-term improvements, is typically applied. There is, however, a growing recognition of the importance of travel model improvements in view of the scrutiny by rating agencies and private investors of T&R forecasts, and many agencies have made substantial efforts to improve their models for pricing studies. In many cases, the RFP issued by the interested agency for a T&R study explicitly included a model improvement task. An additional benefit of this effort, as perceived by MPOs, is this study would contribute to the general improvement of the regional model as well and can spur additional useful data collection, model validation, and testing.

There were very different cases observed with respect to the level of model sophistication versus the decision-making stage. In some cases, the agencies advanced their pricing projects to the last stage (and effectively started implementation) with no substantial improvement of the forecasting tools. Despite fulfilling the understandable intention to speed up

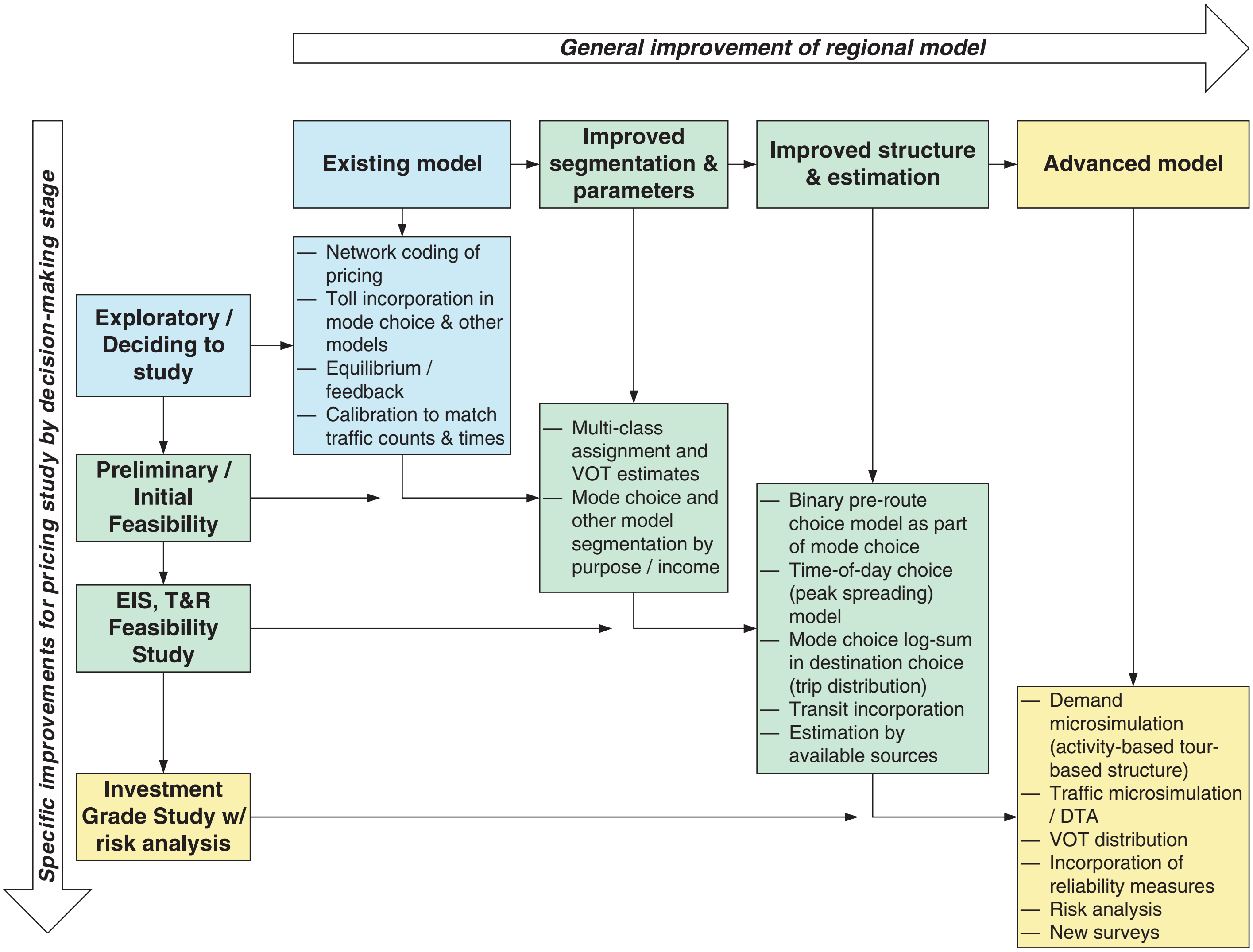

Figure 5. Forecasting tools by stage of project development.

the decision-making process, a more detailed analysis of the existing long-term concessions and associated financial terms has indicated that these may not be examples of unqualified success, especially where the absence of a solid and defendable forecast may have resulted in financial conditions that were highly favorable for the private concessionaire, but leave questions open from the public perspective.

There is also a clear note of warning from the numerous publications of the leading rating agencies that they will increasingly consider the quality of the T&R study as one of the major risk factors that can significantly reduce a project's rating (especially for start-up projects). In some other cases, where agencies had already developed an advanced model, it was employed from the initial stage of the decision making, even though the level of detail provided by the model was probably excessive for this early stage of the preliminary project development.

Notwithstanding possible deviations based on different project development frameworks and varying states of existing regional modeling capabilities, there are several clear patterns that can be generalized and used to characterize both prevailing and best practice. In general, the following correspondence between the stage of decision making and appropriate modeling tools can be recommended.

Stage 1: Exploratory

General strategic go/no-go decisions about highway pricing possibilities are made in this stage. The existing regional model should be applied with at least a minimal set of short-term improvements that would normally include the following common steps, corresponding to the list of general model features essential for all pricing studies identified in the previous sub-section:

- Coding of highway facilities with the corresponding pricing forms (flat, fixed variation by time-of-day, variable real-time, etc.), converted into travel time equivalents for highway assignments and skimming.
- Incorporation of tolls in the current demand models, specifically mode choice and trip distribution models.
- Proper implementation of network equilibrium and associated feedbacks, at least between the assignment and mode choice models, with a subsequent consideration of the trip distribution model as well.
- Calibration effort (through proper adjustment of model coefficients, mode specific constants, and/or distributional K-factors) in order to reasonably match traffic counts in the base year, and observed aggregate district-level OD flows if available, as well as approximate travel times and speeds, in the relevant corridor/sub-area.

Stage 2: Preliminary Feasibility Study

Further improvements are recommended depending on the pricing project nature. These improvements mostly include better model segmentation (poor segmentation that is too crude for analysis of willingness-to-pay is one of the common drawbacks of many conventional models), as well as a differentiation of the model coefficients related to VOT. At least two additional improvements are generally needed:

- Mode choice (and trip distribution if technically possible) segmentation by travel purpose and income group (that have a strong impact on the VOT).
- Multi-class assignment procedure distinguishing traffic by vehicle types (auto, commercial vehicle, heavy truck, taxi, etc) and auto occupancy (SOV, HOV2, HOV3+, etc.) directly related to the pricing differentiation and eligibility.

Stage 3: Environment Impact Statement (EIS)

This stage is associated with full T&R studies, when the model structure should be improved in order to incorporate additional important sub-models. The following improvements are generally warranted at this stage:

- Introduction of a binary pre-route (toll versus non-toll) choice model as part of the mode choice model (at the lower level of mode hierarchy). In cases such as for intercity highways, with high percentages of trucks (where mode choice is not playing a significant role), the binary choice model essentially represents a user decision-making mechanism and the perception of tolls. This is essential in order to incorporate a sensitivity of demand, beyond travel time savings, to the additional travel quality and reliability typically associated with toll roads.
- Introduction of a time-of-day choice and/or an incremental peak-spreading model that is essential for urban toll roads and congestion pricing variable pricing analysis.
- Constructing a proper linkage between mode choice and destination choice (trip distribution) models through the log-sum accessibility measure, essential to ensure logical sensitivities of the model when multiple pricing alternatives are compared.
- The implementation of this linkage may also require model (re)estimation efforts based on the existing household travel survey and other available sources, or the collection of new survey data in the corridor, typically OD, and possibly with a SP component.

Stage 4: Investment Grade Study

In the course of the pricing study's progress, the model improvement process can finally lead to a complete or gradual transition toward an advanced model structure that would fully support specific requirements of the Investment Grade Study, including comprehensive risk analysis across different relevant factors. The following features of advanced model are especially relevant for highway pricing projects at this stage:

- Individual (household/person) microsimulation of the travel demand choices in an Activity-Based Tour-Based structure.
- Individual (vehicle) microsimulation of traffic using DTA technique.
- Detailed analysis of travel markets and associated probabilistic VOT distributions, essential for capturing such important factors as situational variation in VOT.
- Explicit incorporation of travel time reliability measures and willingness to pay for reliability improvements, along with average travel time savings.
- Integration of the T&R forecasting and financial risk analysis through a set of well designed sensitivity tests, and an analytical representation of risk factors with multivariate simulations.
- Implementation of multiple model runs with different toll values for the purpose of toll optimization, implemented with respect to the revenue, network conditions (measured by minimal speed, maximum V/C ratio, or maximum throughput), or by social welfare (utility) function.
- Implementation of new RP household travel surveys, with supplementary SP components, designed to be applied in the estimation of advanced models.

The improvements to the regional model made from stage to stage can be accumulated, and, if the model improvement process is well-coordinated and well-thought out from the beginning, it can result in an advance state-of-the-practice model suitable for robust pricing analysis. The timing and requirements for project development and the model improvement process, however, might not be well correlated in some situations. In these situations, simpler model versions may need to be employed initially and over the course of the decision-making process, with an acknowledgement of the consequence that additional risk will be assigned to the project due to the reliance on simplified T&R forecasting methods and data. While the development of an advanced activity-based model with all these features in place might be the best long-term goal and most desirable for Investment Grade analysis, these do not need to be brought altogether and implemented in the initial development of modeling approach for pricing, but can be staged over time. It will also be shown how some particular improvements (for example, incorporation of reliability measures or preparing data for risk analysis) could be done within the structure of more conventional and commonly used 4-step models.

4.1.3 Specific Requirements for Forecasting Tools for Investment Grade Studies

Rules of Financial World

Rating agencies put travel forecasting procedures under a high level of scrutiny that is generally different from the model evaluation/validation criteria applied in the public sector. This section discusses: risk analysis, risk mitigation methods (including more extensive data collection and model calibration, revised population and jobs forecasts), toll rate optimization, and sensitivity tests with different toll scenarios.

Investment Grade studies are characterized by more stringent requirements on traffic and revenue forecasts, added levels of scrutiny on the model structure and calibration, and a number of additional post-modeling steps compared to the preliminary Financial Feasibility studies. The quality of the forecast may directly affect the project bond rating (i.e., the possibility to obtain the necessary loans and the interest rate associated with them). The three major rating agencies (i.e., Fitch Ratings, Moody's, and Standard & Poor's) conduct various tests on T&R forecasts (especially those produced by public agencies), and examine variations in many of the input parameters, as well as the model structure itself [(Standard and Poor's 2002–2005, Fitch Ratings 2003-2005)].

For these reasons, Investment Grade studies require an advanced and well calibrated travel model integrated with network simulation. It is not uncommon for an investment grade forecast to take approximately one year or longer and upwards of $1 million to complete. While a general principle that "a good model for an Investment Grade study should first be a good behavioral model in a common sense" holds true, it is only a starting point. There are several important technical specifics of an Investment Grade study compared to a T&R forecast produced for Feasibility studies that should be addressed and are not necessarily included even in advanced activity-based models. They relate to the model structure and calibration, model application, and a number of post-modeling steps that convert the model outputs into the inputs needed for a Financial Plan.

The following aspects relate to the model structure and calibration:

- Presence of all three major relevant choice dimensions—route, mode, and time-of-day choice—that represent first-order responses of the travelers as described in Chapter 1.
- More elaborate time-of-day choice or peak-spreading model distinguishing between the peak hour and "shoulders" within each broad period.
- Flexible trip generation model sensitive to accessibility improvements.
- Flexible trip distribution model fundamentally linked to the mode choice model by mode-choice inclusive values (Logsums) as impedance measures.
- User segmentation by VOT across travel purposes, income groups, times of day, vehicle type and occupancy, as described earlier in Chapter 1 and will be elaborated further in Sections 4.3 and 4.4. Special attention should be paid to VOT segmentation by occupancy, since most models in practice assume that VOT is simply proportional to travel party size (as discussed in Chapter 1). In more advanced ABMs, VOT can be specified in a probabilistic way (to account for situational variation), and can include Value of Reliability (VOR) as well (as discussed in Chapter 5).
- Extensive newly collected data and more rigorous model calibration is normally assumed. It should be understood that even a well-calibrated regional model might have certain discrepancies compared to traffic counts and/or speed surveys in a particular corridor or facility. It is essential to recalibrate the model based on the most recently collected data, including traffic counts, special surveys (e.g., users of a particular toll facility), and speed measurements in the relevant corridor. With these data, the calibration targets for a particular pricing study can be set in a more rigorous way. For example, while a range of ±15% from average (daily) traffic counts is considered an acceptable range for a general purpose regional model, a range of ±5% can be set for each time-of-day period for the relevant priced corridor. Additionally, a historical set of traffic counts for validation of the growth tendencies is highly recommended.

The following aspects relate to the model application:

- Toll rate optimization and multiple sensitivity tests with different toll and toll escalation scenarios.

- Risk analysis and risk mitigation measures. This includes identification and quantification of risk factors. A good overview of the common "suspects" in travel forecasting is provided in the periodical publications of the rating agencies (Standard and Poor's 2002–2005; Fitch Ratings 2003–2005) as well as in (Washington State's tolling study CSI 2006). Contrary to the conventional travel forecasting culture that has been based on a deterministic interpretation of the model outcome, the culture of the investment world is based on a probabilistic view of the model outcome. A theoretically consistent inclusion of the probabilistic risk analysis in traffic and revenue forecasting procedures is an important avenue for bringing these two worlds together and is an essential theme of the current synthesis.

The following general risk factors are under scrutiny by rating agencies:

- Start-up toll facilities are considered the most risky and are put under a stress test, especially if the forecast was implemented by a public agency.
- Accurate traffic and revenue forecasting in dense urban areas will always lie at the opposite end of a reliability spectrum from a river crossing with a clear competitive advantage over limited alternatives.
- Traffic patterns associated with well-defined, strong radial corridors appear to be more reliable.
- Forecasts prepared by project sponsors and bidders (interested parties) are generally higher than prepared by investors/bankers; this optimism bias is estimated at 20% or more. More aggressive forecasts can be accepted for PPP that do not need rating.
- VOT miscalculation and improper aggregation across different income groups/travel markets (that's why a proper model segmentation is essential).
- Recession/economic downturn (GDP growth is correlated with traffic growth with some lags).
- Slower future-year land-use development along the corridor. Reconsideration of population, employment, and income growth forecasts prepared by the MPO or DOT for the region/corridor is one of the frequent requests.
- Lower time savings than the modeled ones.
- Improvements considered to competing free roads.
- Potential for lower usage of toll roads and managed lanes by trucks than modeled.
- Lower possible off-peak/weekend traffic (40–50% of weekday) than is normally assumed (70–75% of weekday).
- Specific risk factors for trucking market are essential if trucks constitute a significant share in the traffic. In particular, less reliability should be placed on forecast if the trucking market is composed of a large number of small, owner-driver general haulers. Additionally, markets consisting of several, very large haulage companies transporting high-value or time-sensitive commodities are likely to be less volatile.

The following aspects normally relate to the post-modeling steps, though any of them might be considered for direct modeling as well:

- Annualization of revenues including assumptions on weekend and holiday revenues, seasonality, within-week variability, etc. TTA of TxDOT developed a five-factor qualitative indexing scheme for Equivalent Revenue Days per year (TTA Toll Feasibility Analysis Process 2005). The factors may vary from corridor to corridor and the best way for established facilities is to develop individual factors based on the observed patterns. It is also important to consider that a weekend's VOTs are generally lower due to a mix of purposes and schedule flexibility. Whereas weekend and holiday traffic on a non-toll facility is generally around 70–75% of weekday traffic in urban areas, the portion of traffic using toll roads during weekends tends to be less.
- The yearly T&R stream needed for the Financial Plan is calculated by interpolating between horizon model forecasts and extrapolating beyond modeled years for long periods (40–50 years and longer). Capacity constraints (and adverse effects of congestion when traffic volume approaches capacity) should be taken into account for deep forecasts if they are not directly simulated in the model.
- Detailed consideration of a ramp-up period. If it is not modeled as a dynamic behavioral response in the model (which is unfortunately the case with even the most advance AB models), certain assumptions are made based on the past experience with similar projects. Specific ramp-up considerations are associated with ETC if no cash payment option is provided. In this case, the ramp-up period is almost none for routine users and commuters, but might be significant for occasional users and visitors. The following initial ramp-up period assumptions for start-up projects (as revenue-stressed test) are recommended by Standard & Poor's (2004) (Table 6).
- Detailed consideration of bulk discounts, person/vehicle type discounts, toll evasion (if any), and other revenue loss factors, such as accidents/incidents, extreme weather, or special events, among others.
- Consideration of toll rates escalation (CPI, GDP, floor, ceiling) versus population income (and VOT) growth over a long period of time.
- The model output needs to be processed in a form that is suitable for subsequent analysis. It is important to ensure transparency of the results and identify key areas (OD pairs, core travel markets) for which the calculations can be demonstrated for practitioners (open the "black box"). The following three output formats are very useful for the

Table 6. Recommended ramp-up assumptions for T&R of start-up projects.

Year	Projects		
	Low-risk %	Average-risk %	High-risk %
1st	80	65	45
2nd	90	75	53
3rd	100	80	60
4th		85	65
5th		88	70
6th		90	73
7th			76
8th			78
9th and later			80

subsequent Financial Plan: (1) toll revenues by year (most probable with 80% and 95% confidence intervals forming optimistic and pessimistic curves); (2) toll revenue distribution for some representative years (density and cumulative); and (3) possible distribution of revenue available for Debt and Equity (most probable, lowest reasonable, highest reasonable) and such parameters as likely debt-to-equity ratio and associated debt service residual revenues available for equity participants.

Several preliminary steps are suggested before completion of a T&R forecast and Financial Plan. Rating agencies can be asked to provide a preliminary opinion and advice on how to strengthen the creditability of the forecast. A discussion can be initiated with the TIFIA Credit Program to ascertain the type of assistance that could be reasonably expected.

Investment Grade studies are often completed in parallel with environmental assessments. Information on preliminary capital and annual Operating & Maintenance (O&M) cost from these studies is frequently used in order to obtain a preliminary indication on the financial feasibility. Refined cost estimates are used for the final Financial Plan.

Preparation of T&R for Financial Plan

The Financial Plan is based on a computerized cash flow model that allows the testing of different financial structures and assumptions (Tillman, et al. 2006). Discounted cash flow analysis should demonstrate that the project-specific cash flow payout schedule can be met. It is essential to analyze Financial Plans in detail if there are several competing proposals for the same project. A reasonable criticism of some "fast" practices with accepting private-sector financial proposals, with insufficient detailed scrutiny, can be found in Dornan (2006) and Enright (2006).

Toll-based financial models should be comprehensive and should address different relevant funding sources (government grants, impact fees, and credit enhancements), as well as generated bonding capacity (take advantage of tax-exempt municipal bond market). Tolls can generally supplement the funding, but cannot replace it completely for many expensive projects. General use of the toll revenue includes paying for toll system operation and maintenance, funding (in whole or in part) construction and maintenance (including capital rehabilitation), and funding related parts of the transportation system (potentially, including transit).

The Financial Plan must be based on the detailed estimates of construction and O&M cost for each major segment including all components. The Association for the Advancement of Cost Engineering (AACE) publishes risk factors for cost estimates that can be used in the Risk Analysis.

In general, the Financial Plan should be based on conservative assumptions regarding the cost of financing, interest rates, coverage ratios, and reserve accounts. The specific metrics and limitations of the Financial Plan include:

- Credit quality (equity contributions and guarantees),
- Statutory limitations for the agency to issue investment quality debt and for the state to support the financing,
- Debt service repayment,
- Debt service reserve accounts funded by the bond issue (usually 125% of the average annual debt service),
- Debt service coverage ratio,
- Capitalized Interest During Construction,
- Cost of finance (bonds),
- Cost escalation over years,
- Period of finance and interest rates, including stress tests, and
- Project equity and secondary sources of funds (subordinate debt, TIFIA loans, or direct contributions).

The Financial Plan must be reviewed carefully by potential lenders, as well as any public agencies that may be providing financial support to the project (FHWA, TIFIA Credit program). As a rule, each pricing project must be analyzed as a stand-alone, single asset facility, and then, several selected projects can be analyzed under an integrated system approach to gauge levels of feasibility. Several strategies can be applied depending on the project pool formulation and the adopted regional pricing concept:

- Full funding of construction cost through tolls,
- Leveraging up several projects in a "Regional System" (cross-subsidy), and
- Supporting projects with some federal/state monies.

If the project is to be rated by one of the major rating agencies (i.e., Standard & Poor's, Fitch, or Moody's), the following important aspects should be taken into account.

Documents required by rating agencies include:

- T&R forecast with risk analysis,
- Financial plan,
- Contractual documents for the construction and operation of the project (including all environmental and construction permits needed),
- Financing documents (trust indenture, bond insurance, or letters of credit),
- Regional and local economic trends and other input data (population growth, employment growth, income levels, traffic counts, etc.),
- Independent T&R forecasts (if available) and engineer's feasibility report.

General rules and requirements include:

- Stand-alone basis for assessment,
- Reliable and conservative T&R forecasts,
- BBB rating (minimum needed for issuing bonds) for start-up roads requires net revenue at least 1.7 greater than senior lien debt payments, and
- Government subsidy/credit guarantees are required for non-toll part of funding.

A preliminary rating is often requested to assist a project sponsor in identifying further steps that must be taken to secure an investment-grade ranking BBB or higher. It is likely that most start-up toll roads will require some form of credit assistance and/or guarantees to gain this rating.

Rating analysts evaluate and the most important risk factors:

- Reasonability of T&R forecast assumptions,
- External political and economic factors,
- Existing or planned competition for the roadway,
- Regional economic conditions,
- The break-even point for servicing debt.

Specific Requirements for Forecasting Tools

Modeling tools to support highway pricing decisions need to comply with the specific requirements associated with revenue forecasting in the context of project ratings for private financing. The analysis of the existing models done to date, as well as the tracking history of model applications and associated (well-published) criticism from the rating agencies, have clearly shown that some principal improvements in modeling tools are needed to ensure the credibility of T&R forecasts, as well as to better integrate the transportation modeling culture with the culture of the investment analysis community. As a result, the following important model features could productively be improved:

- Rating agencies and private investors consider stand-alone start-up projects as the most risky, uncertain, and subject to over-optimistic modeling assumptions. It must be recognized that static validation of a transportation model for the base year does not at all guarantee that the model will properly respond to changing travel conditions, including those associated with a new toll road or pricing action.
- Revenue forecasts have to be presented in a probabilistic form (not just a single series of forecast numbers) suitable for subsequent investment risk analysis and rating. The current practice is characterized by a sequential implementation of T&R forecast followed by independent/simplified risk analysis. The latter is frequently based on an arbitrary scaling of the revenue and assigning of risk probabilities based on the record history of toll road forecasts.

The following are the most important factors that should be included in the risk analysis, and the technical methods for their assessment are recommended in Section 4.4.4:

- Model inputs on the demand generation side, such as land-use and socio-economic growth assumptions, overall regional economic trade and political environment, and the cost of fuel (including taxes).
- Model inputs on the network supply side including the improvement of competing roads and transit modes in the corridor, possible delays in the deployment of complementary projects and improvements.
- Travel model structure and parameters including structural assumptions on VOT (savings) by user segments, assumptions regarding traffic that are not directly modeled, such as off-peak, weekend, holiday, seasonal, extreme-weather traffic, etc.
- Non-travel traffic components (modeled by ancillary models) including heavy trucks, light trucks, and commercial vehicles.
- Post-model assumptions that include ramp-up period, toll evasion, bulk discounts, traffic incidents, and their management.

An important improvement in current best practice could be an integration of the revenue forecasting and risk analysis through a two-stage procedure:

1. Set of designed sensitivity tests (scenarios) applied with the full model, and

2. Post-processing of the results through aggregate regression analyses and simulations that will allow for assessment of the "confidence bands" around the forecasts that would be used in the subsequent financial analysis.

This technique will ensure that traffic and revenue forecasts are analyzed and prepared in formats acceptable and trusted by the financial community. At the same time, it should be understood that the uncertainty associated with T&R forecasts is only one of the risk factors for the road pricing projects. There are many other factors associated with these projects, including of course cost estimates, for which a separate risk analysis should be implemented (and the corresponding accuracy ranges are well established).

At the final stage when the financial plan is formed, both sides of the risk equation, revenue and cost, are taken into account, as well as the distributions of such important measures as the likely equity-to-debt ratio, debt service, and residual revenues over years which are produced in a probabilistic fashion. It is believed that improvements of the analytical procedures on the T&R side will be especially helpful for obtaining better rating and acceptance of start-up projects that are subject to very rigorous "stress" tests by rating agencies.

4.2 Prototype Structure of Travel Model for Pricing Studies

4.2.1 Main Travel Dimensions Affected by Pricing

A travel model can be constructed to include a wide range of possible responses to congestion and pricing, in the approximate hierarchical order, from the short-term to long-term, as shown in Table 7.

Most of the existing models applied for pricing (both in research and practice) have been largely focused on the subset of trip-level short-term responses, including route choice, pre-route choice, car occupancy choice, mode choice, and time-of-day (or trip departure time) choice (Brownstone, et al. 2003; Brownstone and Small 2005; Lam and Small 2001; Mahmassani, et al. 2005; Mastako 2003; Verhoef and Small 2004). These choice dimensions are generally recognized as the most important for pricing, and are classified as first-order responses. Within this limited framework, there have been only few examples of a full integration across all these choices—in the existing ABMs developed for Columbus, OH (MORPC 2005] and Montreal, QC (Travel Demand Model Development for Traffic and Revenue Studies in the Montreal

Table 7. Possible traveler responses to congestion and pricing.

Choice Dimension	Time Scale for Modeling	Expected Impact
Network route choice	Short-term – trip episode	Stratified response by user group
Pre-route choice (toll vs. non-toll)	Short-term – trip episode	Stratified response by user group
Car occupancy	Short-term – tour/trip episode	Planned and casual carpool
Mode choice	Short-term – tour/trip episode	Shift to transit, especially to rail and for low/medium income groups
Time-of-day / schedule	Short-term – tour/trip episode	Peak spreading
Destination / stop location	Short-term – tour/trip episode	Improved accessibility effect combined with negative pricing effect on trip distribution for non-work trips.
Joint travel arrangements	Short-term – within day	Planned carpool / escorting
Tour frequency, sequence, and formation of trip chains	Short-term – within day	Lower tour frequency and higher chaining propensity
Daily pattern type	Short-term – weekly (day to day)	More compressed workdays and work from home
Usual locations and schedule for non-mandatory activities	Medium term – 1 month	Compressed / chain patterns; weekly planned shopping in major outlets
Household / person mobility attributes (transponder, transit path, parking arrangements at work)	Medium term – 1-6 months	Higher percentage of transponder users and parking arrangements for high incomes, higher percentage of transit path holders for low incomes
Household car ownership choice	Long term – 1 year	Stratified response by income group (higher car ownership for high incomes, lower car ownership for low incomes)
School / university location and schedule	Long term – 1-5 years	Choice by transit accessibility; flexible schedules
Job /usual workplace location and schedule	Long term – 1-5 years	Local jobs for low incomes; compressed / flexible schedules
Residential location	Long term – 5 years +	Income stratification (high income suburbs around toll roads, low income clusters around transit)
Land-use development	Long term – 5 years +	Urban sprawl if no transit; otherwise shift to transit

Region, 2003). There are, however, many other important travel dimensions that have been less explored in either practice or research. These include long-term impacts of congestion and pricing such as fundamental changes in travel behavior patterns that cannot be captured and understood at the single trip level. For example, in over-congested urban areas (e.g., New York, Chicago, and San Francisco), many employers offer workers compressed work schedule opportunities (e.g., 4 days, 10 hours per day). This new choice dimension can have a very significant impact on the amount of travel produced and its temporal distribution. This choice, however, is clearly not a trip-level decision comparable to choice between Managed and Free Lanes (or between toll and non-toll road) for a particular trip. Choices such as this should be modeled within a proper behavioral framework that includes an extended time scale, with a robust set of explanatory variables, and linkages to the other short-term and long-term choices (Pendyala 2005, Spear 2005). Depending on the project scale and time horizon, these second-order responses might become as significant as the first-order ones.

Important behavioral responses that are generally beyond traditional trip-level modeling choices can be grouped into the following broad classes:

- Trip/tour destination choice that is equally important for both AB and 4-step models; it is normally assumed that impacts of congestion and pricing should be captured through the generalized cost or mode choice Logsum (Erhardt, et al. 2003, Dehghani and Olsen 1999); however, there can be more direct and specific impacts that are worth exploring.
- Short-term choices that relate to daily activity-travel patterns that cannot be fully captured at the elemental trip level. They include explicit joint travel arrangements (Vovsha, et al. 2003, Vovsha and Petersen 2005), tour formation [(NYMTC 2004)], and daily pattern type (MORPC 2005) (for example, decision to stay at home on a given day). These choices can be effectively applied only in an ABM framework. There might be an additional (though very limited) use of this for 4-step models in order to investigate congestion and pricing impacts on trip generation through accessibility measures. It is important to address these dimensions alongside conventional trip dimensions, since many new pricing forms are not trip-based (for example, daily area pricing schemes applied in London (Litman 2005) and currently envisioned/modeled in New York, San Francisco, and Los Angeles).
- Medium-term choices relating to usual location and schedule for non-mandatory activities (like shopping or entertainment). A deeper understanding and ability to forecast such choices may be beneficial in order to put certain choices into a medium-term framework in order to explore the impacts of congestion and pricing beyond the short-term single-trip consideration. These choice dimensions can be incorporated into an advanced AB model only.
- Medium- and long-term choices that relate to person and household mobility attributes (e.g., car ownership, transponder acquisition, transit path, parking arrangements, etc.). There is a growing recognition of the importance of these choices in understanding and modeling impacts of congestion and pricing. There have been some initial attempts to formulate and estimate choice models related to the acquisition of transponders simultaneously with pre-route, departure time, and/or car occupancy choices, although the estimation was implemented at the single-trip level (Yan, et al. 2002, Yan and Small 2002).
- Long-term location choices of residential place, workplace, and school as well as land-use development impacts. A special methodology for analysis of congestion and pricing impacts on these choices has not yet been developed. The existing long-term models of this type operate with standard trip-level measures of accessibility (Vovsha et al. 2005); thus, the effect of different and extended time scales is lost. There are plans, however, to explore data sets that include information on long-term choices (along with trip records) to ascertain the differential impacts of congestion and pricing over various time scales.

Several of these choice dimensions represent relatively new choice models that have not yet been widely accepted or even explored (only first attempts to formulate and estimate these models have been made and reported). These relate to the integration of the binary pre-route choice (toll versus non-toll) in the mode choice nesting structure, payment type, and associated vehicle equipment (cash, E-Z pass, transponder), as well as models of carpooling mechanisms (explicit modeling of joint travel).

4.2.2 Observed Impacts of Pricing on Different Travel Choices (PSRC Experiment)

The Traffic Choices Study was a unique behavioral experiment carried out by Puget Sound Regional Council (PSRC) for the FHWA Value Pricing Pilot Program. A sample of selected Seattle region households reacted to variations in toll levels by road type and time of day over an 18 month period, with in-vehicle GPS units used to record behavior as accurately as possible and to keep track of toll fees charged to respondents. The information in this section is based primarily on two PSRC documents: *Traffic Choices Study: Summary Report,* from April 2008, and Appendix 19 to that report *Traffic Choices Study: Toll Impact Models.*

Description of the Experiment

The Traffic Choices Study combines some of the best features of RP and SP data collection for support of the analysis of travel behavior and the improvement of demand models. Similar to SP, the experiment was able to obtain behavioral responses to a policy that has not yet been implemented—namely ubiquitous, mileage-based congestion pricing on all freeways and main arterials in the Seattle region. In this case, the study was able to overcome the hypothetical nature of SP methods by applying the pricing during real trips that the respondents made over an extended period of time and charging those respondents real money for using specific roads at specific times of day and week. This was done using an innovative approach of providing respondents with a fixed sum of money in an account at the beginning of the experiment. Respondents were also provided a toll map and schedule to inform them of toll levels as they varied across roads and time periods, and in-vehicle GPS determined the level of per-mile toll applied at any instant and that information was relayed to the driver. At the end of the experimental period, respondents were allowed to keep whatever funds remained in their account. This system mimicked as closely as possible the way that funds would be charged against user credit cards for an actual electronic tolling system. The main differences compared to an actual congestion pricing system were that (a) only a small subpopulation of all drivers on the roads were faced with the experimental pricing, so there was no noticeable effect of pricing on overall traffic levels or congestion, and (b) respondents spent money given to them as part of the experiment, which, for some, could evoke the sense that the money is not really their own. The implications that these differences may have for behavioral modeling are discussed later on in this section.

For the study, GPS units were installed in all household vehicles in 275 randomly recruited households in the region, providing a sample of more than 400 instrumented vehicles. Before tolling was "turned on," respondents drove with the GPS units in their vehicles for a period of three months (see timeline in Figure 6). This initial non-priced period served a few different purposes: (a) to make sure that the GPS units were working and transmitting data properly to the central facility, (b) to collect baseline behavioral data against which data from the tolled situation could be compared in analysis, and (c) to get an idea of how many miles each household regularly drove on the tolled links, so that the initial funding level of the user account could be set. The objective was to set the budget high enough so that users would not fully deplete the account and have to leave the pricing experiment early, while at the same time not setting it so high that some households would still receive a significant reward at the end, even if they did not adjust their trips to avoid paying the tolls.

Figure 7 shows the Toll Roads Map that was provided to respondents. The map shows two types of roads that were priced: the main freeways shown in green, and other main arterials shown in white. The toll rates per mile for freeways were set twice as high as for the other arterials, ranging from 10 cents to 50 cents per mile on weekdays and 10 cents to 20 cents per mile on weekends, varying by time of day. On weekdays, the highest priced period was the PM peak from 4 pm to 7 pm, followed by the AM peak from 6 am to 9 am. Prices were lower midday (9 am to 4 pm) and in the evening (7 to 10 pm). On weekends, the high toll period was 10 am to 7 pm. No tolls were charged between 10 pm and 6 am on any day. All respondents received the same toll schedule for the entire experiment—no variation was used across the sample or across seasons/months.

The pricing was operational beginning on July 1, 2005, and continued through February 2006, a period of eight months. During that time, respondents could obtain information in their vehicle indicating the amount being charged at any moment and also in total for that trip or that day. Respondents could also go online to the project website and find the amount of money remaining in their account as well as a historical overview of the toll roads they had used, when they were used, and what tolls had been charged. During the total project period, across the sample, the GPS units logged over 750,000 individual trips, including over 100,000 toll transactions. The central system also sent out over 4,000 customer billing invoices, mimicking the type of monthly invoice that would be sent in an actual system. After the tolling period ended, additional control data was collected for roughly one month.

Behavioral Analysis of Traveler Responses to Pricing

Some behavior analysis has already been performed by PSRC and EcoNorthwest and reported in the study report.

	2005									2006					
Pre-implementation	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J
	Control			Experimental Treatment - Tolls								Control	Analysis →		

Figure 6. Traffic choices project timeline.

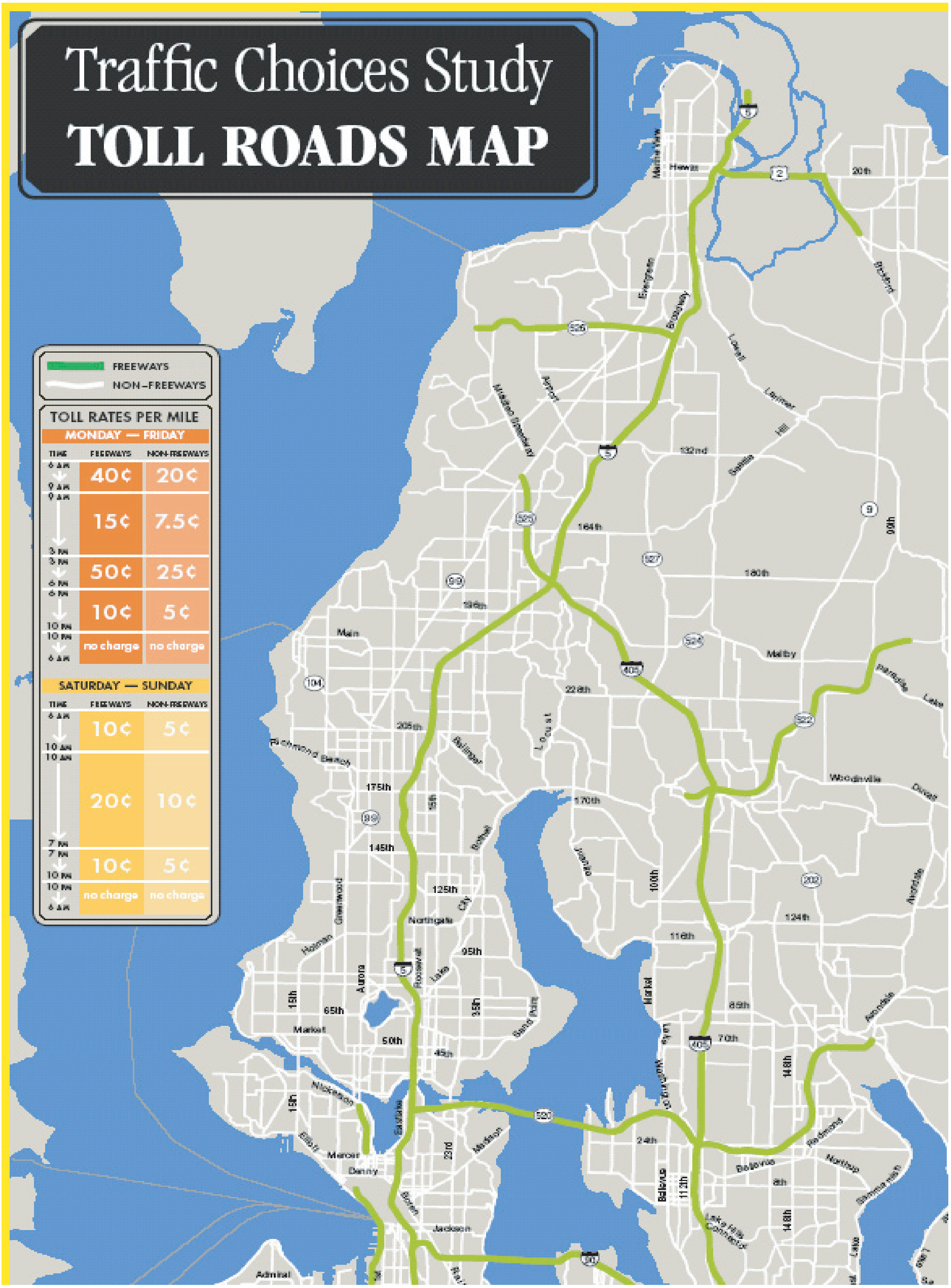

Figure 7. Traffic choices study: toll roads map.

This section provides a brief summary of the findings. The majority of the analyses has been done at a fairly aggregate level where the unit of analysis is not a particular trip or route, but the average travel per week during the tolling period versus during the control period. One reason for a more aggregate level of analysis at this stage, is a data issue particular to GPS data, which any analysis of the data must deal with. This issue is that all the data is passive and vehicle-based. As a result, for any particular trip, the basic GPS data is missing three items of information that are often used in analysis of household travel survey data: (1) the person in the household driving the vehicle, (2) the number of occupants in the vehicle, and (3) the type/purpose of activities completed at each stop location. The initial analyses have partially addressed this issue by identifying the location of regularly visited workplaces. With this information, all tours (or partial tours) could be categorized into four types: home-to-work, work-to-home, home-to-home (non-work tours), and work-to-work (work-based sub-tours). Also, analyses were performed at three levels of aggregation: each household, each vehicle, and each workplace.

Overall, compared to the control period, the introduction of the tolls was found to produce the following impacts on travel patterns across all participating households:

- 7% reduction in all vehicle tours (tours per week)
- 6% reduction in tour segments (segments of tours per week)
- 8% reduction in tour drive time (minutes of driving per week)
- 12% reduction in vehicle miles traveled (miles per week)
- 13% reduction in miles driven on tolled roads (tolled miles per week)

From these numbers, we can infer a number of behavioral findings:

- In the big picture, the tolling had a large enough effect on various dimensions of behavior that the data should be suitable for further analysis on the effects of pricing and congestion.
- Since tour segments (trips) were reduced slightly less than the number of tours, a slight increase in trip chaining was experienced—i.e., the number of trips per tour increased by about 1%.
- Because vehicle miles traveled decreased by 12% while the number of tours decreased by only 7%, the average tour distance was reduced by about 5%. This could be because longer distance tours were most likely to be suppressed, but it could also be due to travelers' switching to closer destinations. A comparison of tour distance distributions with and without tolling would provide further insight.
- The fact that vehicle miles traveled on toll roads decreased slightly more than vehicle miles travelled overall implies at least a small amount of shifting from tolled routes to non-tolled routes and/or to the non-tolled night period (although this comparison does not identify route shifting to routes and/or times of day that are still tolled but at a lower toll level).
- Since total travel distance decreased by 12%, but the total drive time decreased by only 8%, overall average driving speed was reduced by about 4%. This likely results from less travel on the tolled freeways, which have the highest speeds.

An additional analysis was carried out to look at departure time shifts for home-to-work journeys. From the travel patterns in the control period data, it was possible to determine the usual departure time from home to work for the majority of regular commuters. Then, an analysis was performed to relate the percentage of those commuters who shifted to a lower toll period as a function of the number of minutes the departure time had to be shifted away from the usual time. The reported results are shown in Figure 8 from the PSRC report, with a clear relationship showing over 30% of commuters shifting time when the required shift was 30 minutes or less, down to less than 10% shifting when the required shift was more than two hours.

Although it is difficult to interpret these results without knowing more detail about the analysis, some implications of these findings in the context of further research that could be supported with these data are:

- There appears to be enough systematic departure time shifting in the data to support disaggregate departure time modeling, at least for home-to-work journeys. It is likely that work-to-home journeys could be analyzed in a similar way, preferably in a joint context with the home-to-work journey.
- The data could be analyzed to find other regular non-work journeys that particular households make during both the control and tolling periods. Home-to-school/university tours and tours to escort children to school seem likely candidates, and school locations would be fairly easy to pinpoint in the data by matching to a GIS parcel database. School start and end times are typically fixed and home-to-school distances are typically short and thus not a good candidate for departure time shifting to avoid tolls. Perhaps there are other types of regular journeys, although inferring the destination purpose of the journeys would require GIS analysis.
- A multivariate analysis approach would provide more useful behavioral models, including the amount of time shift necessary, but also the direction of shift, the difference in toll levels and travel times between the periods, and other characteristics of the household: the driver (if known), the destination, and the tour.

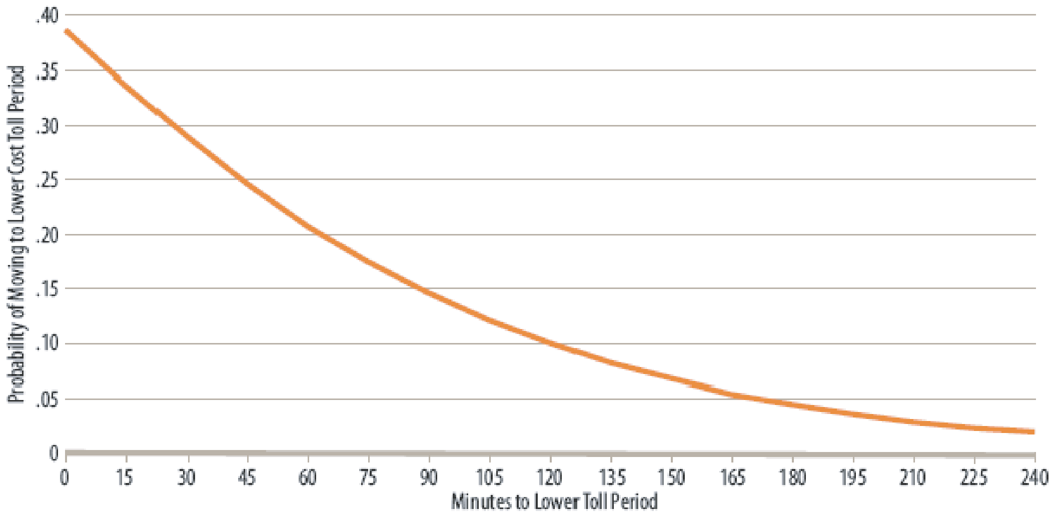

Figure 8. Home-to-work tour probability of moving to lower toll.

- People may shift their route of travel instead of (or in addition to) their departure time. An advantage of GPS data over typical household survey data is that the exact route of travel can be identified. With the data available, it seems that a joint route-departure time choice model would be a more complete and valid way of identifying the simultaneous effects of pricing, travel time, and congestion.

Route choices for home to work journeys were also analyzed by the PSRC project team. Identified in the data was the percentage of times that each commuter chose to use an alternative lower toll or non-tolled route, which was analyzed with respect to the toll difference and travel time difference between the routes, in order to infer VOT for each commuter. The results were then interpreted as a function of household income, with the resulting VOT function shown below in Figure 9 from the PSRC report. Except for the very low income households, the imputed VOT appears to be 70% to 80% of the wage rate across the full range of incomes. These are somewhat higher than VOT typically estimated from SP data on route choice under pricing, although in line with typical VOT from RP data.

It is difficult at this stage to provide an interpretation or critique of these results without knowing more detail about the analysis method. Some key points to be considered in the context of further analysis of the data set are:

- Shifting route is only one possible way that travelers can reduce or avoid paying tolls. Shifting departure time is the

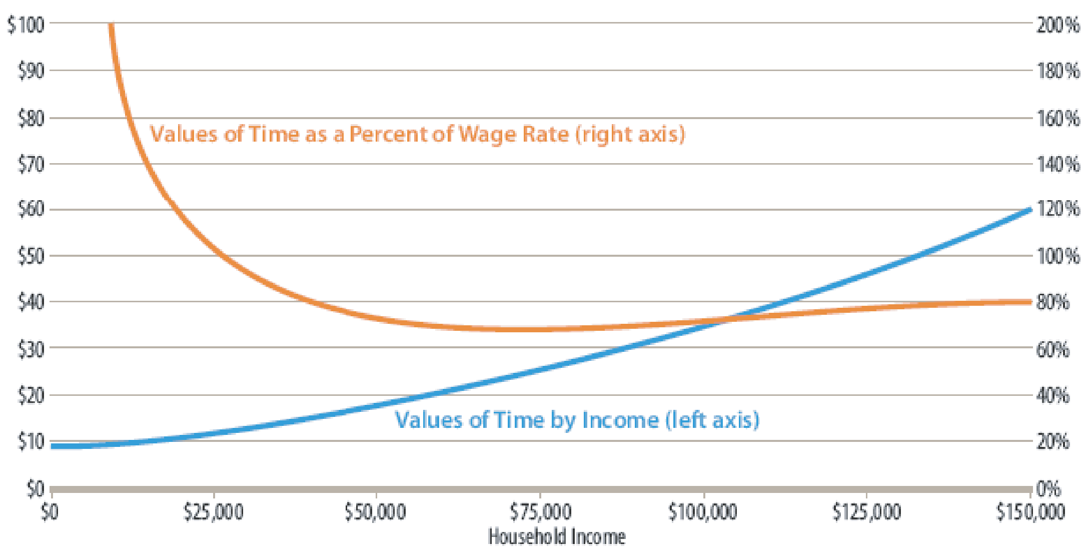

Figure 9. Observed home-to-work VOT (as function of route choice).

other most likely way, but other possibilities include shifting mode to transit or non-motorized (this would only be seen in the GPS data as a reduction of commute frequency), increasing car occupancy (this would not be seen in the GPS data at all), shifting destination (very unlikely for work tours, at least in the short term), and canceling commute trips, e.g. by telecommuting (in the GPS data, this would be indistinguishable from switching mode). Since these other shifts would most likely be made by people with the lowest VOT (highest marginal disutility of toll and/or lowest marginal disutility of travel time) and those cases are not in the route choice data, this may lead to a higher imputed VOT than is typically the case. However, if route choice is truly the "lowest level" choice in the decision hierarchy, then the high VOT may be suitable for the particular context of route choice.

- In the context of departure time choice, the best way to sort out these issues is with a joint model that includes the three main identifiable dimensions of commuting behavior in the data set—route choice, departure time choice, and frequency of commuting by car—and analyzes them in an integrated manner, including as many household, person, land use, and contextual variables as possible.

4.2.3 Prototype Structure of Demand Model—4-Step Approach

Taking into account the accumulated experience in application of 4-step models for pricing studies described in Chapter 2, necessary short-term improvements, and the most important travelers' responses to pricing mentioned in the current section above, we can outline a prototype structure for a 4-step model that includes all features essential for pricing studies; see Figure 10.

The main sub-models have to be segmented by 4–5 trip purposes (for example, home-based-work, home-based-university, home-based-school, home-based other, and non-home-based), 3–4 household income groups (for example, 0–$50K, $50–$100K, $100K+), and 3–4 household car-sufficiency groups (for example, zero cars, cars fewer than drivers, cars equal to or greater than drivers) since these categories are characterized by very different VOTs and willingness to use toll roads, as described in Section 4.3. In general, it is not necessary to preserve a full Cartesian combination of trip purposes and income groups; however, a stratification of home-based-work trips by income group is highly recommended.

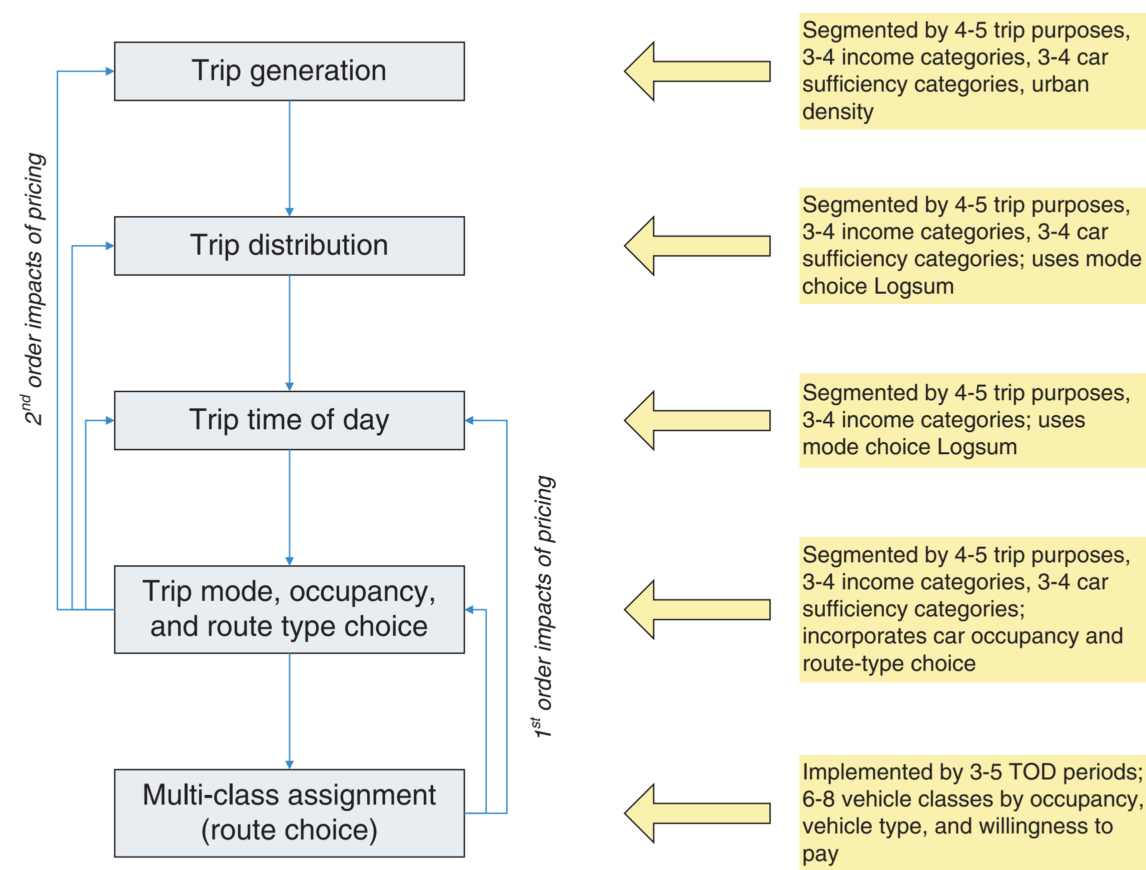

Figure 10. Prototype 4-step model for highway pricing studies.

It is highly recommended to include vehicle occupancy choice (SOV, HOV2, HOV3+) and route type-choice (toll versus free) as lower-level sub-choices in the mode choice structure as explained in Section 2.2. This is especially important for HOV/HOT lane studies. Concurrently, the traffic assignment should be implemented in a multi-class fashion with vehicle classes distinguished by occupancy (SOV, HOV2, HOV3+) and vehicle type (auto, light truck, heavy truck). Auto classes can be additionally segregated by willingness to pay or income as suggested in Section 4.3.2.

It is important to include a time-of-day choice model sensitive to congestion and pricing since it would be unrealistic to assume fixed time-of-day and peak-hour factors if such policies as congestion or dynamic pricing are to be applied. In accordance with the time-of-day choice model, the traffic assignment should be implemented for 3–5 time-of-day periods (AM peak, PM peak, off-peak that can be further subdivided into Midday, Night, and Early morning) that are characterized by different levels of congestion and may also be differentiated by toll rates.

It is essential to integrate all demand sub-models and assignment procedures in an equilibrium framework of the model system. The LOS skims (travel times and cost including tolls) should be fed back to mode and time-of-day choice models to ensure the 1st-order impacts of pricing. Mode choice Logsums (incorporating LOS variables) are then used as impedance measures in trip distribution and time-of-day choice to ensure the second order impacts of pricing. It has been shown that, if trip tables and LOS skims are properly averaged, a good level of convergence can be achieved after 3–4 global iterations (more detailed discussion of equilibration strategies is provided in Sections 6.1 and 6.2)

4.2.4 Prototype Structure of Demand Model—Activity-Based Approach

Taking into account the accumulated experience in application of ABMs for pricing studies, necessary short-term improvements, as well as referring to some advanced model features, an outline for a prototype structure for an ABM that includes all features essential for pricing studies is shown in Figure 11.

All general principles and short-term enhancements discussed in the previous sub-section with respect to 4-step models are basically valid for ABMs. However, a more advanced and flexible ABM structure offers multiple additional advan-

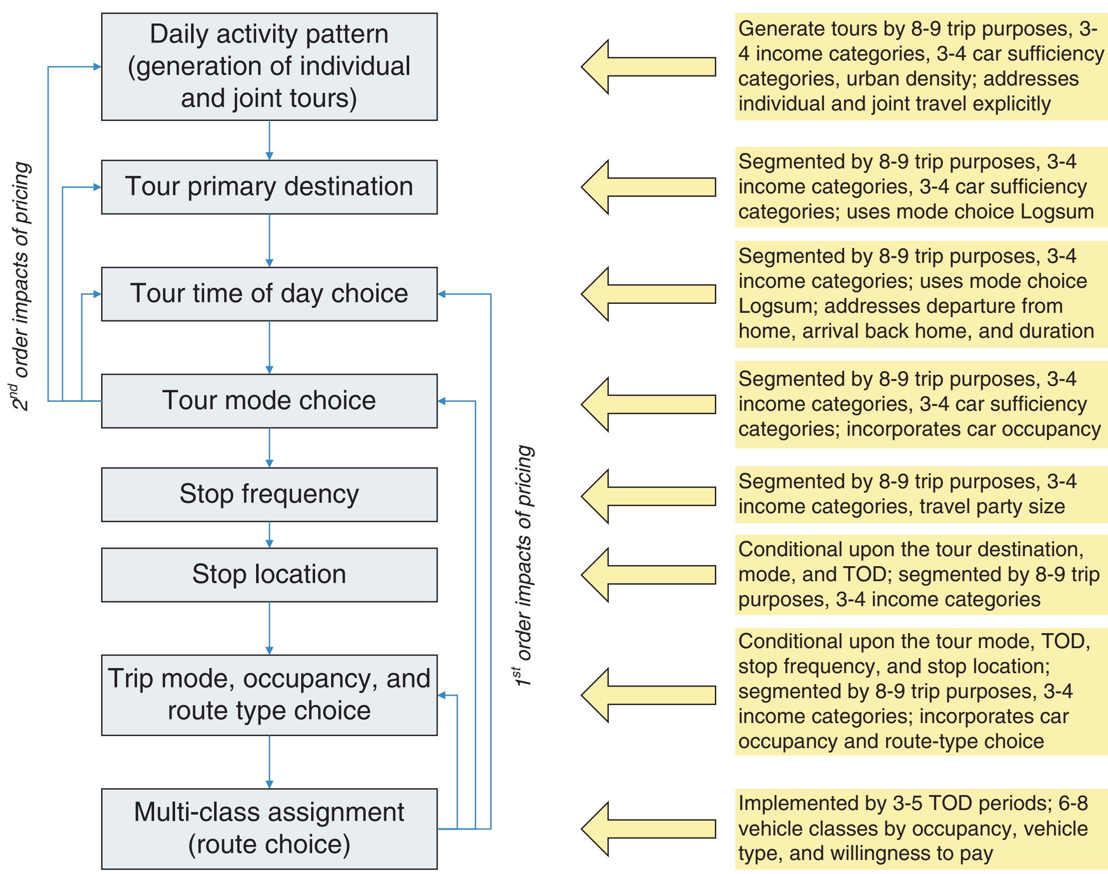

Figure 11. Prototype ABM for highway pricing studies.

tages for pricing studies. First of all, ABMs are inherently richer in terms of travel segmentation. For example, they normally incorporate 8–9 travel purposes (work, university, school, escorting, shopping, other maintenance, eating out, visiting relatives and friends, other discretionary). ABMs treat non-home-based trips as parts of the tours, thus there is no need to consider these trips as a separate purpose.

The ABM framework ensures a more consistent approach to time-of-day choice modeling with an enhanced level of temporal resolution (1 hour or even 30 min). The time-of-day choice models applied in advanced ABMs treat departure time from home (in outbound half-tour direction), arrival back home (in inbound half-tour direction), and tour/activity duration in a coherent way (see Section 5.2.6 for a discussion on time-of-day choice models). This is one of the most clear and essential advantages of ABMs for congestion pricing studies. It has been generally recognized that a tour-based structure provides a more realistic response to congestion and dynamic pricing where a shift of trip departure times is expected or explicitly targeted by the policy.

The ABM framework allows for a better modeling of car occupancy through an explicit treatment of joint travel as a special travel segment (see Section 5.2.7 for a discussion on modeling carpools). This is another significant advantage over 4-step models that is particularly beneficial for HOV/HOT lane studies.

The ABM framework is based on individual microsimulation that opens the way to account for situational variation in VOT for each travel segment. This principal model enhancement is discussed in detail in Section 6.1. In terms of integration of the demand model with network simulation, however, the current generation of ABMs still relies on conventional static assignments (improved by accounting for multiple vehicle classes). From this point of view, the equilibration principles described for 4-step models in the previous subsection are applicable for ABMs. ABMs offer an innovative strategic direction, however, for an integration with advanced network simulation tools, based on the fact that their microsimulation platform can provide a disaggregate input to a microsimulation process of DTA. This aspect is discussed in Section 5.4.

4.2.5 Prototype Structure of Network Assignments

Regional travel models developed and applied so far (including both ABMs and 4-step models) have been integrated with conventional aggregate static equilibrium assignments. Evaluation of pricing (notably managed lanes) in congested areas is closely focused on understanding the effects of congestion, queuing, facility access/spacing, and other operational characteristics. Such aspects are not considered in a static assignment model. Consequently, there is a need for some guidance on how to incorporate a project's unique operational characteristics/limitations into the travel demand forecasts and subsequent use for pricing analysis.

An important issue that is difficult to fully resolve in practice relates to the need for a consistency between the segmentation applied in traffic assignment (vehicle and occupancy classes) and segmentation applied in the mode choice model (modes, travel purposes, and other segments). While it is comparatively straightforward to use the same auto modes (occupancy classes) in both procedures, the additional segmentation by travel purpose, income group, and other possible dimensions pertinent to mode choice is difficult to preserve in the assignment procedure since it would result in an infeasibly large number of vehicle classes. Table 8 illustrates an ideal segmentation structure maintaining consistency across the mode choice and assignment model components, and including approximate VOT estimates for each segment. This structure is typically simplified in practice due to assignment/skimming run time constraints. The demand modeling part may also assume additional segmentation by various non-mandatory purposes, such as shopping, eating out, or other discretionary activities, while the network simulation part rarely includes more than three or four vehicle classes.

The scaling parameters to account for vehicle occupancy O_2 and O_3 should be statistically estimated as part of mode choice model estimation, or by means of a special SP survey. In some model systems, these parameters are not actually estimated, but set equal to the actual occupancy. This means that the carpool willingness to pay is assumed equal to the total willingness to pay of all members of the travel party. More recent statistical evidence suggests that VOT is not directly proportional to the vehicle occupancy, and the actual coefficient values stand lower than 2 and 3.

The logic behind this segmentation structure is to treat VOT consistently across all choices, while avoiding an excessive proliferation of travel segments and vehicle classes. Additional segmentation of the behavioral choice models in the ABM framework is less onerous than in 4-step models, but issues associated with the multiplication of vehicle classes in the assignment procedure are shared by both ABMs and 4-step models.

The choice of the number of vehicle occupancy categories in the assignment procedure should be based on the expected nature of HOV and pricing policies. If significant projects with specific HOV3+ lanes or pricing policies are expected, explicit segmentation of trip tables by SOV, HOV2, and HOV3+ classes may be required. Otherwise, all HOV categories can be collapsed. However, even in the absence of specific traffic restrictions or pricing policies, a better segmentation by vehicle occupancy can be beneficial in capturing differential VOT.

Table 8. Coordinated segmentation of mode choice and assignment.

TOD/Mode choice segments		Assignment vehicle classes	
Purpose	**Occupancy**	**Occupancy**	**Approximate VOT**
Commuting – low-income workers	SOV	SOV	\$10
	HOV2	HOV2	$\$10 \times O_2$
	HOV3+	HOV3+	$\$10 \times O_3$
Commuting – medium-income workers	SOV	SOV	\$15
	HOV2	HOV2	$\$15 \times O_2$
	HOV3+	HOV3+	$\$15 \times O_3$
Commuting – high-income workers	SOV	SOV	\$20
	HOV2	HOV2	$\$20 \times O_2$
	HOV3+	HOV3+	$\$20 \times O_3$
Work-based sub-tours	SOV	SOV	\$30
	HOV2	HOV2	$\$30 \times O_2$
	HOV3+	HOV3+	$\$30 \times O_3$
University / school tours	SOV	SOV	\$6
	HOV2	HOV2	$\$6 \times O_2$
	HOV3+	HOV3+	$\$6 \times O_3$
Non-mandatory tours – low income	SOV	SOV	\$8
	HOV2	HOV2	$\$8 \times O_2$
	HOV3+	HOV3+	$\$8 \times O_3$
Non-mandatory tours – medium income	SOV	SOV	\$10
	HOV2	HOV2	$\$10 \times O_2$
	HOV3+	HOV3+	$\$10 \times O_3$
Non-mandatory tours – high income	SOV	SOV	\$12
	HOV2	HOV2	$\$12 \times O_2$
	HOV3+	HOV3+	$\$12 \times O_3$

In order to reduce the impact on assignment runtimes of the proliferation of segments, it may be possible to combine those segments or trip tables with similar VOT for assignment. This aggregation should also consider additional vehicle classes associated with non-passenger travel, such as heavy and light commercial trucks. A final decision about the aggregation of demand (trip tables) can only be made after statistical estimation of all VOT and occupancy-related coefficients. Table 9 illustrates a possible aggregation of vehicle classes based on the assumed values of time shown in Table 8 and scaling coefficients equal to occupancy. For simplicity, a value of 3.0 for occupancy of the HOV3+ category is used, while in reality it is likely closer to 3.2 or 3.3. In the assignment and skimming procedures, each vehicle class table is assigned based on the weighted average VOT across all components. It is possible to make this weighting specific to each assignment time-of-day period to ensure a better reflection on the differential mix of purposes across time-of-day periods.

In addition to the fundamental issue of highway user segmentation by VOT, another important technical issue has manifested itself in almost all practical model applications. This issue relates to how *t* demand models and network assignments are applied with respect to conditions of equilibrium, assuming multiple iterations between them. The problem manifests itself equally with sophisticated choice models (including many levels of hierarchy) or with simple binary pre-route choice models (most frequently applied in practice and sometimes taking the form of a toll-diversion model). The essence of the problem is that the trip table of toll users generated by the choice model (based on the travel time savings and toll skims from the previous iterations) cannot be fully assigned on toll paths in the next iteration.

The associated leakage of toll users can be significant (frequently 15–20% or even more with sparse trip tables). It hampers the equilibrium process, as well as makes the results difficult to understand and interpret. There are several objective

Table 9. Example of vehicle class aggregation.

Purpose	Occupancy	Approximate VOT	Trip tables by occupancy and VOT					
			SOV $6-12	SOV $15-30	HOV2 $12-24	HOV2 $30-60	HOV3+ $18-36	HOV3+ $45-90
Commuting – low income workers	SOV	$10	X					
	HOV2	$10×2=$20			X			
	HOV3+	$10×3=$30					X	
Commuting – medium income workers	SOV	$15		X				
	HOV2	$15×2=$30				X		
	HOV3+	$15×3=$45						X
Commuting – high income workers	SOV	$20		X				
	HOV2	$20×2=$40				X		
	HOV3+	$20×3=$60						X
Work-based sub-tours	SOV	$30		X				
	HOV2	$30×2=$60				X		
	HOV3+	$30×3=$90						X
University / school tours	SOV	$6	X					
	HOV2	$6×2=$12			X			
	HOV3+	$6×3=$18					X	
Non-mandatory tours – low income	SOV	$8	X					
	HOV2	$8×2=$16			X			
	HOV3+	$8×3=$24					X	
Non-mandatory tours – medium income	SOV	$10	X					
	HOV2	$10×2=$20			X			
	HOV3+	$10×3=$30					X	
Non-mandatory tours – high income	SOV	$12	X					
	HOV2	$12×2=$24			X			
	HOV3+	$12×3=$36					X	

reasons for this discrepancy that should be understood before any solution is considered:

- Non-toll users are assigned onto the highway network with the tolled facilities blocked-out, guaranteeing choice of non-toll routes only. Toll users from the choice models, on the other hand, are assigned onto the highway network with both tolled and non-tolled facilities available to them. For these toll user flow, a full guarantee of choosing toll routes only can only be achieved by restrictive assignment techniques that are too complicated, unrealistically time-consuming, and not supported in any of the available software packages.
- The time and toll skims used in the choice model to generate trip tables of toll and non-toll users at the previous iteration can never be fully identical to the travel times, tolls, and generalized cost produced in the subsequent equilibrium assignment procedure. Full convergence exists only in theory. In practice, with any reasonable number of iterations, there are always going to be certain discrepancies.
- While the equilibrium assignment algorithm essentially produces multi-path assignment results (at each assignment iteration), a single shortest path is found and loaded for each OD pair. This means that for some OD pairs where toll and non-toll routes are comparable in terms of generalized cost, there can be a split between toll and non-toll users in the toll user assignment.

Several (empirical) procedures in applied models have attempted to overcome or at least mitigate the leakage of toll users in assignment:

- Toll route promotion. In this method, tolls are either reduced or fully eliminated in the toll user assignment procedure, since the users have already made a decision to use the toll facility and "paid the toll in the choice model." While this can mechanically reduce the leakage, it is only applicable for single-facility projects (such as a single toll bridge in the area) where essentially a single toll route is feasible. In cases where several toll facilities are involved (either on competing or complementary basis), this technique can produce significant route distortions (biases toward higher tolls).
- Disabling equilibrium time fluctuations. In some practical applications, modelers decided to disable equilibrium time fluctuations after a certain number of iterations (where link travel times area already close to the equilibrium travel times). It means that the final assignment of toll users is implemented with the travel times frozen

from the previous iteration (rather than in an equilibrium fashion). While this technique is helpful to assign almost all toll users onto toll path, it is dangerous in that the final assignment essentially corresponds to an all-or-nothing shortest path choice (despite having used equilibrium travel times) and can produce unrealistic link volumes throughout the network. It is clearly inappropriate for congested metropolitan networks with multiple toll facilities.

- Explicit modeling of toll route components and non-toll access sub-routes. This might be considered as the most theoretically consistent approach that draws upon the applied techniques for combined multimodal transit trips. It is, however, quite complicated and requires additional network coding, and is applicable only for highway networks with a small number of toll facilities. With this approach, each point of entry to and exit from the toll facility is coded as a traffic zone. Then each toll user path is convoluted (using OD matrix manipulations) of the free access sub-route, toll sub-route (from the entry to exit), and free aggress sub-route. This technique becomes especially problematic in the presence of multiple toll facilities that might be intertwined with free facilities on the same route.
- Using more elaborate skims to identify toll users. Most of the applied models are based on a simplified method of identification of toll users by a presence of a non-zero toll in the skim. The toll skim that is used for identification of toll users can be further elaborated by the addition of the facility index and toll route proportion (that is a fractional number between 0 and 1, rather than just a binary indicator). These "flags" in the OD skims can be used to prepare more effective promotion strategies, as well as to create more (facility-specific) trip tables for multi-class assignment.

It is generally recognized that a combination of elaborate skimming and promotion would probably be the best general strategy, while the disabling of equilibrium and the explicit modeling of toll route components could be methods used for specific subset of projects only.

An additional complexity is associated with modeling real-time variable tolls. In this case, several intermediate iterations of toll calculations have to be implemented between the assignment procedure and choice model. Modeling variable tolls depends on the adopted form of toll calculation. This technique has been currently tried in only a few applications and is still evolving. Several basic operational approaches have already been identified as possible methods for further evaluation:

- Predetermined toll scales as function of LOS on the toll facility/lanes. In this case tolls are specified in advance as a function of V/C or speed, and depend solely on the traffic conditions on the toll facility/lanes. The application of tolls does not guarantee that the traffic conditions will meet the requirement. Model testing with different tolls is required.
- Predetermined toll scales as function of LOS on the managed toll lanes compared to free general-purpose lanes. In this case tolls are specified in advance as a function of speed differences and are intended to maintain a better LOS on toll lanes. The application of tolls does not guarantee that the traffic conditions will meet the requirement, however, and model testing with different tolls is required.
- Variable tolls as function of LOS on the toll facility/lanes. In this case tolls are incrementally adjusted as a function of the achieved V/C or speed and depend solely on the traffic conditions on the toll facility/lanes. It can be thought of as a shadow pricing technique, reflecting the scarcity of road capacity. The application of tolls guarantees that the traffic conditions will meet the requirement, assuming there are alternative free routes/general purpose lanes.
- Variable tolls as function of LOS on the managed toll lanes compared to free general-purpose lanes. In this case tolls are incrementally adjusted as a function of the achieved speed differences between the toll and free lanes. The application of tolls guarantees that the traffic conditions will meet the requirement.

4.3 Summary of Key Model Parameters

4.3.1 VOT Values in Applied Models

Tables 10–12 summarize VOT, the key model parameter that has been adopted in different applied models for selected pricing studies. This summary is intended to serve as a useful set of reference points for modelers who may need to borrow these coefficients for local pricing studies. Table 10 contains a summary of VOT estimates for travel demand models, Table 11 summarizes VOTs used for trucks and commercial vehicles, and Table 12 summarizes VOTs used in network assignment procedures.

There is a great deal of variation in estimated and applied VOT across different studies, and it is difficult to find a clear common denominator. Part of the problem is due to the different choice contexts and segmentation rules adopted in the different studies and models. Another important source of variation relates to the data used and method of estimation. It is well known that RP and SP data tend to have built-in differences, while calibration based on the aggregate data yields only very crude proxies for individual VOTs. Additionally, there may be objective regional differences in transportation conditions, including the level of congestion, prevailing highway facility types, impacts of climate/weather, as well as the population mix by income and occupation that manifests itself in travel behavior (at least for passenger travel). Finally,

Table 10. Summary of VOT estimates for passenger travel demand.

Source	Location	Existing toll facilities	Survey type, estimation method	Choice context	Year of data for estimation	Segment	VOT, $/hour
San Francisco County Transportation Authority (SFCTA), Regional Pricing Model	9-County San Francisco Region, CA	Yes	RP/SP	Mode & occupancy, route type (toll vs. non-toll)	2000 (RP) 2007 (SP)	Work tours, low household income ($0-$30K)	3.6
						Work tours, medium household income ($30-$60K)	10.9
						Work tours, high household income ($60K+)	17.9
						Other tours, low income	2.4
						Other tours, medium income	7.2
						Other tours, high income	12.0
New York Metropolitan Transportation Council (NYMTC), Applied Travel Demand Model	28-County New York Region, NY	Yes	RP	Mode & occupancy	1997	Work tours	15.8
						School tours	6,5
						University tours	11.7
						Maintenance tours	12.4
						Discretionary tours	10.7
						At-work sub-tours	40.0
Ministry of Transportation of Quebec (MTQ), Travel Demand Model for T&R Studies	Montreal Region, QC	No	RP/SP	Mode, occupancy, route type (toll vs. non-toll)	2000 (RP) 2003 (SP)	Work tours, low income (0-$40K), peak	10.2 (CAD)
						Work tours, low income, off-peak	7.3 (CAD)
						Work tours, male, high income ($40K+)	10.2 (CAD)
						Work tours, female, high income	10.6 (CAD)
						Maintenance tours, male	4.0 (CAD)
						Maintenance tours, female, low income	6.4 (CAD)
						Maintenance tours, female, high income	7.3 (CAD)
						Discretionary tours, male	3.0 (CAD)
						Discretionary tours, female, low income	6.0 (CAD)
						Discretionary tours, female, high income	7.6 (CAD)
Orange County Transportation Authority (OCTA), Applied Travel Demand Model	Orange County, CA	Yes	Synthetic calibration	Mode	1989	Home-based-work trips, low income	3.1
						Home-based-work trips, medium income	8.4
						Home-based-work trips, high income	19.4
						Home-based-other trips, low income	1.5
						Home-based-other trips, medium income	4.1
						Home-based-other trips, high income	9.7
						Non-home-based trips	6.7

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Table 10. (Continued).

Source	Location	Existing toll facilities	Survey type, estimation method	Choice context	Year of data for estimation	Segment	VOT, $/hour
Mountain View Corridor, Applied Travel Demand Model	Salt Lake, UT	No	RP	Mode	1992	Home-based-work trips, low income	1.3
						Home-based-work trips, high income	11.5
						Home-based-school trips, low income	2.2
						Home-based-school trips, high income	4.2
						Home-based-other trips, low income	0.8
						Home-based-other trips, high income	5.6
						Non-home-based trips, low income	2.8
						Non-home-based trips, high income	5.7
North-Central Texas Council of Governments (NCTCOG), Travel Demand Model Applied for T&R Studies	Dallas-Fort Worth, TX	Yes	RP	Mode	1999	Home-based-work trips	5.9
						Home-based-other trips	4.1
						Non-home-based trips	3.3
San Diego Association of Governments (SANDAG), Applied Travel Demand Model	San Diego, CA	No	Synthetic calibration	Mode	1995	Home-based-work trips, low income	1.8
						Home-based-work trips, medium income	5.5
						Home-based-work trips, high income	11.2
						Home-based-other trips, low income	0.9
						Home-based-other trips, medium income	2.7
						Home-based-other trips, high income	5.6
						Non-home-based trips	2.7
Applied Mode Choice model for Twin Cities	Minneapolis –St. Paul, MN	No	RP	Mode	2000	Home-based-work trips	12.2
						Non-home-based-work trips	3.7
						Home-based-other trips	1.9
						Non-home-based-other trips	2.0
Denver Regional Council of Governments (DRCOG), Applied Travel Demand Model	Denver, CO	Yes	Synthetic calibration	Mode	1996	Home-based-work trips, low income	4.0
						Home-based-work trips, medium income	8.0
						Home-based-work trips, high income	16.0
						Home-based-other trips	8.8
						Non-home-based trips	8.4
Atlanta Regional Commission (ARC), Travel Demand Model Applied for Mobility 2030 Study	Atlanta, GA	Yes	RP	Mode	2000	Home-based-work trips	14.9
						Home-based-other trips	13.5
						Non-home-based trips	3.4

Table 10. (Continued).

Source	Location	Existing toll facilities	Survey type, estimation method	Choice context	Year of data for estimation	Segment	VOT, $/hour
Dehghani et al, 2003	Florida Turnpike, Orlando, FL	Yes	RP/SP	Mode	2000	Home-based-work trips, low income, peak	4.5
						Home-based-work trips, high income, peak	9.5
						Home-based-work trips, low income, off-peak	4.0
						Home-based-work trips, high income, off-peak	13.5
						Home-based-other trips, low income, peak	4.0
						Home-based-other trips, high income, peak	7.5
						Home-based-other trips, low income, off-peak	3.0
						Home-based-other trips, high income, off-peak	8.0
Puget Sound Regional Council (PSRC), VOT for Travel Forecasting and Benefits Analysis	Seattle, WA	No	RP, Traffic Choices Study	Mode	2000 (RP) 2006 (Traffic Choices)	Home-based-work trips, low income	6.0
						Home-based-work trips, medium-low income	10.9
						Home-based-work trips, medium-high income	16.4
						Home-based-work trips, high income	20.9
						Home-based-other trips	9.7
						Non-home-based trips	15.6
Validation of the Pennsylvania Statewide Travel Model (2007), TRB CD (paper 07-2401)	Different locations in PA	No	Synthetic calibration	Route & Mode	2002	Auto trips	18.5
The VOT: Estimates of the Hourly VOT for Vehicles in Oregon (2006), Oregon DOT Policy & Economic Analysis Unit	Different locations in OR	No	Synthetic calibration	Route & Mode	2005	Auto trips	16.3
Zmud, J, Bradley M, Douma F, Simek C. (2007) Panel Survey Evaluation of Attitudes and Willingness to Pay for Toll Facilities	I-394/I-35W corridor, MN	Yes	SP	Route & Mode	2005-2006 (3 waives)	Baseline VOT for which different additions are applied:	9.6
						Household income $100K-$125K	+2.1
						Household income $125K+	+6.2
						Age under 35	+2.4
						Age 35-45	+1.4
						Age 65+	-2.9
						AM commute trips	+3.5
						PM commute trips	+0.9
						Other PM trips	-2.1
						Work-related trips	+3.8
						Shopping, personal business trips	+1.5
						Trip length under 10 miles	-1.9
						Trip length over 20 miles	+2.3

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Table 10. (Continued).

Source	Location	Existing toll facilities	Survey type, estimation method	Choice context	Year of data for estimation	Segment	VOT, $/hour
Lam, T, & K. Small (2001) The Value of Time and Reliability: Measurement from a Value Pricing Experiment	SR-91, Orange County, CA	Yes	RP/SP	Route	1998	All SR-91 users (auto)	19.2
				Route & TOD			4.7
				Route & Mode			24.5
				Route & transponder			18.4
				Route mode & transponder			22.9
Liu, H, and W. Recker (2006) Estimation of the Time-Dependency of VOT and its Reliability from Loop Detector Data	SR-91, Orange County, CA	Yes	RP	Route	2001	Auto trips, departure time 5-6 am	19.5
						Auto trips, departure time 6-7 am	24.4
						Auto trips, departure time 7-8 am	28.5
						Auto trips, departure time 8-9 am	28.7
						Auto trips, departure time 9-9:30 am	22.1
Brownstone et al. (2003) The San Diego I-15 Congestion Pricing Project	I-15, San Diego, CA	Yes	RP	Route	1998	Auto trips	30.0
Sullivan, E. (2000) Continuation Study to Evaluate the Impacts of the SR-91 Value-Priced Express Lanes	SR-91, Orange County, CA	Yes	RP/SP	Route	1999	Auto trips	16.3
Light, T. (2007) A Time-Use Approach for Estimating Commuter's VOT,	American Time Use Survey	No	RP	Mode	2003	Full-time urban worker	5.4
Urban Transportation Economics, Second Edition, (2003) Chapters 2 & 3	Different metropolitan areas	No	RP, synthetic	Destination	2003	Auto trips	9.1
Bertini, R. (2006) You are the Traffic Jam: An Examination of Congestion Measures	Different metropolitan areas	Yes	Synthetic	Route & mode	2002	Auto trips	13.5
Kriger, D. (2007) The Cost of Urban Congestion in Canada: A Model-Based Approach	Vancouver Edmonton Calgary Winnipeg Hamilton Toronto Ottawa-Gatineau Montreal Quebec City	No	Synthetic	Mode & route	1992-2003	Work trips by auto	24.7-31.4 (CAD)
						Non-work trips by auto	7.6-9.7 CAD
Ozbay, K. (2006) Theoretical Derivation of VOT and Demand Elasticity: Evidence from NJ Turnpike Toll Road	NJ Turnpike, NJ	Yes	RP	Route, Mode, TOD, Destination, & Frequency	2000	Auto trips	15.0-20.0

Table 11. Summary of VOT estimates for trucks and commercial vehicles.

Source	Location	Existing toll facilities	Survey type, estimation method	Choice context	Year of data for estimation	Segment	VOT, $/hour
San Francisco County Transportation Authority (SFCTA), Regional Pricing Model	San Francisco, CA	Yes	RP/SP, synthetic calibration	Route type (toll vs. non-toll)	2008	All trucks	30.0
New York Metropolitan Transportation Council (NYMTC), Applied Travel Demand Model	28-County New York Region, NY	Yes	RP, synthetic calibration	Route type (toll vs. non-toll)	1997	Commercial vehicles	60.0
						Trucks	120.0
Ministry of Transportation of Quebec (MTQ), Travel Demand Model for T&R Studies	Montreal Region, QC	No	SP, synthetic calibration	Route type (toll vs. non-toll)	2000-2003	Commercial vehicle	12.0 (CAD)
						Light truck	24.0 (CAD)
						Heavy truck	36.0 (CAD)
Puget Sound Regional Council (PSRC), VOT for Travel Forecasting and Benefits Analysis	Seattle, WA	No	Synthetic	Route type (toll vs. non-toll)	2000, 2006	Light trucks	40.0
						Medium trucks	45.0
						Heavy trucks	50.0
The VOT: Estimates of the Hourly VOT for Vehicles in Oregon (2006), Oregon DOT Policy & Economic Analysis Unit	Different locations in OR	No	Synthetic	Route type (toll vs. non-toll)	2005	Light trucks	20.4
						Heavy trucks	29.5
Meyer, M. and L. Saben (2006) Feasibility of a Truck-Only-Toll (TOT) Lane Network in Atlanta, GA	Atlanta, GA	No	Synthetic	Route type (toll vs. non-toll)	2000	Light trucks	18.0
						Heavy trucks	35.0
North-Central Texas Council of Governments (NCTCOG), Travel Demand Model Applied for T&R Studies	Dallas-Fort Worth, TX	Yes	Network calibration, synthetic	Route type (toll vs. non-toll)	1999	All trucks	12.0
Atlanta Regional Commission (ARC), Travel Demand Model Applied for Mobility 2030 Study	Atlanta, GA	Yes	Synthetic calibration	Route type (toll vs. non-toll)	2000	All trucks	25.0
Kawamura, K. (2000) Perceived VOT for Truck Operators	Different locations in CA	Yes	SP	Route type (toll vs. non-toll)	1998-1999	All trucks	23.4
						Private business	17.6
						For hire business	28.0
						Truck load business	25.0
						Less than truck load business	22.6
						Hourly pay group	25.4
						Other pay scale	15.1

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Table 11. (Continued).

Source	Location	Existing toll facilities	Survey type, estimation method	Choice context	Year of data for estimation	Segment	VOT, $/hour
Kawamura, K (2007) Evaluation of the Application of Delivery Consolidation in the U.S. Urban Area Using Logistics Cost Analysis	Different cities	No	Synthetic	Route type (toll vs. non-toll)	2002	All trucks	28.1
Wilbur Smith Associates (2003) The National I-10 Freight Corridor Study	I-10 Corridor	No	RP, synthetic	Route type (toll vs. non-toll)	2003	All trucks	25.0
An Economic Analysis of Segregating Cars and Trucks, (2007) TRB CD (Paper 07-1331)	Different locations	No	Synthetic	Route type (toll vs. non-toll)	2007	Light trucks	12.0
						Heavy trucks	50.0
Survey of Motor Carrier Opinions on Potential Optional Truck Only Toll (TOT) Lanes on Atlanta Interstate Highways. (2007) TRB CD (Paper 07-1664)	Atlanta, GA	Yes	SP	Route type (toll vs. non-toll)	2005	40% with low willingness to pay for TOT (5 cents per mile)	3.0
						24% with medium willingness to pay for TOT (10 cent per mile)	6.0
						7% with high willingness to pay for TOT (30 cents per mile)	18.0
Bertini, R (2006) You are the Traffic Jam: An Examination of Congestion Measures	Different metropolitan areas	Yes	Synthetic	Route type (toll vs. non-toll)	2002	All trucks	71.0

Table 12. Summary of VOT estimates applied in network assignments.

Source	Location	Existing toll facilities	Survey type, estimation method	Choice context	Year of data for estimation	Segment (vehicle class)	VOT, $/hour
San Francisco County Transportation Authority (SFCTA), Regional Pricing Model	San Francisco, CA	Yes	Synthetic calibration	Route	2008	SOV, external traffic	15.0
						HOV2	30.0
						HOV3+	45.0
						Trucks	30.0
New York Metropolitan Transportation Council (NYMTC), Applied Travel Demand Model	28-County New York Region, NY	Yes	RP, synthetic calibration	Route	1997	SOV, external traffic	15.0
						HOV2	30.0
						HOV3+	45.0
						Taxis	30.0
						Commercial vehicles	60.0
						Trucks	120.0
Ministry of Transportation of Quebec (MTQ), Travel Demand Model for T&R Studies	Montreal Region, QC	No	RP/SP, synthetic calibration	Mode & occupancy	2000, 2003 (SP)	Auto	8.0 (CAD)
						Commercial vehicle	12.0 (CAD)
						Light truck	24.0 (CAD)
						Heavy truck	36.0 (CAD)

Table 12. (Continued).

Source	Location	Existing toll facilities	Survey type, estimation method	Choice context	Year of data for estimation	Segment (vehicle class)	VOT, $/hour
Puget Sound Regional Council (PSRC), VOT for Travel Forecasting and Benefits Analysis	Seattle, WA	No	RP, Traffic Choices Study	Route	2000 (RP), 2006 (Traffic Choices)	SOV, home-based work trips, low income	9.6
						SOV, home-based work trips, medium-low income	17.6
						SOV, home-based work trips, medium-high income	25.7
						SOV, home-based work trips, high income	33.3
						SOV, non-home-based Work trips	10.0
						HOV2, AM peak	27.9
						HOV3+, AM peak	35.8
						Vanpool, AM peak	99.4
						HOV2, Midday	14.5
						HOV3+, Midday	16.4
						Vanpool, Midday	32.4
						HOV2, PM peak	18.9
						HOV3+, PM peak	22.9
						Vanpool, PM peak	54.7
						HOV2, evening	16.0
						HOV3+, evening	16.4
						Vanpool, evening	32.4
						HOV2, night	23.4
						HOV3+, night	31.5
						Vanpool, night	84.5
						Light trucks	40.0
						Medium trucks	45.0
						Heavy trucks	50.0
Mountain View Corridor, Applied Travel Demand Model	Salt Lake, UT	No	Network calibration, synthetic	Route	1992	All vehicles	20.0
North-Central Texas Council of Governments (NCTCOG), Travel Demand Model Applied for T&R Studies	Dallas-Fort Worth, TX	Yes	Synthetic calibration	Route	1999	Autos	10.0
						Trucks	12.0
San Diego Association of Governments (SANDAG), Applied Travel Demand Model	San Diego, CA	No	Synthetic calibration	Route	1995	All vehicles	21.0
Denver Regional Council of Governments (DRCOG), Applied Travel Demand Model	Denver, CO	Yes	Synthetic calibration	Route	1996	All vehicles, peak	8.0
						All vehicles, off-peak	6.0
Atlanta Regional Commission (ARC), Travel Demand Model Applied for Mobility 2030 Study	Atlanta, GA	Yes	Synthetic calibration	Route	2000	SOV	15.0
						HOV	20.0
						Trucks	25.0

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Table 12. (Continued).

Source	Location	Existing toll facilities	Survey type, estimation method	Choice context	Year of data for estimation	Segment (vehicle class)	VOT, $/hour
Dehghani et al, 2003	Florida Turnpike, Orlando, FL	Yes	RP/SP	Route	2000	All vehicles, peak	12.0
						All vehicles, Midday	6.0
						All vehicles, Night	4.7
Evaluating the effectiveness of toll strategies on route diversion and travel times for specific OD-pairs in a regional transportation network, 2007, TRB CD (Paper 07-0806)	Orlando, FL	Yes	Synthetic calibration	Route	2007	All vehicles	15.0
A Cordon Charge for the District Of Columbia: A Solution for DC's Fiscal Problems and Region's Congestion? (2007) TRB CD (Paper 07-0806)	Washington, DC	No	Synthetic calibration	Route	2004	All vehicles	13.8

different studies relate to different years and can only be compared after a scaling of the VOTs to account for inflation and income growth as explained in Section 4.5.

It is yet to be fully demonstrated to what extent VOT estimates can be transferred in space (i.e., between regions) and in time (i.e., applied to different years). Some general patterns and orders of magnitudes, however, are quite clear, and serve as the basis for the set of recommended default VOTs provided in the following section.

4.3.2 Recommended Values for VOT, Travel Time, and Cost Coefficients

Based on the review and analysis of the estimated and applied VOTs, we have developed default values that can be recommended for travel demand models and traffic assignment procedures. It should be understood that these values represent something like a common denominator across very different regions and model structures. It will always be preferable to estimate VOT (and underlying time and cost coefficients in the utility functions) based on local RP and SP surveys. The suggested values might be helpful as reasonable defaults when a local survey or other supporting data are not available.

The recommended default VOTs for travel demand models (specifically mode and occupancy choice) are presented in Table 13. The values are scaled to correspond to the year 2008. The underlying time and cost coefficients are also presented for each VOT value. Following the prevailing modeling practice, we assume that travel time is measured in minutes, and travel cost (including toll) is measured and coded in cents. The values of travel time and cost coefficients intended for use in the (mode) utility functions are scaled accordingly. The VOT, however, is presented in $/hour units, again, to follow the conventional practice.

For HOV vehicles, using scale parameters for VOT of 1.75 for HOV2 and 2.5 for HOV3+ is suggested. These multipliers are somewhat lower than the number of travelers in the party. It is believed that it is more realistic than scaling VOT directly proportional to the number of travelers, as was assumed in many applied models. In particular, for intra-household carpools (many of them with children) it is unrealistic to assume that the willingness of the all passengers to pay will be equal to driver's willingness to pay.

The recommended default VOTs for multi-class traffic assignments are presented in Table 14. Again, following conventional practice, VOT values are presented in $/hour units. However, the coefficient for cost (including toll) is scaled in min/cent units in order to be used as a multiplier for cost in the link generalized cost function. Thus, we assume that link travel time function is coded in minutes and link cost is coded in cents, as in most transportation models.

A word of caution is needed before the default VOTs are adopted for network assignments. Whenever possible, a consistency between travel demand model and network assignment procedures should be held. This means that if some travel segments applied in the demand model (like travel purposes or income categories) are to be aggregated for the

Table 13. Recommended default VOT for travel demand models.

Travel purpose	Household income group	TOD period	SOV			HOV2 (scale 1.75)			HOV3+ (scale 2.5)		
			VOT, $/h	Time coeff, 1/min	Cost coeff, 1/cent	VOT, $/h	Time coeff, 1/min	Cost coeff, 1/cent	VOT, $/h	Time coeff, 1/min	Cost coeff, 1/cent
Work commute	Low (0-$50K)	AM peak	8.0	-0.025	-0.00 188	14.0	-0.025	-0.00107	20.0	-0.025	-0.00075
		PM peak	7.0	-0.025	-0.00214	12.3	-0.025	-0.00122	17.5	-0.025	-0.00086
		Off-peak	6.0	-0.025	-0.00250	10.5	-0.025	-0.00143	15.0	-0.025	-0.00100
	Med ($50K-$100K)	AM peak	15.0	-0.025	-0.00100	26.3	-0.025	-0.00057	37.5	-0.025	-0.00040
		PM peak	13.5	-0.025	-0.00111	23.6	-0.025	-0.00063	33.8	-0.025	-0.00044
		Off-peak	11.0	-0.025	-0.00136	19.3	-0.025	-0.00078	27.5	-0.025	-0.00055
	High ($100K+)	AM peak	22.0	-0.025	-0.00068	38.5	-0.025	-0.00039	55.0	-0.025	-0.00027
		PM peak	20.0	-0.025	-0.00075	35.0	-0.025	-0.00043	50.0	-0.025	-0.00030
		Off-peak	18.0	-0.025	-0.00083	31.5	-0.025	-0.00048	45.0	-0.025	-0.00033
Business, at-work	Low (0-$50K)	Peak	12.0	-0.040	-0.00200	21.0	-0.040	-0.00114	30.0	-0.040	-0.00080
		Off-peak	10.0	-0.040	-0.00240	17.5	-0.040	-0.00137	25.0	-0.040	-0.00096
	Med ($50K-$100K)	Peak	20.0	-0.040	-0.00120	35.0	-0.040	-0.00069	50.0	-0.040	-0.00048
		Off-peak	17.0	-0.040	-0.00141	29.8	-0.040	-0.00081	42.5	-0.040	-0.00056
	High ($100K+)	Peak	28.0	-0.040	-0.00086	49.0	-0.040	-0.00049	70.0	-0.040	-0.00034
		Off-peak	24.0	-0.040	-0.00100	42.0	-0.040	-0.00057	60.0	-0.040	-0.00040
University, college	All	Peak	8.5	-0.030	-0.00212	14.9	-0.030	-0.00121	21.3	-0.030	-0.00085
		Off-peak	6.5	-0.030	-0.00277	11.4	-0.030	-0.00158	16.3	-0.030	-0.00111
School	All	All	4.0	-0.035	-0.00525	7.0	-0.035	-0.003	10.0	-0.035	-0.00210
Shopping, escorting, personal business, household maintenance, medical	Low (0-$50K)	Peak	6.5	-0.035	-0.00323	11.4	-0.035	-0.00185	16.3	-0.035	-0.00129
		Off-peak	5.5	-0.035	-0.00382	9.6	-0.035	-0.00218	13.8	-0.035	-0.00153
	Med ($50K-$100K)	Peak	11.0	-0.035	-0.00191	19.3	-0.035	-0.00109	27.5	-0.035	-0.00076
		Off-peak	9.0	-0.035	-0.00233	15.8	-0.035	-0.00133	22.5	-0.035	-0.00093
	High ($100K+)	Peak	15.0	-0.035	-0.00140	26.3	-0.035	-0.0008	37.5	-0.035	-0.00056
		Off-peak	13.0	-0.035	-0.00162	22.8	-0.035	-0.00092	32.5	-0.035	-0.00065
Leisure, sport, entertainment, discretionary, eating out, visiting relatives and friends	Low (0-$50K)	Peak	5.5	-0.030	-0.00327	9.6	-0.030	-0.00187	13.8	-0.030	-0.00131
		Off-peak	4.5	-0.030	-0.00400	7.9	-0.030	-0.00229	11.3	-0.030	-0.00160
	Med ($50K-$100K)	Peak	10.0	-0.030	-0.00180	17.5	-0.030	-0.00103	25.0	-0.030	-0.00072
		Off-peak	8.0	-0.030	-0.00225	14.0	-0.030	-0.00129	20.0	-0.030	-0.00090
	High ($100K+)	Peak	14.0	-0.030	-0.00129	24.5	-0.030	-0.00073	35.0	-0.030	-0.00051
		Off-peak	12.0	-0.030	-0.00150	21.0	-0.030	-0.00086	30.0	-0.030	-0.00060

Table 14. Recommended default VOT for multi-class traffic assignments.

Vehicle class	Household income & purpose sub-class	TOD period	VOT, $/h	Cost/toll coefficient for time equivalent in generalized cost function, min/cent
SOV	Work trips, medium & high income	AM	20.00	0.0300
		PM	18.00	0.0333
		Off-peak	15.00	0.0400
	Other trips and incomes	AM	12.00	0.0500
		PM	10.00	0.0600
		Off-peak	8.00	0.0750
HOV2 (scale 1.75)	Work trips, medium & high income	AM	35.00	0.0171
		PM	31.50	0.0190
		Off-peak	26.25	0.0229
	Other trips and incomes	AM	21.00	0.0286
		PM	17.50	0.0343
		Off-peak	14.00	0.0429
HOV3+ (scale 2.5)	Work trips, medium & high income	AM	50.00	0.0120
		PM	45.00	0.0133
		Off-peak	37.50	0.0160
	Other trips and incomes	AM	30.00	0.0200
		PM	25.00	0.0240
		Off-peak	20.00	0.0300
Taxi	All	All	20.00	0.030 0
Light trucks and commercial vehicles	All	All	30.00	0.0200
Heavy trucks	All	All	60.00	0.0100

assignment procedure, the VOT for the aggregate segment (vehicle class) should be calculated as a weighted average across all included demand segments. This method derives the assignment VOTs from travel demand model VOTs, and is preferred compared to the default assignment VOTs (or any other assignment VOTs established independently of the demand model VOTs). The default values should be used only if the linkage between the demand model segments and assignment vehicle classes is not unambiguous. It can be ambiguous, for example, if the demand model does not differentiate VOTs by vehicle occupancy and time-of-day period (relying on trip purpose, income, and other variables). It is essential to differentiate VOTs by vehicle occupancy and time-of-day, since the tolls are differentiated by these categories.

4.4 Model Validation, Calibration, and Sensitivity Testing

4.4.1 Dimensions and Data for Model Validation

Travel models in the United States (both 4-step and ABM) are subject to certain acceptance criteria established by the FHWA and FTA. Virtually all of this guidance relates to the base year calibration and replication of the most important aggregate targets that are established from data independent of the model. There is, however, a great deal of variation in the practice of travel modeling from region to region. The rigor and completeness of the criteria are normally subject to specific project or policy considerations, and are consequently focused on either highway side (matching traffic counts) or transit side (matching observed ridership and travel times), but rarely both.

It should also be considered that the validation and calibration of a travel model solely on the highway side, with no attention paid to the transit side, is problematic even though only the highway statistics are the focus of road pricing studies. The need for a reasonable transit validation stems from the fact that mode choice represents one of the four key travel dimensions (i.e., first-order travel responses to pricing) along with route choice, time-of-day choice, and car occupancy choice.

For pricing studies we suggest a comprehensive approach to model validation that is based on the following system of basic criteria:

- Highway validation:
  - Replication of daily traffic counts and daily AADT/VMT statistics in the study corridor with 0.95 level of correlation.

  - Replication of AM period counts (normally, 6:00–9:00 but can be adjusted to reflect the observed regional conditions) with 0.90 level of correlation.
  - Replication of PM period counts (normally, 3:30–6:30 but can be adjusted to reflect the observed regional conditions) with 0.90 level of correlation.
  - Replication of Midday off-peak period counts (normally, 9:00 AM–3:30 PM but can be adjusted to reflect the observed regional conditions) with 0.80 level of correlation.
  - Replication of travel speed and LOS/congestion levels (if the data is available) by time-of-day period with 0.80 level of correlation.
- Transit validation:
  - Replication of the daily synthetic trip matrix from the on-board survey (if available) with 0.80 level of correlation at the level of aggregate districts for each time-of-day period.
  - Replication of daily transit line ridership for the most loaded rapid transit lines (commuter rail, LRT), bus lines (grouped by corridors), and major station boarding counts with 0.80 level of correlation. Focusing on transit validation in key corridors where a mode choice shift might be expected due to the pricing projects is suggested.
- Modal split validation:
  - Replication of the observed modal split from the Household Travel Survey by purpose, time of day, and aggregate district-to-district OD pairs with 0.80 level of correlation.
- Spatial distribution (destination choice) validation:
  - Replication of the observed daily journey-to-work patterns from the Population Census by mode and aggregate district-to-district OD pairs with 0.90 level of correlation.
  - Matching average trip distance and trip length frequency distributions extracted from the Household Travel Survey (after expansion) and Census data (CTPP tables) by travel purpose with a good level of statistical confidence.

Traffic counts should be prepared for major corridors and screenlines that are relevant for the project under study. The usual practice is to augment the basic set of traffic counts used for the regional model validation with additional counts collected along the project corridor and for feeder and competing roads. Currently, most regional agencies set the bar for model validation in terms of the percent root mean square error for highway volumes differently. While the existing regional culture represents a good starting point, it makes sense to discuss and agree upon exact validation criteria at the outset of the project, to ensure that the team understands what will be acceptable for all key stakeholders.

For model validation and calibration, it is essential to establish a compact districting system, which will be used for data summaries of mode choice calibration and destination choice calibration. The districting system should ideally have not more than 15–20 districts that would geographically allow for a full capturing of the major traffic flows, corridors, and screenlines. District boundaries used for general regional modeling can be specifically adjusted to the pricing study or project. Remote and irrelevant areas can be combined into large districts while in the vicinity of the study area the district system should be finer.

A good replication of the observed journey-to-work flows remains the cornerstone of travel model validation, and is especially important for congestion pricing studies since commuting represents the largest travel segment in peak periods. In 4-step models, this relates to the home-based-work component. In ABMs, this relates to the usual workplace choice model. Before any validation or calibration effort is undertaken with respect to journey-to-work flows, a comparison of home-interview and census journey-to-work data sets at a district level is necessary in order to determine whether significant differences exist between datasets. Any differences between datasets should be identified and resolved before beginning the calibration of the model. In particular, prior to a mode choice model calibration, the expanded survey data should be extensively compared with census journey-to-work data in order to understand potential differences in data and develop a reasonable set of district-level model calibration targets.

The main sources for model validation relate the observed statistics for the base year. Consequently, the main calibration effort is associated with making the model replicate these statistics by way of adjustment of the parameters. This, however, is not the only important aspect of validation. Another potentially useful way to check the model system's performance includes forecasting: either by showing that the model performs reasonably when future-year scenarios are modeled or by back-casting to an earlier year and comparing results to independent data. These options should be explored and other useful reasonableness checks should be undertaken and documented. This step should be closely intertwined with the model application. It is not unusual in practice that a model that was well calibrated for the base year without pricing would require some adjustments when the pricing projects are introduced. The main reason for this can be the discovery of an unreasonable sensitivity to pricing that could not be detected if the base year network is characterized by a no or only a limited number of existing priced facilities.

4.4.2 Region-Level Calibration Procedures

In general, it is a non-trivial task to identify the sources of discrepancies that manifest in the final model validation against traffic counts and then decide upon the best course of action. The reason for discrepancies can be related to any of the model components applied prior to the assignment stage: population and employment data; car ownership; tour and trip generation; spatial distribution of tours and trips; time-of-day choice; mode choice; as well as in the assignment parameters themselves. It is generally not possible to diagnose the assignment results and conclude what specific fixes needed based solely on the detected discrepancy between the traffic counts and assigned volumes. The only consistent way to screen out the reasons for discrepancy, and to identify the model components that should be adjusted accordingly is to carefully validate and calibrate (if needed) all sub-models in the sequence in which they are applied in the model system. The sequential validation and calibration of all sub-models may be time-taking compared to such fast fixes as a trip table adjustment to traffic counts. This is the most preferable way, however, to promote consistency and accuracy throughout the entire model system.

The following sequence of the major validation and calibration steps can be outlined, where each subsequent step can be undertaken only after the previous step has been completed:

- The travel generation models (trip and/or tour production and attraction components) should be validated and calibrated (if needed) to closely match the established aggregate targets. The targets should be segmented by household/person type and travel purpose as well as by geography. Several sources of information on travel generation will be combined and consolidated in order to develop reliable base-year targets. They include relevant CTPP tables, Household Travel Survey (after expansion), data on actual employment, etc. Trip and tour rates should match those observed in the GPS, traffic generator studies, and other available inventories. Generated trips in combination with the average trip length should match the regional VMT statistics.
- The trip distribution (destination choice) models have to be validated and calibrated against the statistics observed in the Household Travel Survey and/or the CTPP journey-to-work tables. Calibration criteria include matching average trip distance, trip length frequency distributions, and district-level flows.
- The time-of-day choice (peak-spreading) model should be validated and calibrated across several dimensions and against different sources of information. One routine validation includes structural comparison of aggregate distributions of departure times, arrival times, and tour durations (that latter is relevant for ABMs only) to the observed distributions tabulated from the Household Travel Survey for each travel purpose. Another set of tests involves validation of the resulted trip departure/arrival time distributions for highway modes (after application of destination choice, time-of-day choice, and mode choice models for all types of tours) to the time-of-day distributions observed in traffic counts on major screen-lines and along major corridors.
- The mode choice model should be validated and calibrated against aggregate mode shares developed from the expanded Household Travel Survey, and Transit On-Board Survey data, as well as against other available independent sources of information. In particular, the CTPP tables provide good aggregate estimates of mode shores for work tours, while the Transit On-Board Survey provides the most reliable estimates for the total number and spatial distribution of transit trips.

Validation and calibration of all main models should be implemented at county, district, and (if necessary) TAZ levels. In general, it is always preferable to operate with large-unit parameters in model calibration, rather than to introduce parameters specific to a smaller geographic unit that might result in a model over-specification.

Despite the fact that the model components are validated and calibrated one by one, it is essential to have the entire model application system in place at this stage, where final (feedback) iteration LOS matrices are used and final trip tables by mode and time-of-day period are tested to ensure that they are consistent with survey data, and also checked against screenline traffic flows in order to determine whether further adjustments are necessary at a geographic level to better match traffic counts. In general, the equilibration procedure itself may introduce significant changes in one of the travel dimensions (specifically mode choice) compared to any validation or calibration with static LOS variables.

In practical terms, after all model components have been validated and reasonably calibrated, there still can be a residual level of discrepancy with respect to particular traffic counts that is difficult or too time-taking to resolve, either with the counts or with the model. This might require trip table adjustment to traffic counts. The methodological difference between model calibration and trip table adjustment to traffic counts should be well understood. Trip table adjustment to traffic counts can improve the match further but is problematic for carrying over into future as discussed below.

In general, the adjustment of a trip table to traffic counts is a technically effective procedure with a set of methods available (in some cases, built-in in the transportation software packages), but it should be taken with a necessary level of cautiousness. First of all, adjustment of a trip table to traffic counts is a fairly mechanical procedure that tends to create unrealistic OD patterns (or unrealistic production and/or attraction marginals) and can significantly change the observed trip-length distribution. While this procedure can be somewhat embedded in the aggregate trip distribution structure of a 4-step model in a form of so-called K-factors, it is more problematic to integrate trip table adjustments with an advanced ABM structure.

Two additional aspects of model validation and calibration should be taken into account before adjustment to traffic counts is employed:

- The validation criteria can always be matched by mechanical adjustment of the trip tables to traffic counts or by over-specification of the model with multiple constants including K-factors for destination choice or trip distribution and area-specific mode choice constants. We recommend that these methods of calibration are applied with caution and adjustment of certain model parameters, only if it makes behavioral sense. This calibration process takes longer than mechanical adjustment and over-specification and may result in a lower level of match, but it is preferable, since the predictive power of the model will be fully preserved.
- The calibration targets themselves are not perfect and normally have numerous internal inconsistencies. All types of surveys have certain built-in biases, including under-reporting of travel. Different data sources are synthetic and relate to different years. By bringing them together to the same reference year, it is impossible to fully ensure internal consistency. For this reason, some discrepancies are inevitable and the model cannot match all targets exactly. The process of model validation and calibration normally includes numerous iterations with improvement of the data itself (for example, re-weighting of the Household Survey by the commuting pattern observed in the Population Census).

It is important to recognize several objective factors that require post-model adjustment of the highway trip tables produced by the core demand model in order to better replicate traffic counts. These factors can be aggregated into two meaningful groups that are important in view of the need for application of the procedure for future year forecasts:

- Built-in biases in a household survey, like under-reporting of short trips and intermediate stops, and the adjustment factors (ratio of the adjusted trip table to original trip table at the district-to-district level) calculated for the base year for this group should be applied for the future years in a multiplicative way, accounting for residential population growth and assuming that the structural share of the under-reported trips stays the same over years.
- Missing non-residential-population components like commercial vehicles' traffic and tourists' travel that are not strictly linked to the population growth; the adjustment factors calculated for the base year for this group should be applied for the future years in an additive incremental way, i.e., the same absolute addition calculated for the base year (difference between the adjusted trip table and original trip table at the district-to-district level) is applied for all target years, assuming that the underlying activities do not grow (or decline) significantly.

Both procedures (multiplicative and incremental) have been applied in practice frameworks. They both produce reasonable results that are not dramatically different for regions with overall stability or moderate growth of land-use characteristics in future years. It should be noted that in most cases where a moderate population and employment growth is expected, the additive incremental procedure tends to produce a slightly more conservative forecast, while the multiplicative procedure usually tends to slightly overestimate traffic. In view of the need to use the model in a real planning environment for pricing analysis, conservatism of the forecasts is normally preferred.

4.4.3 Corridor-Level and Sub-Area-Level Calibration Procedures

Local calibration and adjustments represent a frequent step of regional model application for a particular study. Even if the regional model is well-calibrated and satisfies all the criteria, it may need an additional local calibration for application in a specific corridor or sub-area where more disaggregate level of analysis is undertaken, more detailed data for calibration are available, or smaller-scale differences in pricing project alternatives are under scrutiny.

For example, while the basic version of the regional model should generally be applied to identify the main pricing projects and alternatives in terms of the layout, number of lanes, and base toll rates, the subsequent analysis might focus on details of the access ramps or toll discounts by vehicle types (SOV, HOV, taxi, commercial vehicle, truck, bus, etc.). For the modeling of access ramps, the level of calibration of the regional model may not be sufficient to address the details needed for this analysis. In particular a reasonable level of replication of traffic counts on links for broad time-of-day periods like AM, Midday, and PM may not be enough. An additional singling out of peak hours within AM and PM periods, as well as replication of counts on turns, is highly desirable. For the analysis of impacts of different discounts by vehicle types, an additional calibration effort may be needed to ensure a reasonable level of replication of traffic counts by vehicle type rather than just total traffic flow.

In particular, the core set of trip tables by vehicle class can be adjusted to the subset of local counts in the sub-area under the study. Taking into account a limited subset of counts and additional network details in the sub-area application, the adjustment can be made to the extent that each traffic count is replicated almost exactly. Then, depending on the proportion of the commercial versus residential-based traffic, area-specific decision can be made, using either additive or multiplicative strategy for future years as discussed above.

4.4.4 Sensitivity Tests, Risk Analysis, and Mitigation

Survey of Reported T&R Forecast Errors

The evaluation of model quality and capabilities is directly related to the degree of accuracy and the identification of likely sources of error. This section discusses the methods developed and applied by rating agencies to eliminate built-in optimistic biases and produce more realistic and conservative forecasts.

Uncertainty in demand for tolled roadways compared to free highways is compounded by the introduction of more unknown variables (like willingness to pay). Yet such new understanding can be critical, since private investment generally depends on cost recovery through toll collection. In order to begin to address this clear gap in the literature, Standard & Poor's (Bain and Wilkins 2002, Bain and Plantagie 2003 and 2004, Bain and Polakovic 2005) and Fitch Ratings (George, et al. 2003 and George, et al. 2007) produced a series of studies that examine the risk and uncertainty of tolled highway projects.

Standard & Poor's (S&P's) study of traffic forecasts began in 2002 with data from 32 toll road projects around the world. The sample was then increased to 68 and 87 projects in 2003 and 2004, respectively. However, in both updates the conclusions remained largely the same.

In the first study, Bain and Wilkins (2002) found that traffic forecasts for new toll roads suffered from substantial optimism bias, a finding that was supported in the subsequent studies. The average ratio of actual-to-forecast traffic volumes in the first year of operation was about 0.73 (versus 0.74, 0.76, and 0.77 in the 2003, 2004, and 2005 studies). Figure 12 shows the distribution of forecasting errors in the 2005 update. (Comparisons to non-tolled projects are drawn later in this section.) Of course, due to the nature of averaging ratios such as these, traffic forecasts for toll roads may be over-predicting actual volumes by even more than 33% (implied by an actual-to-forecast ratio of 0.75). A volume-weighted average of ratios (essentially the sum of predicted values over the sum of actual values) yields a much more robust indicator of the average percentage error, reflecting whether an investor will win (average >1) or lose (<1) – on average, across projects. Essentially, the issue is that the ratios are non-negative and bounded by zero, leaving a right-side skew that tends to bias averages to the high side. For instance, if predicted-to-actual ratios for two projects are 0.5 and 2.0, the average is 1.25, suggesting predictions are biased high. If the ratios are first inverted and then averaged, the result is again 1.25, but the interpretation is that predictions are biased low. Thus, one must use caution when dealing with averages of ratios.

Moreover, the 2002 study found that 78% of actual-to-forecast traffic volume ratios were less than 0.9 while only 12% were over 1.05. In the 2003 study, 63% of such ratios were less than 0.85 and 12% were over 1.05. Essentially three quarters of first-year traffic forecasts for tolled facilities are overestimated by 10% or more, suggesting that planners, bankers, and communities should be wary, and modelers need to improve their methods.

One of the main diagnostics to come out of the 2002 study was S&P's Traffic Risk Index (TRI). While the exact details for its estimation are proprietary in nature (and thus not provided), the index attempts to predict the amount of project risk based

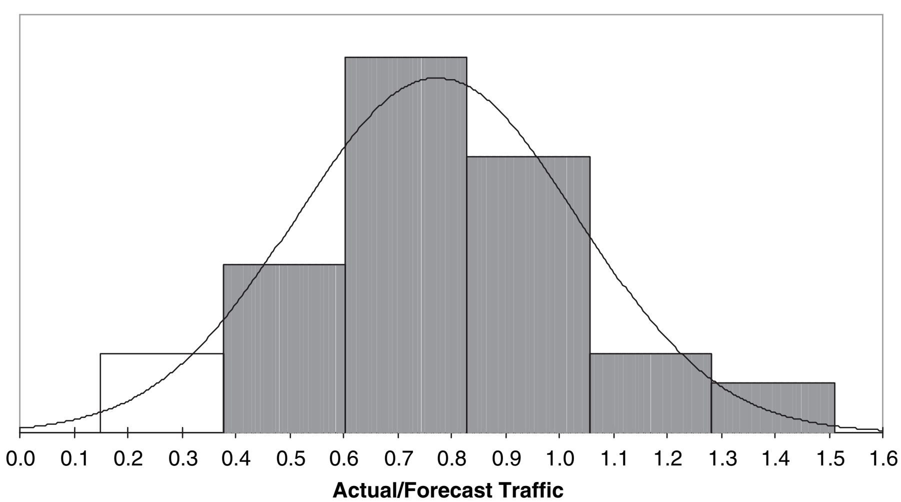

Figure 12. Distribution of actual-to-forecast traffic volumes (Bain and Polakovic 2005).

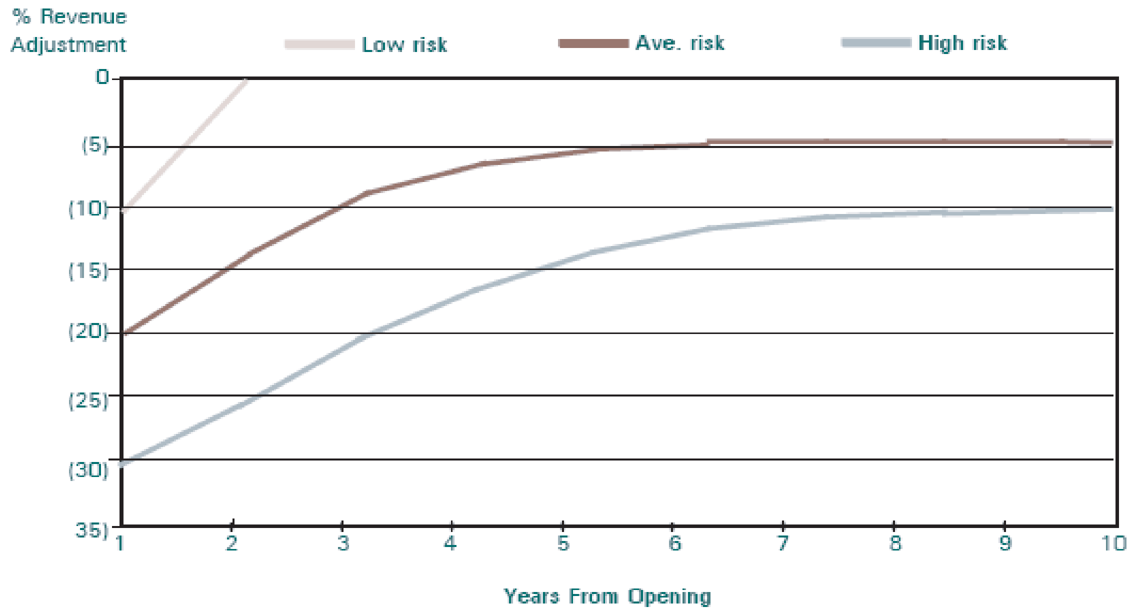

Figure 13. Estimated errors in tolled highway projects commissioned by banks (Bain and Wilkins 2002).

on many project attributes, as discussed later in this section. Based on the TRI, Bain and Wilkins (2002) determined a risk level (low, average, or high) for each project, and divided its discussion by forecast source: those commissioned by banks versus those commissioned by others. Figures 13 and 14 show the TRI profiles over time.

The findings suggest that actual-to-forecast traffic volume ratios in the first year of operation average about 0.9 for low-risk bank-commissioned projects, and 0.8 for low-risk projects commissioned by others. Both types of low-risk projects had average ramp-up durations of about 2 years (after which actual volumes closely match forecasts). For average-risk projects, year one volume ratios were found to be 0.8 and 0.65 for bank- and non-bank-commissioned projects, respectively. Ramp-up duration was about 5 years in both cases. However, those commissioned by banks ramped-up to about 95% of forecast volumes over those first five years, while others ramped-up to only 90%. For high-risk projects, the volume

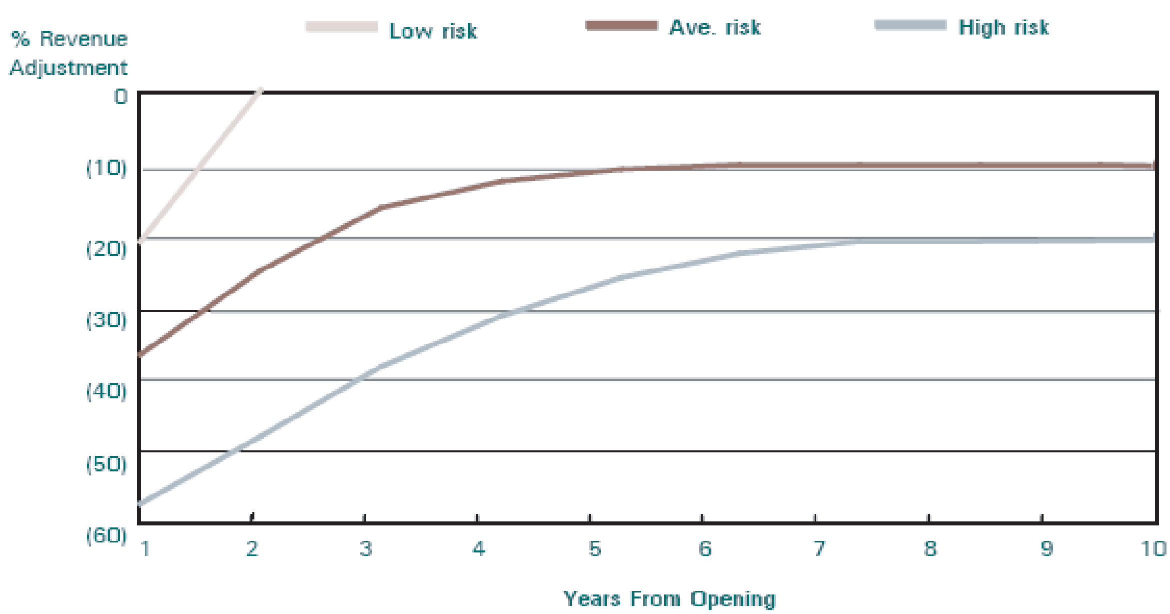

Figure 14. Estimated errors in tolled highway projects commissioned by others (Bain and Wilkins 2002).

ratios were just 0.7 and 0.45, respectively, and ramp-up durations were about 8 years. After ramp-up, bank-commissioned projects reached about 90% of forecast volumes while other projects reached approximately 80% of forecast. What this suggests is that projects with greater uncertainty (and thus risk) underestimate initial traffic volumes by a greater amount, on average, experience a longer ramp-up duration (to reach stable volumes), and stabilize at lower final traffic volumes (versus predictions). Moreover, the magnitude of risk is greater for projects not commissioned by banks, which is not so surprising given that banks are much more directly accountable for investors' monies than are public agencies. Moreover, other project commissioners (public agencies, interest groups, and bidders) may have interests that are best served when predicted traffic volumes are high (Bain and Wilkins 2002).

With the 2003 study's increased sample size, Bain and Plantagie (2003) were able to conduct several less aggregate analyses. Multiple factors were investigated, but only one with significance was found, in distinguishing countries with and without a tolling history. The findings suggest that actual-to-forecast volume ratios in the first year of operations averaged 0.81 in countries with a history of tolling, but just 0.58 in other countries. Thus, forecast risks appear much higher in countries without a history of tolling. This is intuitive, given that user adoption will be much faster (thanks to existing toll tag and manual payment experiences) and that contractor and operator familiarity will be higher. In several U.S. regions (e.g., Florida, Southern California, New York, and Houston), flat-rate tolling is already well-established; so, in these regions it may be reasonable to expect first-year ratios in the neighborhood of 0.8. However, most other U.S. regions may dramatically under-perform if more appropriate modeling assumptions are not used (particularly for the ramp-up period).

In the 2004 update, Bain and Plantagie (2004) traffic forecasts along new tolled highways were compared to those of new non-tolled facilities. The sample size was increased to 87 highway projects, with all data for non-tolled facilities coming from Flyvbjerg, et al.'s (2005 and 2006) work. The comparisons suggest that new non-tolled roadways exhibit little optimism bias, though the same amount of uncertainty or spread in the distribution (of volume ratios) remains. Figure 15 shows how the two distributions appear similar, but with an added –20% optimism-bias shift in the distribution of tolled road (forecast-to-actual) volume ratios. This suggests that, after controlling for the added optimism bias of tolled projects, there may be little difference in the accuracy of traffic forecasts for tolled and non-tolled projects.

In Standard & Poor's 2005 update (Bain and Polakovic 2005), the uncertainty in project ramp-up years was investigated in greater depth. The expectation is that uncertainty falls slightly from opening year forecasts, since traffic demand would have an opportunity to stabilize, as drivers learn of route alternatives and obtain toll accounts, for example. The sample size was just 25 projects for years 1 through 5, and the hypothesis was not supported (Bain and Polakovic 2005). The mean ratio (of actual-to-forecast traffic volumes) was 0.77 in year 1, and 0.79 (negligibly higher) in Year 5. These results suggest that traffic performance generally remains much less than forecast, even into Year 5 of operation. While Vassallo and Baeza's (2007) much smaller sample (of Spanish toll roads) identified similar optimism biases, forecast ratios generally improved following year one. So there is room for differences in average results, due to regional economic conditions, marketing campaigns or other factors.

Sources of Risk and Uncertainty

While significant uncertainty in traffic forecasts clearly exists, the causes of such uncertainty vary, including the sources of forecast error. Numerous studies have identified and examined several sources of forecast error (Flyvbjerg, et al. 2005 and 2006, Bain and Wilkins 2002, George, et al. 2003, George,

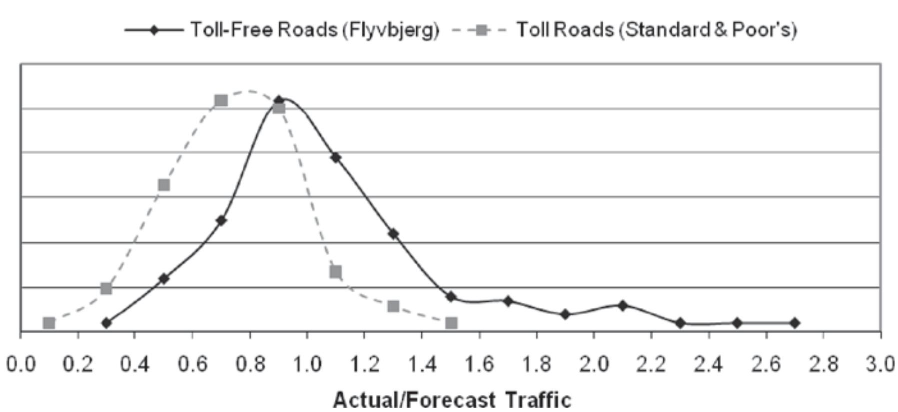

Figure 15. Distribution of actual-to-forecast traffic volumes for tolled and non-tolled projects (Bain and Plantagie 2004).

et al. 2007), and for the most part, these are similar for tolled and non-tolled highways, but differences do exist.

Flyvbjerg, et al. (2005 and 2006), interviewed project managers who identified a variety of sources, including several travel demand modeling components. Figure 16 provides the percentage of projects, found by Flyvbjerg, et al. (2005 and 2006), with stated sources of traffic forecasting error, for both passenger rail and road projects. The two top-stated sources of error for toll-free road projects are estimates of trip generation-related factors and land development, though trip distribution-factors and the forecasting model (mode choice and route choice) are close runners-up.

Zhao and Kockelman (2002) tracked the propagation of uncertainty through a four-step travel demand model. They controlled the uncertainty of model inputs and parameters, and performed 100 simulations of the model. Overall, Zhao and Kockelman's (2002) work suggests that link-flow estimates enjoy the same level of uncertainty as inputs and parameters, and simple regressions of outputs on inputs (and aggregations of inputs) offer very high predictive power, suggesting that prime sources of forecast uncertainties can be rather quickly deduced (and exploited) for better prediction.

Network attributes can also play a key role in forecast reliability. Analysts do not know the actual future network, and coded networks are significant simplifications of actual networks (generally ignoring local streets, signal timing plans, turning lane presence and lengths, etc.). Forecasts that depend on future network changes (such as nearby highway extensions) tend to be less reliable (Bain and Wilkins 2002). Traffic congestion is also a key. As noted by Bain and Wilkins (2002) and Zhao and Kockelman (2002), uncongested networks often are more difficult to anticipate flows on, since congestion feedbacks distribute traffic more evenly over space and time while establishing something like an upper bound (due to inherent capacity limitations) on all links. Thus, low-volume corridors tend to have greater uncertainty in their forecasts (Bain and Wilkins 2002).

Another key source of error in traffic forecasts comes from uncertainty in land development patterns (Rodier 2003, Flyvbjerg, et al. 2005 and 2006, Land Transport New Zealand 2006). Rodier's (2003) application of the Sacramento, California, travel demand model for year 2000 conditions found that about half of the 11% overestimation of VMT was due to demographic and employment projections, which serve as inputs to the demand models. The other half was due to the model itself.

George, et al. (2007) suggest that user fees make a tolled road more susceptible to changes in demand caused by economic downturns/recessions, toll rate increases, and escalating fuel costs. Other special or relatively rare events (e.g., natural disasters or acts of terrorism among other events) are often key sources of uncertainty as well (George, et al. 2007). Of course, such events are difficult to predict, though *HLB Decision Economics* (2004) suggests that the number and duration of recessions in the forecast period should be considered in investment grade studies.

Another important consideration in understanding project risk is the "tolling culture" of a region (Bain and Wilkins 2002). This is essentially the degree to which tolls have been used in the past. In nations and regions where tolling has not pre-

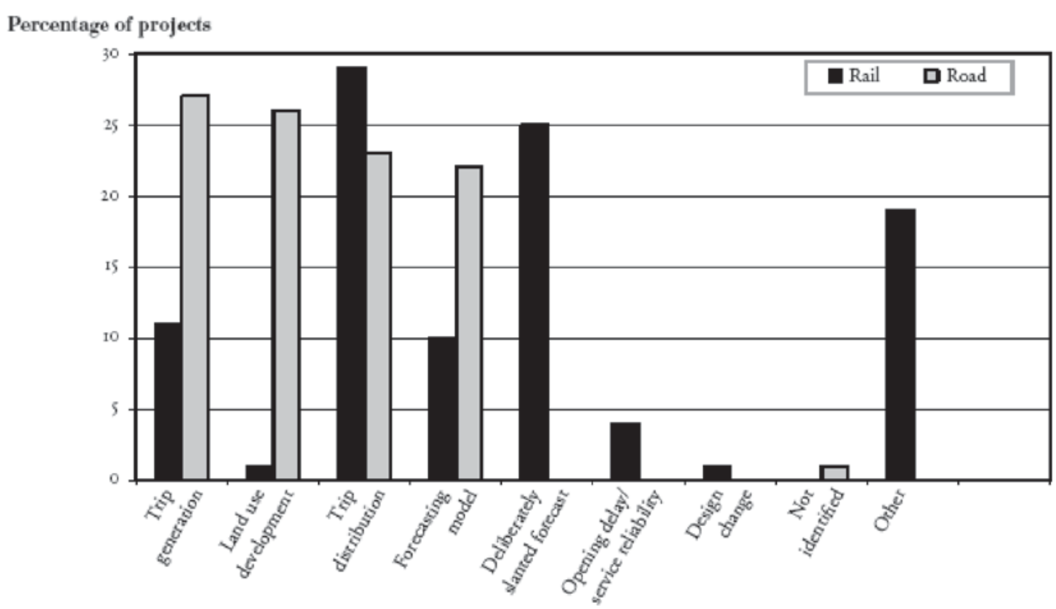

Figure 16. Project manager-stated sources of forecast error for non-tolled facilities (Flyvbjerg, et al. 2005).

viously been used, there is greater uncertainty surrounding traffic forecasts. If travelers are accustomed to paying tolls for other road facilities, forecasts tend to be much more reliable. As noted earlier, this appears to result in 20% greater average optimism bias (Bain and Plantagie 2003).

Of course, travel demand model imperfections are a key source of error in traffic forecasts. For instance, the robustness and heterogeneity (across travelers and trip types) of value of travel time estimates are generally ignored, but may be crucial in producing accurate forecasts. The use of imported parameters (calibrated for other regions or even other countries) can also cause much error (Bain and Wilkins 2002).

Facilities enjoying a competitive advantage of some sort also tend to offer more reliable forecasts (Bain and Wilkins 2002; George, et al. 2007). For instance, forecasts for projects in dense, urban networks (with many alternative routes) generally will be less certain than those for projects with a clear competitive advantage over alternatives (e.g., a corridor with the only river crossing in a region). Moreover, many privately financed projects rely on protection against competition in the future. If protection is provided (via non-compete clauses, for example), long-run traffic forecasts tend to be more reliable (Bain and Wilkins 2002).

Meaningful distinctions can also arise in the context of user attributes. Bain and Wilkins (2002) assert that toll facilities serving mostly a small market segment of travelers allow for more reliable traffic forecasts. This is because smaller markets are easier to model than more heterogeneous populations (Bain and Wilkins 2002). For example, beltways (orbital style facilities) are likely to carry more forecasting risk than radial facilities (which typically carry a high share of commuters into and out of the city center, for work purposes).

Overall, Bain and Wilkins (2002) indicate seven top drivers of forecast failure:

- Poorly estimated VOTs,
- Economic downturns,
- Mis-prediction of future land use conditions,
- Lower-than-predicted time savings,
- Added competition (e.g., improvements to competing roads or the addition of new roads),
- Lower than anticipated truck usage, and
- High variability in traffic volumes (by time-of-day or day of the year).

Bain and Plantagie (2003) added several other top drivers:

- Complexity of the tolling regime,
- Underestimation of the duration and severity of the ramp-up period,
- Reliance on a single VOT (as opposed to segmenting user groups).

Another rating agency, Fitch Ratings (George, et al. 2003), also suggested several of these same drivers, but added that the use of a regional travel demand model developed for other planning purposes also can cause great error in traffic forecasts.

Relevant Risk Factors and Mitigation Measures for Pricing Projects

To review the national and international experience, accommodating risk and uncertainty in demand and revenue forecasts is an important component of any toll road study. While a single best statistical forecast is useful, it lacks the information needed for making long-term financial decisions. With the great number of assumptions, inputs, and estimated parameters entering travel demand models, model outputs can be highly uncertain and inaccurate. Neglecting this uncertainty (or equivalently, assuming determinism) can invite scrutiny from stakeholders, since not all will agree with assumed inputs and parameter values (Duthie 2008).

Most analysts, policy makers, and investors agree that it is imperative that modelers quantify forecasting risk in a meaningful way (Rodier 2007), and while the financial community has understood the need to address risk in toll road studies, Kriger, et al. (2006) believe that very few practitioners conduct any sort of risk assessment. Some simply verify results by use of reality checks (e.g., comparing to older forecasts and using simple intuition to verify whether results seem reasonable), while others use no verification methods at all.

One key component of risk assessment in model outputs lies in explicitly stating all major modeling assumptions (Kriger, et al. 2006), making the model specification as transparent as possible. If modelers and users understand the implications of alternative assumptions, the uncertainty in the forecasting process will be better understood.

A relatively common and reasonably effective method for accommodating risk in T&R forecasts is the use of sensitivity analyses or "stress tests" (Kriger, et al. 2006). Most sensitivity analyses rely on the exploration of a very limited set of different values for key variables, such as a region's or neighborhood's population growth rate, values of travel time, and planned tolls (Kriger, et al. 2006). Though such analyses can provide key insights, many practitioners and financial analysts feel that they inadequately reveal the range of possible outcomes (HLB Decision Economics 2003, Kriger, et al. 2006). As their name implies, stress tests seek to understand the outcomes of relatively extreme conditions, generally to anticipate worst- and best-case investment scenarios. In this way they help analysts anticipate lower (and upper) bounds on project outcomes, but certainly not a distribution of outcomes, or probability of financial loss.

Model validation studies offer another method for quantifying uncertainty, by examining how well model forecasts match observed data not used in model calibration (Rodier 2007). Such studies measure forecast uncertainty directly from the observed data and thus require data from two points in time: the older data set is used for model estimation and calibration while the newer one is used for validation. It can be impossible to conduct such tests of models developed from recent data, but at least one obtains a sense of the magnitudes of errors that can emerge from transferring behavioral parameters calibrated on old data to current-year contexts.

Of course, sensitivity testing and model validation studies have their limitations. For example, sensitivity tests are quite constrained, to typically three or four scenarios. In contrast, Monte Carlo simulation techniques more fully explore the range of possible outcomes by defining and drawing from probability distributions for key inputs. Of course, such techniques also exhibit limitations: They require assumptions of input distributions (and their covariances), when these are often unknown, and generally more sophisticated programming techniques (to ensure rapid run times for testing a high number of scenarios).

Monte Carlo techniques are at the heart of the four-step Risk Analysis Process (RAP) used by HLB Decision Economics (2003). In Step 1, HLB defines a structure and logic model, in order to forecast traffic and revenue on the basis of an array of inputs and parameters. In Step 2, central estimates and probability ranges are assigned to each relevant input and parameter. In Step 3, expert opinions regarding the results of Step 2 are obtained, and probability ranges and central estimates are revised. In the final step, Monte Carlo simulation techniques are employed, drawing inputs and parameters from their respective probability distributions, and traffic and revenue probability ranges are derived based on the simulation outcomes. This approach allows firms like HLB to determine the likelihood that revenue cannot cover the debt service, an important criteria for issuance of debt.

As discussed earlier, Zhao and Kockelman (2002) performed a similar analysis (for a non-tolled case), using a four-step travel demand model for a sub-network of the extensive Dallas-Fort Worth region with 118 variable input and parameter values. They assigned density functions to the 18 random model parameters (13 in trip generation, one in trip distribution, two in mode choice, and two in assignment) and four major model inputs for each of 25 zones (household counts along with basic, retail, and service job counts). This analysis indicated that inputs and trip generation parameter values were the most important factors in forecasts of total VMT.

Consistent with such analyses, the National Federation of Municipal Analysts (NFMA 2005) formally recommends that a range of possible road project and policy outcomes should be explored based on different scenarios (or assumptions) and varying variables or parameters one at a time is insufficient. By assigning realistic probability distributions to parameter values and inputs, the probability of a given scenario can be understood. The NFMA (2005) guidelines for traffic and revenue studies include several highlights: a no-build traffic forecast should be produced; a baseline traffic and revenue forecast should be produced; sensitivity analyses should be performed on inputs (including population, employment, and income growth, toll elasticity by consumers, and acceleration of the planned transportation network); and debt service analysis should be performed.

Another approach is reference class forecasting, as described by Flyvbjerg, et al. (2005). This method essentially relies on past experiences with a sample of similar projects in order to estimate outcome distributions and thus the probability of various events occurring. By comparing the forecasts with past experience, judgments can be made regarding the validity of results. Of course, this is difficult to do without good data on a variety of reasonably comparable projects. But it is a useful strategy when such data exist.

To determine an investment's credit rating, credit agencies and financial analysts use varied approaches to account for revenue forecast risk. For example, Fitch Ratings (George, et al., 2003, George, et al. 2007) claims to study the key assumptions and inputs of the travel demand model used in creating future forecasts, and then considers a range of possible outcomes associated with each factor in order to develop a stress scenario alongside a base scenario (essentially sensitivity testing, but with relatively extreme scenarios). The base case is generally more conservative than the base case developed by the project sponsor, eliminating any evident forecast optimism. The stress case is developed to determine the project's ability to withstand rather severe (but not unreasonable) circumstances in which the ability to pay debt service is stressed. Based on the results of the stress scenario, an investment rating is assigned to the project.

For credit analysis of longer-term traffic forecasts, Bain, et al. (2006) suggest taking a conservative approach, reducing growth rate expectations and carefully examining future toll schedule increases. They also suggest that long-term growth rates exceeding 1% and toll increases beyond those suggested by reasonable correction for inflation should be viewed with caution. While these techniques simplify uncertainty testing dramatically and help investors understand the real possibility of loss, they do not illuminate the variety (and likelihood) of futures that truly exist, and associated investment risk cannot be fully understood using such methods.

Comparing the most frequently used analytical techniques, sensitivity testing and Monte Carlo simulation, the following difference should be understood. Sensitivity testing allows for greater understanding of the magnitudes of uncertainty in the model. By allowing key model inputs and parameters to vary simultaneously, creating multiple possible scenarios, uncertainty in traffic and revenue forecasts can be better bounded. Indeed, this appears to be the most common method for dealing with uncertainty by credit agencies. However, sensitivity testing generally does not provide a probability of particular outcomes occurring. Therefore, it can be difficult for policy makers to truly understand inherent risks. Monte Carlo simulation may be most appropriate to identify a more probable set of possible futures. By drawing parameters and inputs from reasonable sets of distributions, the probability of particular outcomes can be understood.

It should be, of course, taking into account that Monte Carlo simulation requires multiple model runs to build a distribution of the outcomes that is difficult to implement in practice since each run of a full regional travel model normally takes several hours (or even days). A possible way to overcome this technical limitation is to build an auxiliary regression of the model outcomes of interest (for example, total traffic or revenue) to a set of predetermined input parameters (for example, population growth, basic toll rate, capacity of the alternative road, etc.) based on several full-model runs that would serve as pivot points in the Monte Carlo simulation. Then multiple points are added using the simple regression model to interpolate between the pivot points. This interpolation is of course very crude and is intended for only estimation of the probability distribution around the true model runs.

Secondly, risk mitigation methods are recommended for each specific project type and model. The following general approach is recommended. At first stage, major risk factors are identified for each project depending on the project scale, network topology, affected population, etc. The following approximate check-list of factors should be considered, although this list should be built for each project specifically:

- Population growth in the relevant project corridor. This growth should be compared to the observed tendencies in the past and the entire region and the corridor. If the projected growth is significantly higher than the observed past trends, it should be considered as a high risk factor. Creating optimistic and pessimistic scenarios with estimated probability to occur is recommended.
- Employment growth in the relevant project corridor. Similar to the population growth, the realistic comparisons to the observed trends should be made. Each case of growth rates higher than the observed trends should be carefully substantiated; otherwise high risk is assigned to this factor. Creating optimistic and pessimistic scenarios with estimated probability to occur is recommended.
- Competing highway and transit projects in the corridor. This factor is relevant for the pricing projects that are located in the corridors where another significant and competing project may take place (including a significant improvement of the existing free road or transit service). If this is a realistic option, the competing projects should be described, coded, and included in the pessimistic network scenarios.
- Complementary (feeding) highway projects in the corridor and beyond. This factor is relevant for pricing projects that are located in such a way that a substantial share of travelers might use this facility in combination with some other future projects. It specifically affects such projects and policies as HOV/HOT lanes where network connectivity is essential. If this is a real factor, the complementary projects should be described, coded, and included in the optimistic network scenarios.
- VOT estimates and related travel time and cost coefficients used in the traffic assignment, mode choice, time-of-day choice and other models. This is a fundamental behavioral parameter in the travel model that always represents a source of uncertainty, simply because of the randomness known to be inherent to travel behavior. It should be determined that the average VOT values applied for each segment are reasonable. A high risk is assigned to this factor if the VOT value was not estimated, but instead was assumed or borrowed. No matter how well structured and segmented the model system, a ±20% variation in VOT can generally be considered within the 99% confidence interval. For simple models with poor segmentation, the range should be extended to at least ±40%. Variation of VOT also incorporates uncertainty associated with real income growth, possible economic recession, and other related factors (if they are not considered explicitly).
- Toll escalation scenarios that may be affected by economic conditions or government intervention. Constraints on the ability to escalate tolls over years represent a risk factor, even if the toll escalation strategy is well defined in the contract between the toll road operator and government. Normally, it is assumed that the toll rates will automatically grow every year with the GDP, CPI or other index (with some floor and ceiling thresholds). In reality, tolls may be frozen for several years and reconsidered only intermittently. A sensitivity test with tolls updated only every 10 years is recommended.
- Ramp-up period, especially for Greenfield projects and policies represents a risk factor that can significantly affect the revenue stream for the first years of the project that are the least discounted. It is recommended, depending on the project type, to establish a realistic ramp-up period, and then run a sensitivity test with a longer ramp-up period by at least two years.

The risk factors should first be identified and measured one at a time. For each factor, it is recommended that at least three possible scenarios are formulated (optimistic, average, and pessimistic) and probabilities are assigned to each of them. The optimistic and pessimistic scenarios do not have to be the best and worst possible scenarios. As a matter of fact, the absolutely worst and absolutely best scenarios are not extremely informative for the risk analysis since they are normally characterized by a very low probability. Instead, the optimistic and pessimistic scenarios should capture an average of the forecast region that yields approximately a half of the cumulative probability, i.e., 25th percentile and 75th percentile. With respect to the model parameters, the average scenario should correspond to the model calibrated for the base year with a good level of fidelity.

Depending on the number of risk factors and the model run time, two strategies can be applied:

- Run the model for each possible combination of the input factors and relate the results (T&R forecast) to the joint probability of the scenario occurring. The joint probability can be calculated as the product of assigned probabilities for each factor, assuming the factors are independent; otherwise a more complicated conditional calculation is needed. This is a theoretically preferable method, but it may result in an infeasible number of scenarios to test. For example, with five factors and three possible states for each of them, the total number of scenarios to test will be $3^5=243$.
- Run the model for several pivot combinations of the input factors and use auxiliary regression to interpolate the results for the other (non-modeled) combinations as described above. It is important for each particular factor state to appear at least once in the pivot combinations. For example, with the same example of 5 factors (denoted as A, B, C, D, and E) and 3 possible states for each of them (denoted as 1=optimistic, 2=average, 3=pessimistic), the total number of states to explore will be $5 \times 3=15$. All these states can be covered in three model runs with the following combinatorial logic. The first run would combine A1, B2, C3, D1, E2; the second run would combine A2, B3, C1, D2, E3; the third run would combine A3, B1, C2, D3, E1. These three runs would normally provide enough information about possible interactions between the risk factors versus the base scenario of A2, B2, C2, D2, E2. In order to provide more variation for the auxiliary regression the base run and three runs described above could be complemented by two extreme runs: optimistic (A1, B1, C1, D1, E1) and pessimistic (A3, B3, C3, D3, E3). These six combinations are normally enough to approximate all possible 243 combinations.

4.5 Adjustment of Travel Cost Inputs and Coefficients for Future Years

4.5.1 Model Input and Coefficient Consistency for Different Years

Long-term T&R forecasts for toll roads have brought to the fore from the general issue of the proper treatment of input cost variables (tolls, parking cost, vehicle operating cost, transit fare), and their associated model coefficients (used in the mode/route choice utilities) as related to the different years for which models are applied. There are three different general time points relevant to a travel demand model and its applications:

- Year of the survey implementation (estimation),
- Year of the last model calibration (base year), and
- Year of model application (future year that might be any year after the project opening).

A full consistency between cost related input data and corresponding coefficients across these years is required. Unfortunately, the current modeling practices tend to obscure this point and/or limit it to an accounting for the monetary inflation only, which is done by escalation/discounting of the cost variables along the time line, while the model coefficients are not changed from when the estimation was done. Very rarely considered is a systematic adjustment of the model parameters, like time and cost coefficients, as well as the resulting VOT (beyond the inflation factor). For example, model coefficients estimated in 1995 are used for base year 2005 and recalibration process frequently includes only adjustment of (mode choice) constants. Additional confusion is associated with using income-related variables or variables, where cost is scaled by income, along with linearly included time and cost. This section outlines a systematic approach to the adjustment of cost variables and associated model coefficients (if necessary).

4.5.2 Reasons for Adjustment

There are three major reasons that make an adjustment of cost variables and coefficients essential for future years:

- Inflation that makes dollars from different years incomparable. This factor alone is comparatively easy to incorporate through a proper scaling (escalation/discounting) of all cost inputs of the model including tolls. A commonly used inflation index is CPI and reasonable assumptions can normally be made for future years (2.5-4.0%). By using the inflation index, all input cost variables can be expressed in the base year dollars, which is the preferred practice when the model is run for several future years. Alternatively, if revenue forecasts are requested in expenditure years (to explicitly consider different toll rate escalation agreements), the preferred approach can be adjusted through appropriate (inverse) scaling of the cost coefficients in the model utility expressions.
- Real growth in income (above inflation) that affects the model coefficients that should reflect changes in travel behavior with respect to change in wealth. This effect is supposed to be equal to the observed cross-sectional differences in travel behavior across travelers from different

income groups and could have been fully captured if income had been fully included in the utility expressions for all cost variables (or better if income had been considered as an explicit budget constraint in line with the microeconomic theory). However, if the income variable is included as just an additional categorized (mode-specific) dummy along with time and cost coefficients, it means that income does not directly affect VOT (frequently the case with the existing models), and an adjustment of coefficients is needed. There are several commonly used indices for real income growth, like GDP per capita (net of CPI) and again assumptions can be made for future years (1.5-2.0%). Essentially, assumptions/scenarios for the regional (and even corridor-specific) income growth must be considered for Investment Grade Studies, long recognized in toll road industry as one of the important factors affecting future toll roads.
- Trends in behavior and associated policies (beyond inflation and real income growth). This is the most complicated factor and is not normally incorporated in travel models (including the most advanced activity-based models) despite a unanimous agreement among researches and practitioners that trends in behavior are quite strong and should be analyzed and eventually included in travel models. However, the larger and more general issue of "longitudinal" or time series analysis is not explored in this research. Instead, assumed that many observed trends (like VMT growth per capita or growing time pressures that result in higher VOT for the same income) can actually be fully or partially reduced to cross-sectional effects and captured by explanatory variables, as demonstrated with the advanced activity-based models. Also note that policies or projected trends related to fuel and vehicle taxation can be modeled explicitly through reasonable forecasting of the operating cost variables, as a exogenous inputs to the demand models.

If both the inflation rate and real income growth are negligible, the model would be perfectly transferable in time and would not require any adjustments of inputs or parameters. This is probably not true, however, for long-term forecasts associated with most T&R studies where inflation and income growth indices are compounded over 30-40 years into significant multipliers.

4.5.3 Approaches and Time Horizons for Adjustment

If it is assumed that all cost inputs are properly expressed in the base year dollars, then inflation is accounted for. Assume also that there is a standard structure of the mode/route choice utility expression for a certain trip purpose that includes some constants (might be income specific), time, and cost terms. If the cost variables are not scaled by income, then accounting for real growth in income will require adjustment of the model coefficients.

Arguably, the most reasonable and most conservative assumption is that the VOT (ratio of time to cost coefficient) would be growing proportionally to real income. With this assumption in mind, the following three adjustment strategies can be considered:

- Reduce the absolute value of cost coefficients inversely to the real income growth index. An equivalent formulation proposed by Adler and Dehghani and used for the Tampa Toll Model Application to I-4 Connector Study (unpublished draft memo) is based on freezing the model coefficients, but discounting the future toll values by the total index of inflation and income growth. The additional discounting by income growth is just applied to the cost itself rather than to the cost coefficient. The behavioral assumption behind this technique is that travelers with growing income would pay money easier but the sensitivity to time savings would be essentially the same. It means that they would appreciate 10 min savings in the same way today and 30 years from now, but would be ready to pay more for it in real dollars. This is probably not the most behaviorally appealing approach.
- Make the absolute value of time coefficient grow proportionately to the real income. Form the behavioral standpoint this assumes that travelers would appreciate 10 min savings in the future more than they do today. However, their sensitivity to one dollar increase in cost (in the base year dollars) would be the same regardless of the real income growth. This seems behaviorally more appealing compared to the first approach, but is still not fully convincing.
- Change both time and cost coefficients in different directions controlling for VOT change to be proportional to the real income growth. This looks like the most behaviorally appealing strategy and can be achieved by the following simple transformations: 1) reduce the absolute value of time coefficient inversely to the square root of real income growth, and 2) make the absolute value of cost coefficient grow proportionally to the square root of real income.

We will currently consider the third approach as the base for the subsequent discussion, although the first two approaches are also practical options. Additionally, the third approach can be refined by a more elaborate (weighted) split between the time and cost coefficient changes.

4.5.4 Adjustment Strategies for Different Types of Cost Variables

Even before consideration of future year forecasting, it is also important to adjust the model coefficients between the

Table 15. Adjustment strategies for different cost-related variables.

Variables / Inputs	Recommended adjustments to variable	Recommended adjustments to coefficient
Linearly included cost (toll, parking, operating cost, transit fare)	Express in the base year dollars (account for inflation)	Change inversely to the square root of real income growth
Travel time		Change proportionately to the square root of real income growth
VOT		Change proportionately to the real income growth
Cost variable relative to (zonal or individual) income		Change inversely to the square root of real income growth
Zonal or individual income as a separate linearly included variable	Express in the base year dollars (account for inflation)	
Zonal or individual income relative to the average regional income as a separate linearly included variable		Change inversely to the real income growth
Income group dummy, income-mode-specific constants, and/or segmentation based on absolute thresholds	Progress thresholds proportionally to the real income growth	
Income group dummy, income-mode-specific constants, and/or segmentation based on a fixed percentile	Recalculate percentiles based on the progressing of the underlying thresholds	

estimation and base year. Ideally, these adjustments should be made first and before model recalibration for the base year, taking into account that the input cost related variables will be in the base year dollars. This means that the model coefficients should be adjusted based on the combined effect of inflation and real income growth between the estimation and base year, more specifically:

- Reduce the absolute value of time coefficient inversely to the square root of real income growth.
- Make the absolute value of cost coefficient grow proportionally to the square route of real income, but also inversely proportional to the inflation index.

The subsequent adjustments for future years should be as described in the previous section assuming that all cost inputs are in the base year dollars.

The adjustment strategies for different types of variables are summarized in Table 15.

4.6 Evaluation of Pricing Projects

This section describes the role for cost-benefit analysis (CBA), and the requirements a comprehensive CBA places on the travel demand modeling of tolling. In order to make informed decisions, policy makers must be aware of the costs and benefits that stem from different projects and policies. Accordingly, analysts must be able to produce solid estimates of metrics relating to key evaluation criteria. This is particularly important and challenging for policies involving tolled roadway alternatives, since accurate revenue forecasts can be critical to investor support, and at the same time, traveler behavior is made more complex by the presence of tolls and different tolling plans. To this end, welfare economics can play a central role in identifying and quantifying policy benefits based on travel demand model outputs.

CBA is the most common approach for thorough project evaluation. Its primary advantage is that all costs and benefits accruing over a project's life are transformed into a single measure, facilitating the comparison of distinct policies. In order to perform a CBA, all project costs and benefits are generally converted into present-dollar values (Small 1999, FHWA 2003)]. Most costs are relatively easy to estimate, thanks to past project experiences (e.g., construction and operation expenditures), although significant cost overruns are common—particularly for large public transit projects (Flyvbjerg, et al. 2003). Benefits, however, are often less tangible, require application of travel demand models to obtain toll revenue and traffic forecasts, and involve the conversion of travel time savings, improved travel reliability, and other benefits into dollar values.

Once the dollar value of all project impacts is estimated, one or more discount rates are used to transform future cash flows into present values (Small and Verhoef 2007). The choice of such discount rates is critical and can have important implications for project viability, since many benefits and costs may not occur for several years after project completion. The U.S. Office of Management and Budget (OMB 2003)] specifies a real (as opposed to nominal) discount rate of 7% for all public investments and regulations, which approximates the marginal rate of return on private investments. However, OMB (2003) suggests that sensitivity analyses of the discount rate be performed. Selection of appropriate discount rates is discussed in more detail in a later section.

While CBA seeks to place every detail in an economic perspective, the assumption that everything can be measured in monetary terms and that all decision-makers agree on all values may not be entirely realistic (Small 1999). CBA methods should be viewed as a way to objectively inform policy making, but ultimately cannot totally replace expert judgment (Small 1999). Another issue is equity: can policies that help many individuals by a small amount, and hurt a few a great deal, really be supported simply on the basis that the aggregate benefits exceed aggregate costs? Small (1999) argues that if these two objections to CBA methods could be alleviated, policy making could be reduced to a simple mathematical exercise.

Despite its limitations, CBA offers a powerful tool for decision makers. The remainder of this section focuses on CBA as a means of connecting the decision-making process to predictive models for pricing applications. The next section describes methods of calculating user benefits and costs, net present values, and discount rates. The subsequent section illustrates different approaches for selecting toll rates. An example application, illustrating the key concepts and methods described in this chapter, is provided in Appendix A, Section A.6.

4.6.1 Benefit and Cost Calculation

Traveler Welfare

In theory and in practice, traveler benefits can be described using economic terms like consumer surplus, compensating variation, and equivalent variation. While each metric is a measure of something slightly different, the idea behind each is the same: a change in price or quality affects perceived demand and benefits accruing to those already purchasing a good (de Jong, et al. 2005). For instance, if the price of travel increases on one road and the demand for that road is a (decreasing) linear function of price, then the demand curve can be drawn as in Figure 17. Some travelers are willing to pay more than the actual price, and thus they use that route and receive a net benefit equal to the difference between the price they were willing to pay and the actual price. The sum of net

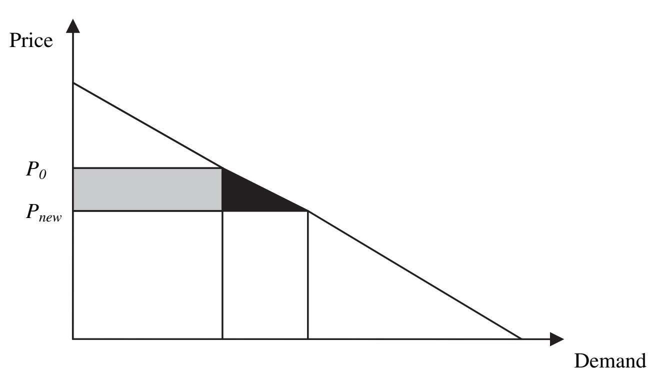

Figure 17. Linear demand curve.

benefits over all travelers is the consumer surplus (de Jong, et al. 2005, Small and Verhoef 2007). If the price increases, an overall decrease in consumer surplus results, whereas if the price falls an overall increase in consumer surplus results (this increase corresponds to the two shaded regions in the figure). This is the basis of welfare economics.

Generally, there is no simple, single relationship between travel demand and travel cost, but transportation modelers often turn to simplifying techniques in order to produce such estimates. One common technique is the Rule-of-Half (RoH) (de Jong, et al. 2005 and 2007, Small and Verhoef 2007). The basic concept behind the RoH is if a policy reduces the cost of travel, the change in consumer surplus can be estimated as the change in cost multiplied by the number of users under the old policy, plus one half of the change in the cost multiplied by the number of new users. The first part of this is the area shaded in gray in Figure 17 and the second part corresponds to the area shaded in black. More formally, for a single link, the RoH estimate for the change in consumer surplus can be computed as follows:

$$\Delta CS_i = (c_{i,0} - c_{i,1}) \times \left[v_{i,0} + \frac{1}{2}(v_{i,1} - v_{i,0}) \right] \qquad \text{(Equation 10)}$$

Here, $c_{i,0}$ and $c_{i,1}$ correspond to the cost on link *i* before and after the policy change, respectively, and $v_{i,0}$ and $v_{i,1}$ represent the traffic volumes on link *i* before and after the policy change. Since transportation policies typically affect travel times on routes, this formula can easily be extended to include changes in travel times by using the value of travel time (VOTT). Moreover, the total change in consumer surplus is simply the sum of changes across all links in the network. Thus, the more complete RoH formulation is as follows:

$$\Delta CS_{tot} = \sum_{i \in l} \Delta CS_i = \sum_{i \in l} \frac{1}{2}[(c_{i,0} - c_{i,1}) + VOT \times (tt_{i,0} - tt_{i,1})] \times (v_{i,0} + v_{i,1}) \qquad \text{(Equation 11)}$$

Here, $tt_{i,0}$ and $tt_{i,1}$ are the before and after travel times on link *i*, and $c_{i,0}$ and $c_{i,1}$ are the out-of-pocket costs of travel on link *i* before and after the policy change (where out-of-pocket costs can include vehicle operating costs, transit fares, and link tolls).

RoH holds exactly if the demand function is linear with price and cross-demand effects are also linear (i.e., choice alternatives are perfect substitutes). But if the demand function is more complex (as is generally the case in transport systems), the RoH only produces a rough estimate of the actual change in consumer surplus. In addition, the RoH provides the best estimates of consumer surplus for small price changes (Small and Verhoef 2007). Furthermore, RoH estimates cannot address situations where the set of alternatives changes, as when new routes/links are added and/or new modes are made available (de Jong, et al. 2007). When a new alternative is present, its demand under the base scenario can easily be assumed to be zero. However, to employ the RoH, one must know the price at which demand becomes zero (i.e., the point at which the demand curve crosses the axis). With a new alternative, this price is unknown, and the assumptions that need to be made about this price heavily affect the RoH estimates. So in some cases, such as a new tolled road where price changes can be dramatic or prior travel costs or times simply do not exist (since the new alternative did not exist), the RoH is inappropriate and other techniques will be needed.

Due to their behavioral basis and computational tractability, discrete choice models such as the multinomial logit (MNL) and nested logit (NL) have become mainstays in travel demand forecasting. With these models, link-level demand curves emerge from the application of these models, and such behavioral specifications allow analysts to more formally estimate changes in user benefits. Random utility maximization (RUM) is the basis for the logit model (McFadden 1978 and 1981), where the utility that individual i associates with alternative a is as follows:

$$U_{ia} = V_{ia} + \varepsilon_{ia} \qquad \text{(Equation 12)}$$

Here, V_{ia} is the systematic component of the utility, as parameterized by the analyst, and ε_{ia} is a random error term representing unobserved contributions. In the case of the MNL model, ε_{ia} values are independent and identically distributed (iid), following a Generalized Extreme Value (GEV) type 1 distribution.

For such a model, normalized Logsums of systematic utilities provide the basis for consumer surplus calculations. When divided by the marginal utility of money, the welfare change from one scenario to another can then be computed simply as logsum differences between any two scenarios (Small and Rosen 1981; Ben-Akiva and Lerman 1985; de Jong, et al. 2005; Zhao, et al. 2008)]. The calculation is as follows:

$$\Delta CS_i = \frac{1}{\gamma}\left[\ln\left(\sum_{a\in A}\exp\left(V_{ia}^{2}\right)\right) - \ln\left(\sum_{a\in A}\exp\left(V_{ia}^{1}\right)\right)\right] \qquad \text{(Equation 13)}$$

Here, γ denotes the marginal utility of money ($\gamma = -\frac{dV}{dc}$, where c = cost), A represents the set of alternatives, and superscripts 1 and 2 refer to before and after conditions, respectively. Of course, if the marginal utility of money is not constant (i.e., income effects are present), complications will arise and special methods are needed (Karlström 1998 and 2001, Franklin 2006, Small, et al. 2006)] beyond those described here. Furthermore, the error terms in the two scenarios (i.e., before and after) are assumed to be held constant—or can be independent. In other words, an individual's unobserved affinity for alternatives is assumed to be the same—or uncorrelated—across scenarios. Zhao et al. (2008) examined the consequences of intermediate levels of correlation and simulated welfare differences at the level of individuals, illustrating how highly variable group-level welfare changes can be.

While the MNL model is more common in practice, the nested logit has become quite popular as well, since it allows for certain useful forms of correlation across alternatives. With the NL logit model, the utility expression for individual i and alternative a can be formulated as a function of the systematic utility and multiple error terms.

$$U_{ia} = V_{ia} + \eta_{in} + \varepsilon_{ia}, \qquad a \in n \qquad \text{(Equation 14)}$$

Here, $_n$ denotes the set of alternatives that exhibit correlation. And the inclusive value, or expected maximum utility, Γ, for nest n can be formulated as follows:

$$\Gamma_{in} = \frac{1}{\mu_n}\ln\left[\sum_{a\in n}\exp(\mu_n V_{ia})\right] \qquad \text{(Equation 15)}$$

Here, μ_n is a scale parameter for nest n's error component. For a model such as this, the welfare change from one scenario to another can be written as follows:

$$\Delta CS_i = \frac{1}{\gamma}\left(\ln\left[\sum_{n\in N}\exp\left(\Gamma_{in}^{2}\right)\right] - \ln\left[\sum_{n\in N}\exp\left(\Gamma_{in}^{1}\right)\right]\right) \qquad \text{(Equation 16)}$$

Again, γ is the marginal utility of money, superscripts 1 and 2 refer to before and after conditions, and N is the set of all nests in the model specification.

This formulation can easily be extended to models with differential effects of users. For instance, if discrete variables in the model relate to travelers with different attributes, welfare can be computed individually for each traveler type. At an extreme, welfare may be computed for each traveler individually, which is important as region-wide microsimulation has become more widespread. Of course, the more individual traveler types that exist, more and more welfare calculations are required. But in comparison to the computational effort needed to run a complicated model of travel demand, the effort required for such welfare calculations is quite minimal.

The use of Logsums in welfare calculations allows for a nearly comprehensive measure of net traveler benefits (or losses, depending on the case) resulting from different transportation policies. While the idea of using Logsums for these purposes is nothing new [equations such as these were first developed by McFadden (1981) and Small and Rosen (1981)], their use in general highway or road pricing project evaluation applications has been somewhat limited [de Jong, et al. 2005 and 2007)]. De Jong, et al. (2005, 2007), suggest that there is no particular reason for this other than inertia in the field. In practice, Logsum measures are not much more difficult to compute than other measures (like the RoH). In reality, they are easier to compute than traffic flows and various other calculations that modelers undertake, and they provide an exact measure of user benefits (as long as logit assumptions hold). Thus, the Logsum would appear to be the most appropriate welfare measure for transportation projects that rely on logit models for traffic forecasting. Such an approach is the basis of current FTA guidance for the assessment of transit New Starts project cost-effectiveness.

It is also important to differentiate nested choice specifications from downward-conditional/sequential or un-nested/largely independent model specifications, which are not uncommon in practice. The NL model's nested choice sets imply that the Logsum term across lower-level choice alternatives appears in the utility function for upper-level choice alternatives, interacting with an inclusive value coefficient (Ben-Akiva and Lerman 1985). In some models, however, choices are not fully nested and lower-level choices are simply conditioned upon the outcomes of upper-level choices. For instance, many practitioners specify an MNL or gravity-based model for destination choice using simply drive-alone travel costs and model mode choice separately, conditioned on destination choice (recognizing all competing modes' travel costs for each zone pair). In such cases, the mode and destination choices are not fully integrated; yet it may be tempting to compute Logsum differences for both models and add them to estimate total consumer surplus. Unfortunately, this will generally result in a fair amount of double counting. If only one choice dimension exists (e.g., mode and destination choices are modeled together in a single multinomial specification), this is not an issue. But for accurate welfare calculations across multiple choice dimensions, Logsums only make sense when welfare calculations are consistent with random utility maximization across all choice dimensions (as opposed to less rigorous, sequential application).

Other Costs and Benefits

Just as user welfare predictions are an essential part of project evaluation, so are estimates of project costs: design, construction, operations and maintenance. Generally, cost estimates are simpler to develop than user welfare, since the former are based on straightforward engineering practices that apply to all road projects, while the latter depend on systems models of travel behavior in response to pricing and congestion. Nonetheless, costs remain very important. Typically, project costs for a new toll road include right-of-way acquisition, construction, maintenance, technology, and management costs and can average \$5 to 10 million per lane-mile (Litman 2006).

In addition, other benefits and costs exist, including changes in crash occurrence and crash severity, changes in noise levels, improvements in travel reliability, and emissions impacts. Such costs and benefits are not discussed at length here, mostly because they are generally relevant in the evaluation of most major transportation projects, not just toll roads. However, it may be useful to note that there often are perceived safety and environmental benefits for tolled roads (Perez and Sciara 2003). FHWA (2006) provides several tools for the analysis of these benefits and costs (including the Sketch Planning Analysis Spreadsheet Model (SPASM), the Surface Transportation Efficiency Analysis Model (STEAM), and IMPACTS. Small (1999), Litman (2006) and Small and Verhoef (2007) offer detailed discussions of these.

Net Present Value and Discount Rates

In any large-scale transportation project, a variety of costs and benefits accrue over a relatively long period of time. Performing a cost-benefit analysis requires converting these into a single measure, based on the present value of each. The present value for any future cash flow is computed by converting future values into an equivalent present value by discounting. As shown by Weisbrod and Weisbrod (1997) and FHWA (2003) the present value of any future cash flow can be found by multiplying the future value by a simple factor, *f*, based on the following formula:

$$f = \frac{1}{(1+d)^n} \qquad \text{(Equation 17)}$$

where n is the number of years in the future that the cost or benefit is observed and d is the discount rate.

By summing all present values, one obtains the Net Present Value (NPV) of an investment (FHWA 2003). If the NPV is positive, then the investment is one worth pursuing, but if it is negative, it is not. Alternatively, one may want to calculate the Benefit-Cost (B/C) Ratio as the sum of the present value of all project benefits divided by the sum of the present value of all project costs (FHWA 2003). A B/C ratio of 1.0 or greater is one worth pursuing. Of course, if alternative projects are to be compared using both measures, different results may follow, since a small project with very high B/C ratio may have a small NPV, while a large project with a lower B/C ratio may have a relatively high NPV. Of consequence is how benefits and costs are defined, since many costs can be defined as negative benefits (e.g., an increase in noise or crashes). If one defined everything in terms of benefits (some positive and some negative), the B/C ratio would be undefined (since costs would be zero). FHWA (2003) recommends that only an agency's initial investment be included as costs, while all other gains and losses be tallied as positive and negative benefits, respectively.

Another useful measure in project evaluation is the Internal Rate of Return (IRR), which measures the discount rate needed in order that a project's NPV equal zero (Blank and Tarquin 1989). In other words, it answers the question of what discount rate is needed to break even on an investment. Since large infrastructure projects generally have high up-front capital costs and benefits that accrue over many years, a higher IRR generally indicates a good investment, while a lower IRR indicates a poor investment.

Of course, since the present value of any future cash flow depends greatly on the chosen discount rate, so do the NPV and B/C ratio, and selection of an appropriate discount rate can be critical for large investments (Small 1999). However, it is not often clear what the appropriate discount rate should be for transportation projects. Small (1999) and Small and Verhoef (2007) consider two specific rates of particular importance:

- The first deals with the time preference of individuals in consuming goods, or the social rate of time preference. Small (1999) notes that this is often taken to be the real, after-tax interest rate one would expect to receive on a government bond of about 4%, though Boardman, et al. (2006) suggest a lower real, after-tax rate of 1.5%. (The real interest rate refers to the interest rate after accounting for inflation. This is in contrast to a nominal interest rate, which does not account for inflation.)
- The second deals with the rate a private investor may expect to receive on investments before taxes. Small and Verhoef (2007) refer to this as the marginal product of capital. Boardman, et al. (2006) recommend a real rate at 4.5%, while Small and Verhoef (2007) state that most analysts recommend substantially higher real rates closer to 9 or 10%.

Many times a single discount rate is chosen by weighting the rates described above ([Small 1999, Boardman, et al. 2006, Small and Verhoef 2007)]. Boardman, et al. (2006) suggest an appropriate weight for the social rate of time preference to be the amount of tax-based financing for the project and a weight equal to the amount of project financing coming from private investors for the marginal product of capital. Other times, however, an analyst may follow U.S. Office of Management and Budget (OMB 2003) guidelines, which recommend a real discount rate of 7%, reflecting OMB's estimate of the average before-tax rate of return to private capital, and which suggest a 30-year historical rate of social time preference of 3%. The OMB (2003) guidelines also suggest that sensitivity testing of the discount rate always be performed and the chosen discount rate clearly reported.

In general, there should be little distinction between choosing discount rates in a non-tolled road project versus a tolled one. However, in many tolled projects, project costs are leveraged against expected revenues. In such cases, the project endures added investment risk, and some literature (see Savvides 1994, Hacura, et al. 2001, Poole 2007) suggests that added risk requires the use of higher discount rates. However, the primary purpose of discounting is not to account for risk. OMB (2003) offers the following reasons for discounting future values: money invested today generally earns a positive real rate of return over time (i.e., the opportunity cost of capital) and people have a time preference for consumption (due to future uncertainties and the obvious nature of near-term gratification).

4.6.2 Criteria for Evaluation of Pricing Projects

Three main criteria are applied for evaluation of pricing projects:

- Economic welfare,
- Generated revenue, and
- Vehicular throughput.

In many cases, obtaining the maximum social welfare provides a solid basis for toll rate selection since it offers the greatest good for the average road user, although it does not address the costs borne by non-road users. On the other hand, privately operated toll road investors will seek to maximize profits. When tolls are under consideration for congestion relief, throughput maximization is often a focus. In general, these three selection criteria will result in very different toll levels.

If all roads in a network can be tolled, the maximization of welfare (as it relates to traveler delay) is actually rather straightforward. In this case, the optimal (congestion-based) tolls will equal the cost each traveler imposes on all other drivers (collectively) on the road or link in question. This is the marginal social cost of such travel and presumes fixed link capacities. (Of course, if one adds in the costs of tailpipe emissions, noise, and crashes, the formulation will differ.) In terms of maximizing social welfare, this is a first-best solution. However, there are many situations that make first-best tolls impractical. When considering tolls on a single road or subset of links, first-best tolls clearly do not apply, since first-best tolls generally require tolling on most (or all) links (at least in a welfare maximizing sense). In general, the marginal cost toll on a single road will be higher than the second-best toll. This is because marginal social cost tolls on all links represent a first-best equilibrium, where net social welfare is maximized. If the marginal social cost toll is applied on only a subset of links, leaving all others untolled, the traffic equilibrium will enjoy too few users on the tolled routes overall (relative to the second-best optimum traffic conditions).

Thus, if marginal cost pricing were used for a single road, non-optimal tolls would emerge (from a welfare standpoint). First-best tolls may be impractical for a variety of other reasons as well. For example, it may not be possible to differentiate tolls across users, it may be infeasible to adjust tolls dynamically, and tolls may be set before actual demand is realized (Small and Verhoef 2007). Nonetheless, it is still possible to attain a welfare-maximizing toll even when first-best conditions do not apply, and much research has been devoted to investigating these circumstances. Small and Verhoef (2007) examine how many issues can be handled in second-best environments.

Similar to the case of welfare maximization, maximizing revenues results in distinctions between first- and second-best solutions. For instance, very different tolls will arise if all roads in a network can be tolled, versus tolling a single road. In comparison to an objective of maximizing welfare, Verhoef, et al. (1996) show that revenue-maximizing tolls on all links can be much better (in terms of overall social welfare) than a revenue-maximizing toll on a single link, though it depends on the specific conditions of the network being analyzed. However, by definition, such tolls cannot produce greater welfare gains than when welfare itself is maximized.

Of course, throughput (flow) maximization focuses on maximizing traffic flow on the tolled road or along the tolled corridor over a period of time (e.g., over a 24-hour day). Interestingly, this criterion is the same as maximizing net social welfare when the focus is on a single road in isolation and both toll level and capacity of the roadway are chosen optimally (Verhoef 2007). In addition, Verhoef (2007) shows that the throughput maximizing toll level and capacity (assuming capacity is a decision variable as well) is identical to the second-best welfare maximizing toll and capacity (in the presence of unpriced complements and substitutes) when zero-profit/revenue-neutral capacity expansion is considered for a network. However, because of its reliance on traffic flow, this criterion can be quite difficult to apply in practice, since most forecasting models rely on static traffic assignment procedures, thus neglecting traffic queuing conditions. In such cases, flow is usually taken to be the same as demand, and maximizing demand on a link in a network can result in crippling congestion and dramatically reduced flows (in contrast to maximized flows) upstream of network bottlenecks. While application of this objective does not necessarily require DTA procedures, it will require models with some recognition of travel times and queuing so that reasonable estimates of toll road flows across peak times of day can be evaluated.

Overall, it may be best to first evaluate and seek some compromise across all three toll selection criteria, in order to produce a more robust tolling strategy, sensitive to competing stakeholders' interests. In general, selected toll levels should be compared to optimal toll estimates under each selection criteria. Ratios of anticipated welfare gains, revenues, and flows to maximized levels are key results meriting consideration and reporting.

An example application illustrating the differences between approaches is presented in Appendix A, Section A.6.

CHAPTER 5

Strategic Directions for Improvement

5.1 Coordination with the SHRP 2 C04 Project

The second Strategic Highway Research Program (SHRP 2) includes the closely related large-scale project C04 "Improving Our Understanding of How Highway Congestion and Pricing Affect Travel Demand." The principal researchers working on the NCHRP Project 08-57 are also leading the SHRP 2 C04 project and are able to closely coordinate these two projects as one coherent body of research.

The research agenda of the SHRP 2 C04 project demands both theoretical and applied perspectives; the research objectives can be encapsulated as follows:

- Theory and research: Develop mathematical descriptions of the full range of behavioral responses to congestion, travel time reliability, and pricing, by highway user types.
- Application for modeling: Provide guidance for the incorporation of these mathematical specifications into various demand-modeling systems in use (and under development), recognizing the complex nature of supply-side feedbacks (via traffic assignment and simulation techniques).

The SHRP 2 C04 work plan can be conceptualized as a series of three interconnected levels of behavioral rigor and practical application, along with varying levels of sophistication and associated inputs in each. Since supply-demand interactions are critical for congestion and pricing solutions (including network equilibrium), these offer a second dimension, as reflected in Figure 18.

Level 1 – Behavioral Foundations. The first level corresponds to behavioral models intended for a deep understanding and quantitative exploration of travel behavior. These include many kinds of variables, often explicitly controlled under stated-preference settings (e.g., preferred arrival time and schedule flexibility) and not all of which can be produced by most network/supply-side models (e.g., travel time reliability, particularly in the event of non-recurring incidents). These models seek to address the full range of possible short- and long-term responses, but also may focus on selective choice dimensions (for example, route and departure time choices, or home location choice).

Supply-side variables for such models can be based on observed and/or generated measures of congestion, reliability, and price (via, for example, an SP survey design). Multiple, repeated observations can be used for the direct derivation of reliability measures. Typically, there is no consideration of equilibrium at this stage, and the linkage between the demand and supply sides is essentially one-directional (as suggested in Figure 18).

Research associated with the widest possible range of behavioral responses is important for the construction of an "ideal" behavioral model – free of implementation constraints and capable of serving as the starting point for operational models, via some simplifying assumptions. In particular, the exploratory level of the research will consider dynamics—within-day, as well as day-to-day variations; different time frames for travel adjustments—short-term (which must also account for the with effect of information), medium-term and long-term, as well as the correspondence of the time scale to different choice dimensions. For example, in certain situations for short-term analysis, route choice might be the only relevant dimension, while departure time choice is equally important in day-to-day, medium- and long-term responses.

Level 2 – Advanced Operational. The second level relates to relatively advanced, yet operational, tour-based ABMs, integrated with state-of-the-art DTA models. These models allows for the incorporation of a wide range of possible short-term and long-term responses that are embedded in the choice hierarchy of the model structure. For example, a traveler's acquisition of an E-ZPass or transponder may be linked to his/her subsequent choice of payment type (at the lower level of the behavioral hierarchy). The integrity

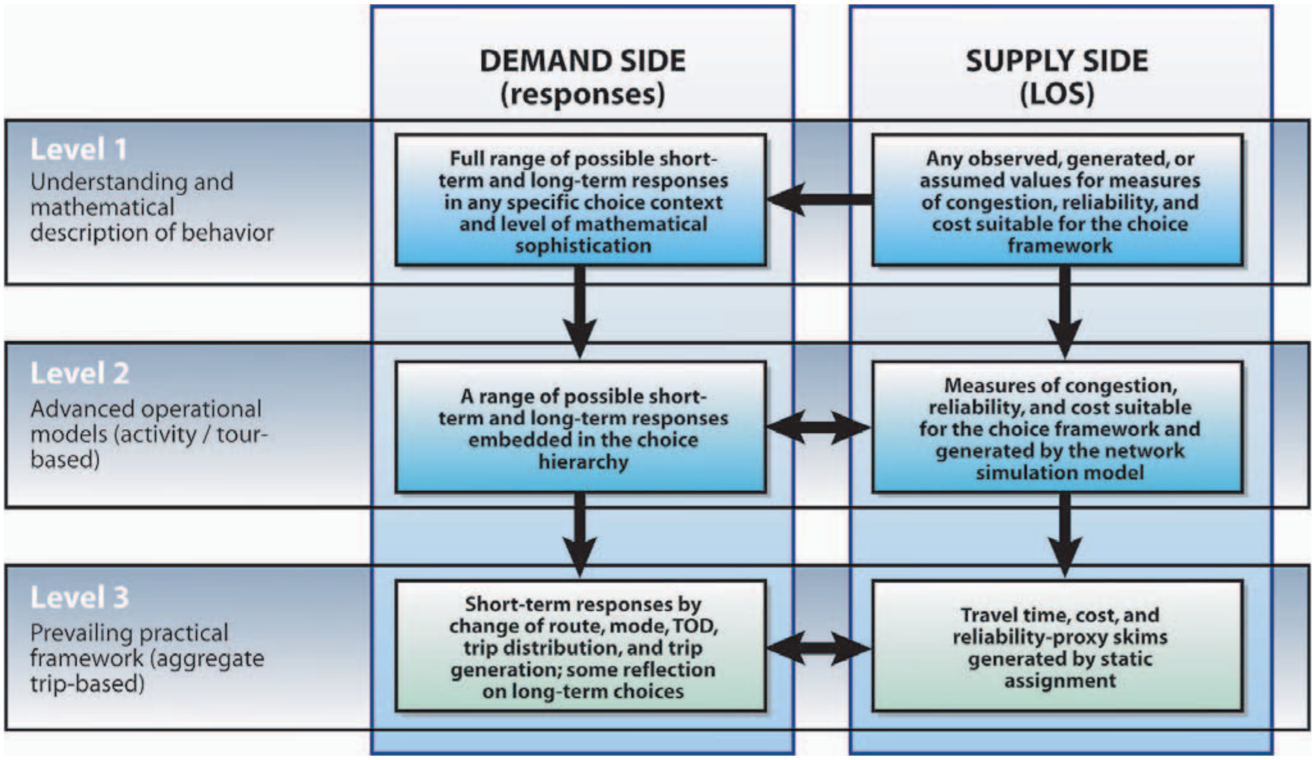

Figure 18. Levels of sophistication in SHRP 2 project.

of operational models requires that each and every choice dimension should be allocated a proper "slot" in the hierarchy, with upward and downward linkages to related choices. Operational/computing time requirements often limit the total number of choice dimensions and alternatives, but this source of restriction is lessening with time. Another relevant constraint in model application is that all measures of congestion, reliability, and price be compatible with the demand model's specification, and can be generated by the network simulation. Moreover, the demand and supply side should be integrated in an equilibrium setting, which imposes certain limitations on how variables like travel time variability are generated, since direct methods based on multiple observations of the same trip typically are generally infeasible in application. Consequently, the issue of generating operational proxies for travel time reliability is one of the focused points of the research.

Level 3 – Opportunities for Prevailing Practice. The third level relates to existing model systems used by most of MPOs and state DOTs, mostly in the form of aggregate 4-step trip-based models. Though rather restrictive in design, such models offer opportunities for meaningful and immediate contributions to the state of travel demand modeling practice. While conventional frameworks emphasize short-term responses to congestion and road pricing policies (including changes in route, mode, and, in some cases departure time choices, for each trip segment), road pricing can be addressed in trip distribution and even trip generation components through generalized cost impedances (or mode choice Logsums) and accessibility measures. The conventional model framework also allows for some indirect reflection of pricing on long-term choices, including workplace location and car ownership. A serious restriction of conventional models (also inherited by most current activity-based tour-based models) is that these rely on static assignment procedures. Static assignments generate only crude average travel time and cost variables, and reliability can be implemented only through simplified proxies.

The adopted approach for the SHRP 2 C04 research is predicated on pushing the boundary of network models in order to achieve greater behavioral sensitivity within the demand models, along with a natural integration of all system components. While several advanced models and methods presently exist, these require special data sets and longer run times, along with other use restrictions, many of which are purely technical. For example, DTA at a full regional scale is not yet realistic, although with ongoing computational advances and parallel processing opportunities a dramatic breakthrough may be anticipated within the next 5 to 10 years. The current constraints on practical applications also place limitations on the demand models in terms of possible number of choice dimensions and numerical realizations in the microsimulation process.

It is important to note that each level is not seen as independent or disconnected from the others, and we aim to establish a consistent and holistic conceptual framework, where simplified and pragmatic models can be derived from more advanced models, rather than re-invented (which is probably the current state of relationship between travel modeling theory and practice). In this way, we believe that the SHRP 2 C04 project can be successful and complement the NCHRP 8-57 project in a very important respect: bridging the gaps between theory and practice to the extent possible.

The major framework for the discussion of proposed models primarily considers the full regional model framework, although the facility/corridor level models are also considered. This also has an important consequence for the evaluation and analysis of the existing data sets to be selected to support the current research. It is based on the recognition that for a deep understanding and proper modeling of congestion and pricing impacts, we need a full framework, with chosen and non-chosen alternatives, available to both users and non-users, for which a full regional travel data set and model is needed. To provide these, it is essential to know at the model estimation stage, and to be able to generate at the application stage, the LOS variables for non-choices routes, modes, time-of-day periods, destinations, etc. This holistic framework is generally missing in simplified models and conventional travel surveys, which limits their utility in this research.

The work under research projects NCHRP 08-57 and SHRP 2 C04 was actively coordinated in order to enhance these related efforts and avoid duplication. Optimal coordination between these related projects, offering a maximization of product benefits, was achieved by definition of the common and exclusive areas as shown in Figure 19.

The primary focus of the NCHRP 08-57 project is on the improvement of the general decision-making framework for highway pricing (exclusive part addressed in Volume 1) with the recognition of applied forecasting models as important decision-supporting tools. The primary focus of the SHRP 2 C04 project is on development of mathematical descriptions of the full range of highway user behavioral responses to congestion, travel time reliability, and pricing (exclusive part) with the subsequent incorporation into various travel demand modeling systems. The NCHRP 08-57 project has a more practical and immediate focus, while the SHRP 2 C04 project relates to more fundamental research issues of travel behavior, expecting to extend our capabilities, including developing methods that can be absorbed in practice, both in the timeframe of the NCHRP 8-57 recommendations, as well as beyond.

Both projects have in common a framework of applied model systems. Ideally, this commonality should be fully coordinated in order to provide a link between the fundamentals of travel behavior established in SHRP 2 C04 and the practical aspects of decision-making on pricing substantiated in NCHRP 08-57. In this sense, the two projects form a valuable and coherent body of research with a clear practical outcome.

Taking into account the common research part, several practical aspects of coordination between the NCHRP 08-57 and SHRP 2 C04 can be outlined this way.

Both projects are based on the same vision of an advanced but ultimately practically implementable travel model for

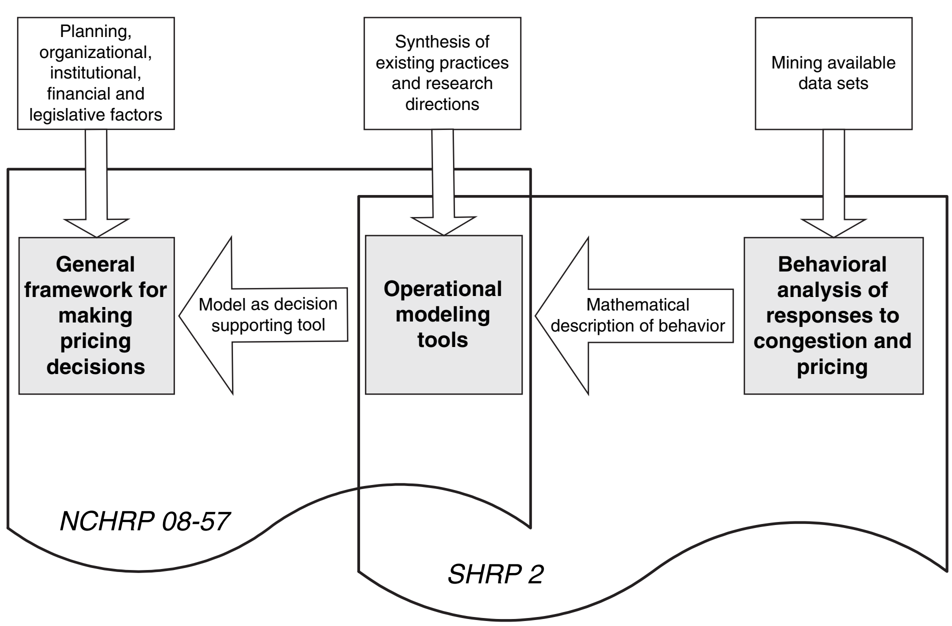

Figure 19. Common and exclusive areas of NCHRP 08-57 and SHRP 2 C04.

highway pricing studies. This model should include a well-defined set of features including synthesis of the best practices (corresponds to the short-term improvements described in Chapter 4) and the most important and realistically projected breakthroughs (long-term improvements classified in the sub-section that follows).

The conceptual model structure that would serve as the core for both research projects will be outlined in two versions that correspond to two existing conventional modeling approaches:

- Aggregate trip-based 4-step models. Although most of the new large-scale regional models developed/being developed after year 2000 have already been activity-based, these models still constitute a majority of the applied models on the market. It should be recognized, however, that while the conventional model structure has many limitations, it does allow for numerous improvements, especially for lower-level choice dimensions (route and mode). Using the SHRP 2 project terminology introduced in Figure 15, only the third level of sophistication can be incorporated in this model structure.
- Activity-based tour-based microsimulation models. These models are now rapidly becoming accepted in practice in major metropolitan regions, including regions undergoing comprehensive pricing studies (San Francisco, New York, Denver, Atlanta, Seattle, Los Angeles). This model structure offers numerous additional opportunities that correspond to the second level of sophistication. Among them are advantages of individual microsimulation (practically any level of deterministic and/or probabilistic segmentation of users), as well as a better framework for capturing upper-level choices (daily activity patterns and schedules, transponder acquisition, car ownership, etc.).

The conceptual model structure can have many specific technical details depending on the pricing project (as discussed in Chapter 4). In practical terms, and taking into account that most of the comprehensive pricing studies consider multiple project alternatives, it makes sense to make an effort to prepare a modeling tool that could serve a wide range of pricing studies rather than a single predetermined study. From this point of view, two principal types of studies can be distinguished:

- Area/Cordon and other global regional pricing studies where multiple facilities are considered in a certain subarea. For these studies, mode choice, time-of-day choice, as well as upper-level (trip-frequency related) choices are in the focus. These pricing forms are frequently non-trip-based, defined instead as a daily charge or access fee (for multiple trips), which makes activity-based models especially appealing for these studies, since the principal limitations of 4-step model structure have become an obstacle for the analysis.
- Intercity and corridor-specific pricing studies where a single facility is considered with possible multiple cross-section design, access, vehicle eligibility, and lane management/pricing form alternatives, including dynamic (state-dependent) pricing. For these studies, the route choice dimension, specifically a binary choice between managed lanes and general-purpose lanes, represents the core issue. Vehicle occupancy and time-of-day choice dimensions are also important if the corresponding pricing forms (HOV/HOT lanes, congestion pricing) are the focus of the study. Mode choice might be a secondary issue, if a strong transit alternative (or integration of BRT in the managed lane) is considered. Upper-level choices that relate to trip frequency are normally less affected. In practical terms, and taking into account that the pricing form itself is a per-trip charge, it makes trip-based models competitive for these projects.

Both projects, NCHRP 08-57 and SHRP 2 C04, are in agreement regarding the major breakthrough directions that can form the long-term model improvement program for highway pricing studies. In the following section, these directions are identified and the possible approaches that will be further explored in the framework of the SHRP 2 C04 project area are outlined.

5.2 Breakthrough Directions on the Demand Side

The most promising directions for the improvement of road pricing models are shown to be associated with advanced ABMs and advanced network simulation tools (DTA and micro-simulation). Certain significant improvements, however, can also be incorporated within the conventional 4-step modeling framework. More specifically, breakthroughs in the following critical areas are needed to provide for the incorporation of improved model features and components essential for a full and accurate analysis of road pricing projects.

- Heterogeneity of road users with respect to their VOT and willingness to pay. This requires a consistent segmentation throughout all of the demand modeling and network simulation procedures to ensure compatibility of implied VOTs. In addition to an explicit segmentation, random coefficient choice models represent a promising tool for capturing heterogeneity.
- Proper incorporation of toll road choice in the general hierarchy of travel choices in the modeling system. Additional travel dimensions (such as whether to pay a toll,

car occupancy, and payment type/technology), and associated choice models should be properly integrated with the other sub-models in the model system.

- Accounting for reliability of travel time associated with toll roads. The incorporation of travel time reliability in applied models requires quantitative measures that could be modeled on both demand and supply sides.
- More comprehensive modeling of time-of-day choice based on the analysis of all constraints associated with changing individual daily schedules.
- More comprehensive modeling of car occupancy related decisions, including differences in carpool types (planned intra-household, planned inter-household, and casual) and associated VOT impacts.
- More advanced traffic simulation procedures such as DTA and microsimulation, and better ways to integrate them with travel demand models.

5.2.1 Approaches to Accounting for Heterogeneity of Highway Users

Heterogeneity of road users with respect to their willingness to pay for travel time savings (expressed VOT) and higher reliability (value of reliability or VOR) has long been a focus of research and practice of travel modelers. Conceptually, VOT has two components: lost participation in activities, and the undesirability of travel per se. Most logit mode choice models use simple representations and assumptions about VOT, typically a single value. Two primary means of addressing the heterogeneity of travelers' values of time are:

- Use of segmentation, in which the time-of-day, mode choice, and assignment procedures (and potentially other components) are all fully consistent, and in which a single average VOT is assumed within each segment. This approach is commonly used in practice.
- Application of probabilistic distributions of VOT instead of single deterministic values, which similarly demands consistent treatment across the time-of-day, mode choice, and assignment procedures. This approach provides far greater behavioral fidelity, but has rarely been used in travel demand forecasting practice.

Explicit segmentation by VOT has been applied in many mode choice and toll road choice models and has also been incorporated in trip distribution and destination choice models through the use of mode choice Logsums as impedance measures. It is uncommon, however, to carry this segmentation through the trip assignment stage, since this leads to a proliferation of trip tables and an accompanying increase in the amount of time consumed by the assignment process.

Additional segmentation also tends to dampen price sensitivity, since a typical sigmoid response curve, like the logit model, has the steepest (most elastic) part in the middle, while the ends are quite flat. Stated otherwise, aggregation across different segments tends to yield average utilities in the middle of the curve, and consequently to overestimate price sensitivity. Explicit segmentation can be an effective way to improve the accuracy of the model, while keeping to a simple analytical form.

There are, however, drawbacks to the use of segmentation. First, the number of segments may quickly become infeasible if the segmentation is applied across all dimensions simultaneously. Secondly, and more importantly, even the most elaborate segmentation cannot include all possible situational variables that create significant additional variation of VOT within each ideally homogeneous segment. For example, a worker may exhibit a different willingness to pay when they have only a short time to get to and participate in an important business meeting than the average willingness to pay of this worker. In addition, another source of VOT variation is that a significant number of workers may have full or partial reimbursement of their travel costs by their employer or client.

The limitations on segmentation make the probabilistic approach to VOT more attractive. Recent theoretical advances in random coefficients (or mixed) logit model estimation make it a plausible option for modeling road-pricing choices. The random coefficient logit form directly represents the situation where the values of time and underlying utility coefficients for travel time and cost are assumed to be randomly distributed, rather than deterministic. As a result, the need for segmentation is reduced. Random coefficient estimation capabilities are already available in some commercial estimation software such as ALOGIT and LIMDEP.

However, there are also significant complications associated with the estimation and implementation of random coefficient logit models. Specification of these models, and analysis of model estimates, requires considerably more effort than is required for traditional closed forms. In addition, the implementation of these models is also different than application of standard logit models and requires additional effort. While the random coefficient models might provide greater behavioral realism, use of this leading edge approach will require significantly more effort and an increase in the commitment of resources.

In many regional models, the segmentation used in travel demand choice models, such as time-of-day and mode choice, is frequently inconsistent or even contradictory to the assignment procedures used. For example, travel models are normally segmented by purpose while vehicle classes in assignment relate to occupancy only. The need to evaluate road pricing policies presents additional complications and may exacerbate VOT inconsistency issues.

The objective behind the optimal segmentation structure is to treat VOT consistently across all choices, while avoiding an excessive proliferation of travel segments and vehicle classes. As noted earlier, additional segmentation of the behavioral choice models in the activity-based framework is less onerous than in conventional 4-step models, but complicating issues associated with the multiplication of vehicle classes in the assignment procedure are shared by both activity-based and conventional models.

The choice of the number of vehicle occupancy categories in the assignment procedure should be based on the expected nature of HOV/pricing policies to be modeled. When significant projects with specific HOV3+ lanes or pricing policies are expected, it generally would require explicit segmentation of trip tables by SOV, HOV2, and HOV3+ classes. Otherwise, collapsing of all HOV categories together can be adopted. Even in the absence of specific traffic restrictions or pricing policies, however, a better segmentation by vehicle occupancy can be beneficial to capture differential VOT.

In order to avoid a proliferation of segments in the assignment step, it may be possible to combine those segments or trip tables with similar VOT. This aggregation should also consider additional vehicle classes associated with non-passenger travel such as heavy and light commercial trucks. A final decision about the aggregation of demand or trip tables can only be made after statistical estimation of all VOT and occupancy-related coefficients.

It should be understood, however, that any conceivable segmentation of VOT by trip purpose, income group, time of day and household/person characteristics will not entirely solve the problem since there is a great deal of situational variability within each segment (and even for the same person during the course of the day). Typical forecasting models, such as logit and probit choice models, assume a normal or bell-shaped distribution around the estimated parameters. If the actual shape of the distribution is not bell-shaped (symmetric), the forecasts are biased, particularly at higher price levels.

There are several practical ways to statistically estimate VOT distributions. Probably the simplest approach is based on SP surveys with multiple observations (experiments) for each person and trip. These surveys can be used to obtain individual-level estimates that can be then used to construct the distribution shape. More complex techniques include the estimation of mixed (random coefficients) logit model and latent class models. Both approaches have strengths and weaknesses. They can also be effectively combined.

While significant progress has been made in estimation methods and software (that essentially make estimation of a probabilistic VOT available), a bigger challenge is associated with the operational incorporation of VOT distributions in applied travel models. The following possible ways to incorporate distributed VOT have been identified:

- Use the VOT distribution for definition of VOT segments and then employ multi-class assignments and segmented models with average VOT estimated for each segment.
- Employ a microsimulation technique that is already embedded in ABMs, where each person trip is assigned a specific VOT from the distribution. These (probabilistic) VOT values are saved for each trip and then serve as an important parameter when individual trips are converted into segmented trip tables for a conventional static assignment, or even as single agent attributes when linked to a possible DTA or traffic microsimulation method.

In the two following sub-sections, we discuss technical details of deterministic travel segmentation that accounts for heterogeneity that is observed, and probabilistic segmentation through continuous distributions of model parameters that accounts for unobserved heterogeneity.

5.2.2 Travel Segmentation (Observed Heterogeneity)

This sub-section is based on the recent synthesis and interim findings from the SHRP 2 C04 project. Significant progress has been made in recent years to better understand how motorists value their time while driving. The two key attributes to consider when identifying and segmenting travel markets are VOT and VOR.

Another long-term gap in understanding and modeling congestion and pricing is associated with poor segmentation of population and travel. It has generally been recognized by both researchers and practitioners that the profession should move away from crude average VOT estimates (and other related behavioral parameters) obtained from aggregate analyses (Hensher and Goodwin 2005).

There are a significant number of research works providing insights into behavioral mechanisms and statistical evidence on heterogeneity of highway users across different dimensions. Although income and trip purpose have been traditionally used in many models as the main factors that determine VOT, VOT is also a function of many other variables in reality. In fact, in many cases, income and trip purpose might not even be the most important factors, especially when situational factors and time pressure come into play Spear (2005), Vovsha, et al. (2005).

A variety of traveler and trip type dimensions are important. The main groups are:

- Socio-economic segments of population. These characteristics are exogenous to all activity and travel choices that

are modeled in the system. The corresponding dimensions can always be applied for any model either for full segmentation or as variables in the utility function.
- Segmentation of activities. These characteristics are exogenous to travel choices but endogenous to activity-related choices. Thus, in the model system, it should be ensured that the corresponding activity choices are modeled prior to the given model; otherwise they cannot be used for model segmentation.
- Travel segmentation. These characteristics are endogenous to the system of travel choices. In the mode estimation they have to be carefully related to the model structure to ensure that all dimensions/variables used in each particular model have been modeled prior in the model chain.

The socio-economic segmentation of the traveler population should address the following characteristics:

- Income, age, and gender. A higher income is normally associated with higher VOT (Brownstone and Small 2005, Dehghani, et al. 2003), along with middle-age female status (Mastako 2003, Travel Demand Model Development for T&R Studies in the Montreal Region 2003).
- Worker status. Employed persons (even when traveling for non-work purposes) are expected to exhibit a higher VOT compared to non-workers because of the tighter time constraints (PB Consult 2005).
- Household size and composition. Larger households, with children, are more likely to carpool and take advantage of managed lanes (Stockton, et al. 2000; Vovsha, et al. 2003).

The segmentation of activities may best address the following list:

- Travel purpose. Work trips and business-related trips normally are associated with higher VOT as compared to non-work purposes (Dehghani, et al. 2003, NYMTC Transportation Model and Data Initiative 2004, Travel Demand Model Development for T&R Studies in the Montreal Region 2003). Airport trips are another frequently cited trip purpose with relatively high VOT (Spear 2005). The list of special trip purposes with high VOT might also include escorting passengers, visiting place of worship, medical appointment, and other fixed-schedule events (theater, sport event, etc). A deeper understanding of the underlying mechanisms for such behavior is valuable, including combinations of schedule inflexibility, low trip frequency, and situational time pressure.
- Day of week: weekday versus weekend. There is statistical evidence that VOT for the same travel purpose, income group, and travel party size on weekends is systematically lower than on weekdays, including some examples of positive travel utility associated with long discretionary trips (Stefan, et al. 2007). It is yet to be determined if these differences can be explained by situational variables or if there is an inherent weekend type of behavior different from the regular weekday behavior. In any case, whether directly or as a proxy for situational time pressure, it would be useful to test the differences statistically. The positive utility of travel manifests itself most notably in choice of distant destinations for discretionary activities on weekends (sometimes with a sightseeing component). This issue should be explored, however, to determine if this is actually correlated with tolerance to congestion delays and unwillingness to pay tolls.
- Activity/schedule flexibility. Fixed-schedule activities are normally associated with higher VOT for trips to activity because of the associated penalty of being late; this has manifested itself in many previous research works when VOT for morning commute proved to be higher compared to the evening commute. Probably a similar mechanism (high penalty of being late) creates higher VOT estimates, as it does for trips to airports reported. Schedule flexibility will also be an important factor for non-work activities; a trip to a theater might exhibit a high VOT while shopping might be more flexible.
- Situational context: time pressure versus flexible time. This is recognized as probably the single most important factor determining VOT that has yet proven difficult to measure and estimate explicitly, as well as to include in applied models (Spear 2005, Vovsha, et al. 2005). There is evidence that even a low-income person would probably be willing to pay a lot for travel time savings if he/she is in danger of being late to a job interview or is escorting a sick child. This factor is correlated with the degree of flexibility in the activity schedule (inflexible activities, trips to airport, fixed schedules, and appointments will be the activities most associated with time pressure), but does not duplicate it. It might be expected that even for a high income person traveling to the airport, the VOT might not be that high if this person has a 4-hour buffer before the departure time. With ABMs we could use the number of trips/activities implemented by the person in the course of a day, as well as the associated time window available for each trip/activity as an instrumental proxy for time pressure.

The segmentation of travel characteristics may best address the following list:

- **Trip frequency.** More regular trips, and their associated costs, may receive more (or less) formal consideration than those that occur infrequently. For example, a $1.50 for auto trip to work may be perceived as $3.00 per day (assuming a symmetric toll) and $60 per month, thus receiving special consideration. This perceptional mechanism is likely very different for infrequent and irregular trips where the toll is perceived as a one-time payment. For intercity trips, travelers' recognition of the return trip is not obvious, since it may occur on a different day.

- **Time-of-day.** Prior research confirms that AM and PM peak periods are generally associated with a higher VOT, as compared to off-peak periods. In particular, it seems this may be the result of more commute trips in these periods and/or higher congestion levels. In addition to that, AM travelers (mostly commuters) are more sensitive to travel time and reliability than PM commuters (who mostly are returning home) (Brownstone, et al. 2003). However, few have explored how these phenomena relate to schedule flexibility, or how time-of-day factors impact VOT for non-work trips. One may reasonably speculate that a model that explicitly accounts for reliability and schedule constraints would not need an additional differentiation by time-of-day periods.
- **Vehicle occupancy and travel party composition.** While a higher occupancy normally is associated with higher VOT (though not necessarily in proportion to party size), it is less clear how travel party composition (for example, a mother traveling with children, rather than household heads traveling together) affects a party's VOT.
- **Trip length or distance.** Interesting concave functions have been estimated for commuters' VOT (Steimetz and Brownstone 2005). For short distances, VOT is comparatively low, since travel time is insignificant and delays are tolerable; for trip distances around 30 miles, VOT reaches a maximum. However, for longer commutes, VOT decreases again since they presumably have chosen residential and work places fully understanding that long-distance commuting will be necessary. Additionally, in the context of mode choice, strong distance-related positive biases have been found for rail modes in the presence of congestion [as a manifestation of reliability (NYMTC 2004)] and carpools (since carpools are associated with extra formation time).
- **Toll payment method.** This is an important additional dimension that has not yet been fully explored. Changes in toll policies implemented by the Port Authority of New York and New Jersey convincingly showed that the introduction of E-Z Pass attracted a significant new wave of users despite a relatively small discount (Evaluation Study of PANYNJ Time of Day Pricing Initiative 2005). In the same way researchers regard perceived time versus actual time differently, they should also probably consider perceived value of money in the context of pricing. Bulk discounts and other non-direct pricing forms should be modeled at the daily pattern level rather than trip level. It is also important to understand congestion impacts on entire daily patterns, rather than by single trips, including an analysis of daily time budgets and trade-offs made to overcome congestion (including work from home, compressed workweeks, compressed shopping, moving activities to weekends, etc.).
- **Congestion level** that has an impact on travelers' perception of time. There is a growing body of evidence that VOT (and willingness to pay) depends on the level of congestion (Wardman, et al. 2009, NCHRP Report 431 1999). In particular, a mark-up value of 2.0–2.5 was reported when VOT in highly congested conditions was compared to free-flow conditions. The concept of perceived highway time differentiated by congestion levels is discussed in Section 5.2.4 as one of the practical ways to account for the effects of reliability on demand. Congestion levels are correlated with time-of-day periods though there are certain specifics of AM and PM periods beyond just the level of congestion. For example, most of the commute trips in AM period are outbound trips to work that are characterized by a constrained schedule. Most of the trips in PM period (as well as in off-peak period) are more flexible in terms of departure and arrival time.

In model formulation, estimation, and application, it is crucial to follow a conceptual model system design and to obey consistent rules of application of those variables that are exogenous to the current model. For example, if TOD model is placed after mode and occupancy choice, the mode and occupancy can be used as the TOD model segmentation. However, time of day in this case cannot be used for segmentation of the mode and occupancy choice models. If the order of models is reversed (TOD choice before mode & occupancy choice) the segmentation restrictions would also be reversed. When different models are estimated, it is essential to keep a conceptual model system (or at least a holistic framework) in mind to make these models compatible and avoid endogeneity-exogeneity conflicts.

It should be understood that these dimensions cannot be simultaneously included in operational models, as explicit segments in a Cartesian combination. With a 4-step model framework, this would immediately result in an unfeasibly large number of trip tables. The ABM framework is more flexible, and, theoretically, can accommodate any number of segments. They are, however, still rather limited in practical terms by the survey sample size (normally several thousands of individuals) that quickly wears thin for multidimensional segments. There are, however, other ways to constructively address segmentation in operational models that we can consider. These include flexible choice structures with parameterized probabilistic distribution for parameters of interest (for example, VOT), as well as aggregation of segments by VOT for assignment and other model components that are especially sensitive to dimensionality.

It should also be understood that VOT represents only one possible behavioral parameter, and that it is essentially a derived one. In most model specifications and corresponding estimation schemes, VOT is not directly estimated, but rather derived either as the ratio of the time coefficient to cost coefficient (in simple linear models as specified in Section 2.2 as the marginal rate of substitution between time and cost (in a general case). Thus, very different behaviors can be associated with the same VOT. For example, both time and cost coefficients can be doubled which leaves the VOT unchanged; however, this would be a manifestation of very different estimated responses to congestion and pricing. Large coefficients will make the model more sensitive to any network improvement or change in costs, while smaller coefficients will make it less sensitive.

One of the most detailed VOT segmentation analyses of the type described in the previous sub-section was carried out for the Netherlands National Value of Time study (Bradley and Gunn 1991), which used 10 simultaneous segmentation variables. A similar approach was used for national studies in the United Kingdom and Sweden.

All else being equal, a more detailed segmentation typically tends to dampen the overall price sensitivity across the population, since a typical sigmoid response curve, like the logit model, has the steepest (most elastic) part in the middle, while the ends are quite flat, and market segmentation tends to move distinct groups away from the middle.

Travel market segmentation is principally different with AB models implemented in a microsimulation fashion compared to aggregate 4-step models. Practically speaking, AB models using microsimulation methods do not have limits in terms of segmentation. They can incorporate all of the dimensions listed, and the only constraint that should be taken into account is the ability to estimate VOT (i.e., time and cost coefficients) for each segment with the available data. Essentially, the model estimation results will dictate the segmentation in the model application. A population synthesis procedure embedded in an ABM provides a list of household and persons with all variables available in PUMS, ACS, or other source that are used as a seed micro-sample.

Travel segmentation with a 4-step model is constrained in the model application by the set of household and person variables available in the population distribution and subsequently by the number of trip tables that would be feasible in the trip distribution and mode choice models. This constraint, though technical in nature, severely limits the segmentation that actually can be applied in a 4-step modeling process. For example, let's consider a maximum feasible number of segments as 100. This limit will be quickly reached with the following Cartesian combination:

- 4 trip purposes (home-based work, home-based school, home-based other, non-home-based),
- 3 income groups (low, medium, high).
- 4 car ownership groups (zero car, cars fewer than workers, cars equal to workers, cars greater than workers), and
- 2 time-of-day periods (peak, off-peak).

There is practically no way to include such variables as age, gender, or person status in a 4-step model on top of the basic variables listed above. It is also theoretically impossible to incorporate situational variables or variables that relate to schedule constraints. There are several limited reserves where the segmentation of a 4-step model can be improved. One of them represents a compromise between the segmentation applied in trip distribution versus segmentation applied in mode choice. Trip distribution could be applied with a limited number of segments (say, 96 segments resulted from the variables listed above, or even less). Then, for the mode choice stage, additional segmentation could be applied on the population side (relevant for home-based trips only) that could include gender, person type, or any other variable. The additional segmentation relates only to the trip origin zones and does not require a separate trip distribution for each segment. In mode choice application, it is assumed that the origin zone proportions for the additional segments are uniform across all destinations. Thus, each trip-distribution segment can be quickly split into sub-segments before mode choice.

Another option is to specifically single out travel segments that are characterized by a very high willingness to pay (trips to airports, business trips during the day, etc.) and model them separately with identification of the strongest trip generators on an individual basis.

5.2.3 Probabilistic Distribution of VOT and VOR (Unobserved Heterogeneity)

Explicit segmentation can be an effective way to improve the model while keeping it in a simple analytical form. However, there are several strong arguments in favor of probabilistic treatment of VOT instead of or in addition to explicit segmentation.

First, the number of segments quickly becomes infeasible if segmentation is applied across all dimensions simultaneously. This is especially apparent with conventional, 4-step modeling techniques, which require replication of full OD tables for each combination of segmentation variables (or at least for each distinct value of VOT) for static network traffic assignment. Such detailed travel market segmentation can be much more effectively incorporated in the ABM framework, where each simulated individual and trip can effectively be modeled as having its own levels of VOT (and VOR). The same may be the case for the newest generation of DTA and traffic microsimulation models.

Secondly, even if maximum possible segmentation is implemented, a travel model cannot include all possible situational variables that create significant additional variation of VOT within each (seemingly homogeneous) segment. For example, when driving for an important business meeting with very little time available to reach his or her destination, a worker can exhibit a higher willingness to pay than the average for the same person. The same can be said about a mother driving home to attend to a sick child. Also, a not insignificant (but generally unknown) percentage of commuters may have a full or partial reimbursement of their travel cost by the employer. These sources of additional variation are poorly captured in travel surveys, if at all. This means that the probabilistic approach of explicitly estimating VOT distributions is bound to be more realistic and more accurate.

For example, a recent SP study of users of the new MnPASS HOT lane facility (Zmud, et al. 2007), used a survey method to explicitly estimate each respondent's individual VOT, and found much more variation across the sample than could be captured through observable segmentation variables alone. The observed distribution resembled the log-normal distribution Ben-Akiva, et al. (1993) pioneered an econometric approach to directly estimate the parameters of such log-normal VOT distributions from typical SP and RP data sets. This research was done as part of a study for Cofiroute of proposed tolls on the French national motorways, and the resulting distributed models were applied using a customized multi-user-class static assignment routine. Now, 15 years later, there are a variety of approaches and software available for estimating and applying such models.

Random Coefficients (mixed) logit model estimation (already available in commercial software like ALOGIT or LIMDEP or BIOGEME) has become a practical tool for modeling choices related to road pricing. The random coefficient logit form directly corresponds to the situation where VOT and underlying utility coefficients for travel time and cost are assumed to be randomly distributed, rather than deterministic (taking single mean values).

Since mixed logit requires (computationally intensive) numeric integration for calculation of the choice probabilities, this is a certain problem for applying it in an aggregate 4-step model that predicts and accumulates fractional probabilities. This problem can be overcome by effective numeric integration. For ABMs based on microsimulation, the situation is even simpler, since there is no need to calculate choice probabilities. Random utilities can be directly simulated from their distributions and then the alternative with the maximum utility would be chosen. This technique eliminates the disadvantages of non-closed form choice models (like probit or mixed logit) and makes them just as convenient as standard logit models in application. In the current research, special attention will be given to the incorporation of mixed logit models (with distributed VOT and VOR) in both microsimulation and aggregate model frameworks. Note that mixed logit models can also incorporate systematic market segmentation, using interaction terms to parameterize (or segment) the distribution according to observed variables.

Small, et al. (2005) provide an interesting example of the estimation of a binary model of choice between a toll and a non-toll route that accounts for the heterogeneity of travelers with respect to VOT (as well as VOR). In this formulation, the non-toll route served as the reference alternative with zero utility while the toll route utility included a constant term, various transformations of cost and time differences between the routes, as well as a measure of travel time unreliability. The constant term was specified as a random parameter dependent on such variables as gender, age, and household size. The cost and time coefficients were specified as random parameters interacting with income and trip distance. In this way, the model was able to capture a significant observed heterogeneity (through variables that differentiate the distribution of constant term and time/cost coefficients), as well as residual unobserved heterogeneity through the specification of the random component of the constant, and time/cost coefficients. The utility structure of the model of this type can be written in the following general way:

$$U_{sn} = \alpha_{sn} + \sum_{k} \beta_{snk} x_{nk} + \varepsilon_n \quad \text{(Equation 18)}$$

where

s = segments by income, travel purpose, person type, etc,
n = observations (instances of choice),
k = independent variables like travel time and cost,
x_{nk} = values of the independent variables for each observation,
α_s = constant that is assumed to be a random,
β_{sk} = coefficients for time and cost that are assumed to be random, and
ε_n = random disturbance term.

The random constants are specified in the following way:

$$\alpha_{sn} = \bar{\alpha} + \sum_{l} \varphi_{sl} y_{nl} + \xi_n \quad \text{(Equation 19)}$$

where

l = variables for capturing observed heterogeneity (like gender and age),
y_{nl} = values of the variables for each observation,
$\bar{\alpha}$ = fixed component (generic alternative-specific bias),

φ_{sl} = coefficients capturing observed heterogeneity, and
ξ_n = random term capturing unobserved heterogeneity.

The random coefficients are specified in the following way:

$$\beta_{skn} = \overline{\beta}_k + \sum_m \gamma_{skm} z_{nm} + \zeta_n \qquad \text{(Equation 20)}$$

where

m = variables capturing observed heterogeneity (like income and distance),
z_{nm} = values of the variables for each observation,
$\overline{\beta}_k$ = fixed components (generic coefficients),
γ_{skm} = coefficients capturing observed heterogeneity,
ζ_n = random term capturing unobserved heterogeneity.

The model was estimated based on the combined RP and SP data sets for the California State Route 91. The authors reported significant observed and unobserved heterogeneity among travelers that affects the forecast; a proper accounting for this heterogeneity could enhance the political viability of pricing. In modeling terms, this means that a combination of an explicit segmentation (to account for the observed heterogeneity) with probabilistic VOT distribution (to account for unobserved heterogeneity) is essential.

Randomly distributed VOT has been already incorporated in the new version of practical ABM developed for San Francisco (Figure 20); see Section 6.1.

Various ways and levels of highway user segmentation can be considered. The central question is to find a right balance between the explicit (observed) heterogeneity (full or partial segmentation of the model coefficients) and unobserved heterogeneity (making some of these coefficients random). For random parameters, different distribution shapes (for example symmetric versus skewed-to-the-left/right VOT distributions) can be explored.

From the technical standpoint, randomized VOT is comparatively simple to apply and it does not affect the model run time. This option, however, is only available with an ABM since it requires an individual microsimulation framework.

5.2.4 Additional Travel Dimensions and Choice Models

In order to more faithfully capture the effects of road pricing options, it will be necessary to address additional travel dimensions, such as the choice of whether to pay a toll charge, or the choice of payment type. These choices reflect the willingness of travelers to make tradeoffs between monetary costs and travel time savings. Current modeling practice and research provide examples of how these two travel dimensions have been incorporated:

- Binary route type choice (toll versus non-toll) can be incorporated at the lower level in the mode choice hierarchy, as has been implemented in the Montreal model. Introduction of pre-route choice in the mode choice model, and corresponding enhancements to the subsequent assignment procedures, allows for better accounting of the LOS on toll roads and associated drivers' perception through toll-road bias, reliability, and other components in the utility function.

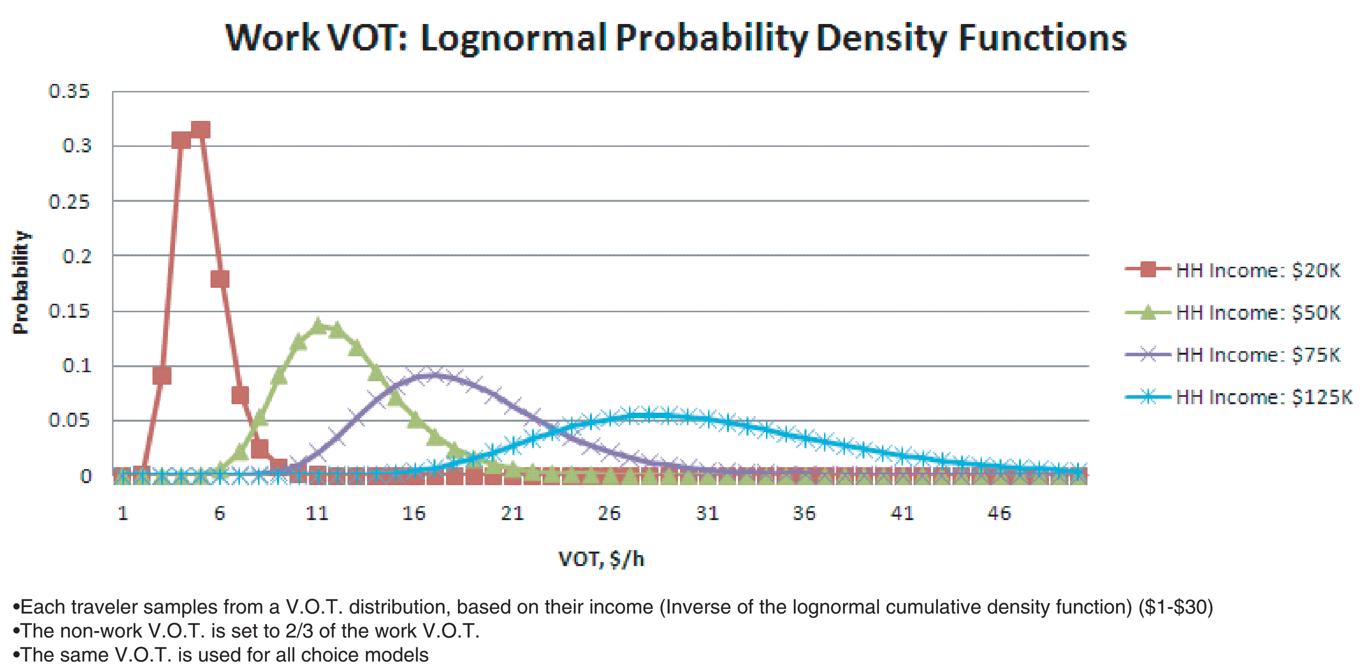

Figure 20. Randomized VOT applied in San Francisco model.

- Car occupancy choice (carpool formation mechanism) can be incorporated either as part of mode choice at the intermediate level (in the auto nest and before pre-route choice) or as an activity-type decision at the tour/trip generation stage. There are also several important differences in formation intra-household and inter-household carpools that should be taken into account through different modeling techniques.
- Payment type/vehicle equipment choice depending on the pricing form and technology can be incorporated in the model system as a lower level in mode choice or time-of-day choice. Representation of a payment type/technology may be essential if several toll-collection technologies with different roadway LOS effects are planned to co-exist for the same facilities.

The estimation of models considering the route type and payment type choice dimensions requires a specific and augmented set of data. Ideally, the binary pre-route choice model is estimated as part of the mode choice model though an independent or sequential estimation (first, pre-route choice and then mode choice carrying pre-route choice log-sums up).

Intra-household and inter-household carpools are generally modeled in different ways. Intra-household carpools with respect to fully joint tours for non-mandatory activities can be modeled explicitly from the tour generation stage. For these tours the travel party size is predetermined by the household composition and joint-tour participation model with the subsequent direct implication for mode choice. For example, if a tour is generated with three participants, SOV and HOV2 modes are automatically made unavailable for this tour (there still can be a choice between HOV3, transit, non-motorized, and taxi modes). For other tours that are either individual or joint (but not modeled explicitly), intra-household carpools are accounted implicitly at the mode choice stage through household size, composition and Daily Activity Pattern variables. For example, for work tours, SOV, HOV2, and HOV3 can be available but such variables as number of workers and school children (or work and school tours) would work in favor of HOV2/HOV3 indicating intra-household carpools and escorting arrangements. Intra-household carpools are generally not extremely sensitive to the HOV LOS characteristics.

Inter-household carpools can generally be modeled only implicitly through mode choice. The probability of inter-household carpools to occur does not relate to the household composition, but rather to opportunities to find permanent partners (frequently other workers) with a similar schedule and OD location on the way. Inter-household carpools are more frequent for longer distances, commuters with permanent schedules, and commuting to employment centers like CBD. These carpools are typically more sensitive to the HOV LOS characteristics since exclusive HOV lanes or HOT lanes with better levels-of-service than mixed flow lanes may make travelers seek joint travel arrangements. In a mode choice framework, these variables are tested statistically in the HOV mode utility functions.

Choice of payment type (including acquisition of transponder) has been recognized as an important dimension for travel segmentation that is currently missing in almost all travel models including the most advanced activity-based models. However, the recent RP surveys of toll users on the existing facilities have clearly shown that travel patterns (and the underlying willingness to pay) of cash users are very different from transponder holders (Yan and Small 2000). In particular, transponder holders are characterized by a higher trip frequency, different trip purpose mix, high percentage of symmetric commuters (using the same toll facility for both trip directions), and higher car occupancy. The introduction of a transponder acquisition model (that is essentially a mid-term travel decision relating to a set of mobility choices) would allow for an effective segmentation of highway users, and consequently yield better results for both choice models and traffic assignments. This is essential for T&R forecast studies of highway facilities where manual and ETC toll collection technologies coexist.

5.2.5 Incorporation of Travel Time Reliability

Quantification of Travel Time Reliability

There is a growing body of research and statistical evidence, as well as model estimation results, indicating that travelers' perception of toll roads and willingness to pay is not a simple consideration of average time and cost compared to the individual VOT. Willingness to pay for toll roads is also influenced by many other attributes, such as the reliability or predictability of travel times through management of roadway capacity, or improved safety through vehicle class restrictions such as trucks.

In particular, travel time reliability associated with toll roads has been recognized as a particularly strong factor, and may be as important as, or in certain contexts more important than, average time savings in determining traveler choice. Willingness to pay for reductions in the day-to-day variability of travel time is referred to as VOR. One of the most important strategic directions for improvement of travel models today is the measurement of highway time reliability and its impact on travel choices. Several published and ongoing research projects like NCHRP Project 8-64, NCHRP Report 618, SHRP 2 C04, SHRP 2 L04, as well as FHWA guidance are devoted to reliability issues.

There has been a considerable body of research regarding the fundamental issues that reflect definition of travel time reliability, its measurement, as well as the computation and treatment of travel time reliability in modeling tools. The suggested reliability measures have been put in the context of effectiveness related to transportation projects, policies, as well as the entire highway system performance.

In general, there are four possible methodological approaches to quantify reliability suggested in either research literature or already applied in operational models:

- (Indirect measure) Perceived highway time by congestion levels. This concept is based on statistical evidence that in congestion conditions, travelers perceived each minute with a certain weight (NCHRP Report 431 1999, Axhausen, et al. 2006, Levinson, et al. 2004, MRC and PB 2008). Perceived highway time is not a direct measure of reliability since only the average travel time is considered though it is segmented by congestion levels. It can, however, serve as a good instrumental proxy for reliability since the perceived weight of each minute spent in congestion is a consequence of associated unreliability. Additionally, it can be mentioned that VOT for different congestion levels does not only include proxies for reliability, but also psychological effects that congestion is more onerous than free-flow travel. For example, a traveler may full well know that he/she will have to sit in highly congested conditions, but perceives the time differently than time spent in free-flow conditions.
- (First direct measure) Time variability (distribution). This is considered the most practical direct approach that has received considerable attention in recent years. This approach assumes that several independent measurements of travel time are known, which allow for travel time distribution formation and calculation of some derived measures like buffer time (Small, et al. 2005, Brownstone and Small 2005, Bogers, et al. 2008). One important technical detail with respect to generation of travel time distributions is that even if the link-level time variations are known, it is a non-trivial task to synthesize the OD-level time distribution (reliability "skims") because of the dependence of travel times across adjacent links due to mutual traffic flow.
- (Second direct measure) Schedule delay cost. This approach has been adopted in many research works on individual behavior in academia (Small 1982, NCHRP Report 431 1999). According to this concept, direct impact of travel time unreliability is measured through cost functions (penalties expressed in monetary terms) of being late (or early) compared to the planned schedule of the activity. This approach assumes that the desired schedule is known for each person and activity in the course of the modeled period. This assumption, however, is difficult to meet in practical model setting.
- (Third direct measure) Loss of activity participation utility. This method can be thought of as a generalization of the schedule delay concept. It is assumed that each activity has a certain temporal utility profile and individuals plan their schedules to achieve maximum total utility over the modeled period (for example, day) taking into account expected (average) travel times. Then, any deviation from the expected travel time due to unreliability can be associated with a loss of participation in the corresponding activity (or gain if travel time proved to be shorter) (Supernak 1992, Kitamura and Supernak 1997, Tseng and Verhoef 2008). Recently this approach was adopted in several research works on DTA formulation integrated with activity scheduling analysis (Kim, at al. 2006, Lam and Yin 2001). Similar to the schedule delay concept, however, this approach suffers from the data requirements that are difficult to meet in practice. The added complexity of estimation and calibration of all temporal utility profiles for all possible activities and person types is significant. This makes it unrealistic to adopt this approach as the main concept for current research, however, it should be considered in future research efforts.

Detailed analysis of all four approaches with application examples can be found in Appendix A, Section A.3. A good example of the time variability measure was presented in Small, et al. (2005). The adopted quantitative measure of variability was the upper tail of the distribution of travel times, such as the difference between the 80th and 50th percentile travel times; see Figure 21. The authors argue that this measure is better than a symmetric standard deviation, since, in most situations, being late is more crucial than being early, and many regular travelers will tend to build a "safety margin" into their departure times that will leave them an acceptably small chance of arriving late (i.e., planning for the 80th percentile travel time would mean arriving late for only 20% of the trips).

The choice context included binary route choice between the Managed (tolled) Lanes and General Purpose (free) lanes on the section of SR-91 in Orange County, CA. The survey included actual users of the facility and the model was estimated on the mix of RP and SP data. The variation of travel times and tolls was significantly enriched by combining RP data from actual choices with SP data from hypothetical situations that were aligned with the pricing experiment. The distribution of travel times was calculated based on the independently observed data. The measures were obtained from field measurements on SR-91 taken at many times of day, on 11 different days. It was assumed that this distribution was known to the travelers based on their past experience. Reliability, as defined above, proved to be valued by travelers as highly as the median travel time.

Numerous variations of this approach based on travel time distribution have been proposed. For example, a 95% buffer time threshold was suggested in (CSI 2005) and some

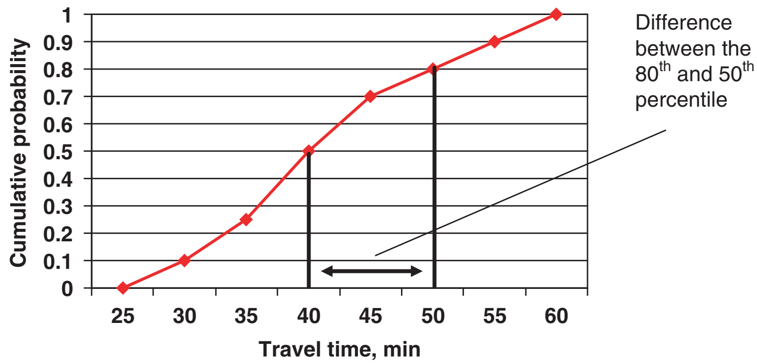

Figure 21. Travel time variability measure.

additional measures of distribution asymmetry and skew were explored in Bogers, et al. (2008). In the ongoing SHRP 2 Project C04, different variability measures are currently being investigated with respect to their impact on travel demand.

Incorporation of Travel Time Reliability in Operational Models

One principal problem that hampers making this approach operational is that it requires the explicit modeling of travel time distributions, as well as making assumptions on how travelers acquire information about the random variability they experience. DTA and micro-simulation tools are crucial for the direct assessment of travel time variability, since static assignment can only predict average travel times. However, application and calibration of these dynamic microsimulation traffic assignment procedures at the regional level has not often been performed. This principal issue needs both theoretical development and more practical experimentation with the available tools and approaches, even if they are currently operational in small networks only. This issue is in the focus of another SHRP 2 project L04, "Incorporating Reliability Performance Measures in Operations and Planning Modeling Tools," as well as several research projects currently underway in Europe (ITS 2008).

There are, however, several possible practical steps for inclusion of instrumental proxies for reliability measures in operational travel models. They include the recent experience with estimation of VOT by congestion levels (NCHRP Report 431 1999, Wardman 2009) and such measures as amount of congestion delay versus free-flow time applied in the Ottawa travel model (Ottawa TRANS 2007) as well as volume-over-capacity ratios as applied in the Seattle travel model (Appendix A, A.1.1.10).

A summary of possible instrumental proxies for indirect measurement of travel time reliability available with a conventional static assignment technique is shown in Table 16. These simplified measures could be included in both 4-step models and ABMs.

A more detailed discussion on the simplified operational approaches of this type can be found in Appendix A, Section A.3.2 in the context of perceived highway time.

5.2.6 Modeling Time-of-Day Choice and Peak Spreading

Time-of-day choice has always been the weakest part of travel models, but this model is essential for forecasting congestion pricing schemes. There has been significant progress in modeling techniques for time-of-day choice achieved recently and documented in several research synthesis efforts, as well as incorporated in the first advanced models applied in practice. The following discussion identifies the important features of the new time-of-day choice models and provides

Table 16. Instrumental proxies for travel time reliability.

Core measure	Link attribute scaling factors*	OD-skim contraction
Volume over Capacity (V/C) ratio	Number of lanes	Average weighted by distance (mean or 50th, 60th, 70th, 80th percentile)
	Highway facility type	
	Network location (bottleneck)	
Delay compared to free-flow condition	Number of lanes	Sum weighted by length
	Highway facility type	
	Network location (bottleneck)	
Travel time differentiated by congestion levels	Number of lanes	Sum weighted by length
	Highway facility type	
	Network location (bottleneck)	

* Accounts for probability and impact of accidents and traffic instability

recommendations on their estimation and incorporation within the structure of the modeling system:

- The new generation of time-of-day models is characterized by a high level of temporal resolution. These models can predict trip distribution by 30–60 min intervals (or even less if necessary). This is a major breakthrough compared to the conventional technique associated with broad (3 hours or longer) time-of-day periods. This advance in practice proved to be possible by hybridizing discrete choice modeling and duration modeling techniques. The results of the time-of-day choice model can be aggregated by broad time-of-day periods in order to provide compatibility with conventional period-specific static assignments. They can be more effectively used, however, in combination with DTA/microsimulation tools since these tools rely on demand (trip tables) stratified by fine time slices that can be effectively provided by the new time-of-day models. Even within the conventional static assignment framework, it can be beneficial to distinguish between the sharpest peak hour and shoulders within each peak period (AM and PM) to better portray impacts of congestion pricing.
- Modeling theory indicates that the best placement of time-of-day choice model is between destination choice (trip distribution) and mode choice. This means that time-of-day choice should operate with mode choice Logsums as explanatory variables, and mode choice should operate with period-specific travel times and cost. This approach is essential if both mode shifts and peak spreading effects are significant. For corridors and areas where substantial mode choice shifts are not expected, time-of-day choice model can be placed after mode choice (and normally applied for highway trips only). This means that the time-of-day choice model would operate with highway travel times and tolls as variables. In both cases, it is absolutely essential to apply equilibrium feedbacks to ensure that the peak spreading effects are consistent with congested travel time and cost estimates.

The new generation of time-of-day choice models can be applied in both 4-step and ABM frameworks. While there are many important similarities in model structure, there are also some principal differences that should be understood:

- Time-of-day choice in the 4-step trip-based model framework is applied for each trip segment separately. It is limited to the trip table segmentation embedded in the trip generation and distribution structure (by trip purpose, income group, car ownership, etc.). In particular, it is applied for each commuting direction (outbound and inbound from home) separately. As a result, AM peak spreading effects is modeled independently of PM spreading effects, and with no explicit control or consistency with the resulting implications for work duration.
- Time-of-day choice in the activity-based tour-based model framework is applied for each tour and preserves a consistency across all sequential trips in the tour and associated activities. It can also incorporate such important additional variables as person work status (full-time workers versus part-time workers) and household composition (presence of children, etc.). It is applied for the entire commuting tour (or round trip) in a process that ensures a logical linkage between changing AM and PM departure time. It allows for the explicit control of the duration of work or other activities.

A detailed description of the advanced time-of-day choice models with enhanced temporal resolution is included in Appendix A, Section A.4.

5.2.7 Modeling Car Occupancy

Several additional factors come into play if pricing or traffic restrictions are differentiated by car occupancy. Different forms of HOV/HOT lanes have been recently applied in many studies and valuable experiences have already been accumulated, as well as a significant body of research and model estimation works published. In this regard, the SHRP 2 C04 project is cooperating with the ongoing NCHRP project 8-36B, Task 52 "Changes in Travel Behavior/Demand Associated with Managed Lanes."

Understanding and modeling of the usage of HOV/HOT lanes must be rooted in an understanding of the behavioral mechanisms associated with formation of carpools. The modeling of carpools has suffered from a long-term stereotype and practice of considering HOV always as part of an individual mode choice. In reality, there are several important factors related to carpooling that cannot be handled in the individual mode choice framework:

- Carpool formation mechanism (intra-household or inter-household) and availability of HOV for each person trip. The assumption made in most existing models that HOV is available for every person/trip is a naïve one, and one that may well ruin the estimation of the model (Vovsha, et al. 2003).
- Extra time associated with carpooling (collecting and distributing passengers), especially for inter-household carpools (Burris and Appiah 2004).

As a result, travelers' perception of HOV/HOT lanes may even go far beyond the mode choice framework. If extensive HOV/HOT sub-networks are created and strong pricing policies promoting carpooling are applied, this might work as a behavioral push for changing travel and activity habits toward more frequent joint travel arrangements, through the synchronization of commuter schedules, as well as other activities.

There has been a very intensive research effort during recent years to better understand and explicitly model joint travel from the carpool formation stage (Vovsha, et al. 2003, Vovsha and Petersen 2005). Several innovative models of joint travel have been incorporated in operational ABM systems developed for Columbus, OH, and the Lake Tahoe Area, as well as those being developed for Atlanta, GA (already fully estimated and available for analysis), San Francisco Bay Area, San Diego, CA, and Phoenix, AZ.

Operational classification of carpools for analysis and modeling include the following dimensions:

- Formation mechanism (intra-household, inter-household planned, inter-household casual),
- Travel party composition (adults only, adults with children),
- Directionality (one-way versus two-way), and
- Carpool associated with joint participation in the same activity versus pure travel arrangements (pick-up and/or drops-off).

A detailed description of the advanced car occupancy and joint travel models is included in Appendix A, Section A.5.

5.3 Breakthrough Directions on the Network Simulation Side

5.3.1 Network Assignment Models and Algorithms in the Context of Pricing

Previous studies addressing user heterogeneity issues in the context of Static User Equilibrium (SUE) assignment for the evaluation of road pricing schemes can be classified into two categories:

- Multi-class approach, in which the entire feasible VOT range is divided into several predetermined intervals according to a discrete VOT distribution, path travel attributes (e.g., monetary cost), or some socio-economic characteristics (such as different income levels). Examples of these include the work of Florian (1998) and Yang, et al. (2002). Effective multi-class SUE assignment procedures are included in all commercially available transportation planning packages like TransCAD, EMME, and CUBE.
- The second category, which has remained mostly in the realm of theoretical research, recognizes VOT to be continuously distributed across the population of trips. For example, Leurent (1993) proposed that a cost versus time equilibrium is achieved when every trip-maker, with his/her own VOT, chooses a path that minimizes his/her own generalized cost. The method of moving successive averages (MSA) was adapted to solve for the cost versus time equilibrium with consideration of elastic demand in a static assignment model. In a seminal paper, Dial (1997) proposed the static bi-criterion user equilibrium traffic assignment model with continuous VOT to predict path choice and associated total arc flows. This model can be reduced to a variational inequality (VI) problem and solved by existing VI algorithms, such as the generalized Frank-Wolfe algorithm. Dial's approach, based on a restricted simplified decomposition framework, assigned every trip to a path with the minimum generalized cost with respect to that trip-maker's VOT, resulting in a large, possibly infinite, number of trip classes in a simultaneous equilibrium. Whereas Leurent's cost versus time (CVT) equilibrium model considered elastic demand, and only one criterion (i.e., travel time), to be flow dependent; Dial's model assumed fixed demand and allowed both criteria to be flow dependent. Marcotte and Zhu (1997) and Marcotte (1999) considered the problem of determining an equilibrium state resulting from the interaction of infinitely many classes of customers, differentiated by a continuously distributed class specific parameter.

Only the first category (multi-class) has been used (and only to a limited extent) in practice, although the continuous approach is more general and affords more flexibility in terms of behavioral modeling. The most common approach in practice is to ignore heterogeneity altogether; static (capacity-restrained) user equilibrium assignment incorporates tolls as a link attribute, strictly additive along the route. Assignment then is performed on the basis of a generalized cost (or time) which combines travel time and toll into a single scalar by multiplying the toll by a constant value of time; shortest path calculations in the assignment procedure are then based on this generalized cost instead of the original time attribute.

Even in the most advanced ABMs applied for pricing studies in practice in San Francisco, New York, and Montreal, user classes in the assignment procedures were defined strictly by vehicle type and occupancy (to account for network prohibitions), but with no differentiation by VOT within each class (details can be found in Appendix A, Section A.1.2). This is in a stark contrast to the behavior-related segmentation of the demand models that have many purpose and income specific segments, and in the case of San-Francisco models, even a distributed VOT within each segment.

Any differentiation of tolls (by vehicle type, occupancy, or time of day) in current practice, using commercially available SUE software, requires a multi-class assignment with a full segmentation of trip OD tables. This frequently leads to the problem of an impractically large number of trip tables, and a lack of convergence in the assignment process, especially when users are segmented by VOT. Certain ad hoc modifications of the link performance functions may be applied to approximate distance-based, time-based, or even congestion-dependent pricing forms. However, the latter two types start pushing the boundaries of applicability of SUE principles underlying the static assignment process. Static assignment models cannot accommodate other (non barrier toll) pricing forms, such as a daily user charge, entrance-exit-based charges, or discounts and exemptions. It is also well recognized that static assignment is unsuitable to model network performance for time varying demand and to capture the effect of operational strategies that entail queuing associated with toll collection or spillback from bottle-neck capacity constraints, which affect the variability of travel times through the network.

It is now generally recognized in the transportation modeling community that a full evaluation of tolls and pricing schemes in congested metropolitan context requires the following features be part of the network simulation procedure:

- Consideration of time-variation (within day) of traffic demand and during peak-periods, which calls for a dynamic analysis of the demand and flows in the network,
- Adoption of a network-level perspective, rather than individual facility, because of the need to consider traffic distribution across paths in a network in response to prices,
- Realistic representation of congestion phenomena and queuing,
- Representation of operational aspects associated with measures that combine lane/facility access, vehicle eligibility, and pricing (e.g., HOT lanes), and
- Consistent representation of user responses to prices in the short-, medium-, and long-terms.

The limitations of SUE assignment models in this regard are generally beyond the reach of "patches" that could be implemented to provide reasonable tools for the evaluation of pricing schemes. Nonetheless, some guidance to practice in the near-term might be beneficial in certain regards, for the following modeling issues (addressed also in Section 4.2.5):

- Formulating a standard practice for multi-class assignment to address traveler heterogeneity (e.g., vehicle type, occupancy, and VOT),
- Developing a set of best practices for network coding rules, toll-equivalent representation of volume-delay functions, and treatment of toll plaza delays.

Dynamic Traffic Assignment (DTA) techniques constitute a natural approach to meet the above requirements for the evaluation of pricing schemes. In particular, simulation-based DTA methods, in which the traffic network performance is captured through the simulation of vehicular flows through the network links and junctions, provides realistic depiction of the time-varying evolution of traffic patterns, congestion, travel times, and delays in all parts of the network. Furthermore, particle-based (traveler or vehicle) simulation, in which individual travelers and/or vehicles are represented and moved through the network, offers considerable flexibility to retain a disaggregate modeling approach for behavioral modeling (on the demand/activity side) all the way through the assignment process. Such assignment models may actually simulate the flow of traffic at two levels of resolution:

- Microscopic. All driving maneuvers are modeled as individual agents (lane changing, car following, etc.), at a level of detail which may not always be warranted for operational planning and pricing applications.
- Mesoscopic. Individual particles are tracked and moved according to speeds consistent with macroscopic (network) relations, subject to various queuing and processing rules reflecting the prevailing traffic controls at junctions.

Recognizing the need for mesoscopic simulation-based assignment tools, FHWA released about three years ago the first such tool for use by MPOs and state agencies, DYNASMART-P, developed at the University of Maryland by a member of the NCHRP Project 8-57 research team. Recent improvements in the software have allowed application to very large networks, such as those of the Southern California Area Government (SCAG) with over 68,000 links and up to 3 million vehicles in the network at any given time, and that of the Baltimore Metropolitan Region, which includes about 50,000 links, and is in actual use by the Baltimore Metropolitan Council staff. However, the version released by FHWA is limited in terms of the pricing schemes that may be evaluated, as well as in terms of allowing only a single VOT.

Developments at the University of Maryland and Northwestern have led to the following additional model features:

- Consideration of virtually any type of pricing scheme, including those based on real-time sensing of traffic conditions (state-dependent, both reactive and anticipatory),
- A novel algorithm to find a bi-criterion (time, cost) DTA with user heterogeneity represented by a continuously-distributed VOT,
- Explicit consideration of travel time reliability in the user response function (route choice),
- Incorporation of higher-order choice dimensions, including mode choice and departure time choice in the response of users, which can be equilibrated as well. The latter capability was illustrated in a recent evaluation for FHWA of the impacts of integrated corridor management programs

in the CHART corridor network between Washington, DC, and Baltimore (Zhou, et al. 2007).

Micro-assignment techniques, coupled with meso-level modeling of traffic interactions, allow representation of a much wider variety of vehicle and traveler types than traditional assignment. While commercially/publicly available software may not be ready for large-scale detailed micro-assignment with heterogeneous users, research and test versions suggest that this gap is rapidly closing. However, while the algorithmic and software aspects may see significant advances, the behavioral underpinnings for capturing users' responses to pricing remain incomplete, especially regarding evolution of users' attitudes, preferences and behavior over time.

There appears to be growing acceptance of DTA tools by the practicing community, and increasingly by user agencies, notwithstanding some of the confusion that may result from the growing number of commercial offerings with competing claims and sometimes inconsistent terminology. As such, simulation-based DTA has emerged as the platform of choice for the evaluation of tolling schemes, and for delivering and translating advances in behavioral modeling into integrated tools for producing practical results and forecasts. In addition to some of the above-noted real-world applications of DYNASMART-P, several other applications are underway using a variety of DTA-like tools.

For example, team members Kockelman, et al. (2005) and Boyles, et al. (2006) have demonstrated the use of TransCAD's dynamic assignment approximator for the Dallas-Ft. Worth network, as compared to microscopic assignment by a (research) package called VISTA, using over 50,000 links along with tolls (and homogeneous user assumptions). This research resolved important questions involving demand profiling/smoothing and comparisons of assignment results obtained with different methods. In addition, Citilabs' new version of CUBE Voyager contains a dynamic assignment module, which will be examined under this research project. Other entries in this category include DYNAMEQ, intended as a companion to EMME. Furthermore, developers of traffic microsimulation software (AIMSUN, VISSIM) are adding modules for mesoscopic simulation with assignment. As noted previously, however, applicability to pricing evaluation remains limited by the inability to include a large number of user classes in a practical multiclass procedure. For this reason, the advance noted earlier in terms of bi-criterion assignment with continuous VOT distribution is especially promising.

It is difficult to point to near-term improvements for DTA without consideration of specific software and capabilities. Advances in the underlying methodology are likely to include the following:

- Incorporating endogenous pricing mechanisms whereby prices are set according to prevailing traffic conditions (this has already been demonstrated in DYNASMART-P).
- Addressing major vehicle types (auto, commercials, trucks), vehicle occupancy (SOV, HOV2, and HOV3+), and VOT segments that correspond to the categories defined in the demand models.
- More effective and seamless integration with upstream demand/activity models.

5.3.2 Heterogeneity of Users in Traffic Network Assignment and Simulation

Accounting for heterogeneity of road users at the network simulation (route choice) stage follows directly from the manner in which user heterogeneity is reflected in the general choice context. As explained previously, we account for different VOT across users either through explicit segmentation or by applying probabilistic distributions in order to eliminate significant aggregation biases associated with using the average VOT. Because different shortest path trees must be calculated for different VOT, the computational burden of introducing VOT classes in the network assignment stage can be significant and may effectively preclude practical applications for real-size regional networks. Furthermore, a large number of classes will lead to significant and non-trivial difficulties in finding a convergent solution to the equilibration problem.

Recent advances in the algorithms for finding bi-criterion paths in large-scale networks open the way to effectively account for heterogeneity of road users in both static and dynamic assignment frameworks. This stems from the fact that for each OD pair there is always only a limited subset of so-called "extreme efficient" paths in the bi-criterion space "time-cost" for the entire range of VOT. A path is considered "extreme efficient" if it is Pareto-optimal and also lying on the boundary of the convex hull of points corresponding to the time and cost skims for the Pareto-optimal paths. With a reasonable assumption regarding the VOT distribution of users, approximate route choice probabilities can be calculated in a computationally effective way even for large DTA applications; see Mahmassani, et al. (2005). The concept of extreme efficient paths is illustrated in Figure 22. For simplicity, three extreme efficient paths and two other Pareto-optimal paths were assumed.

If a probabilistic distribution of VOT for users was assumed, then the probability of choosing one of the three extreme efficient paths can be associated with the fraction of users that belong to one of the following VOT intervals:

1. Users with $0 \le VOT < \omega_1$ will use route 1,
2. Users with $\omega_1 \le VOT < \omega_2$ will use route 2, and
3. Users with $\omega_2 \le VOT$ will use route 3.

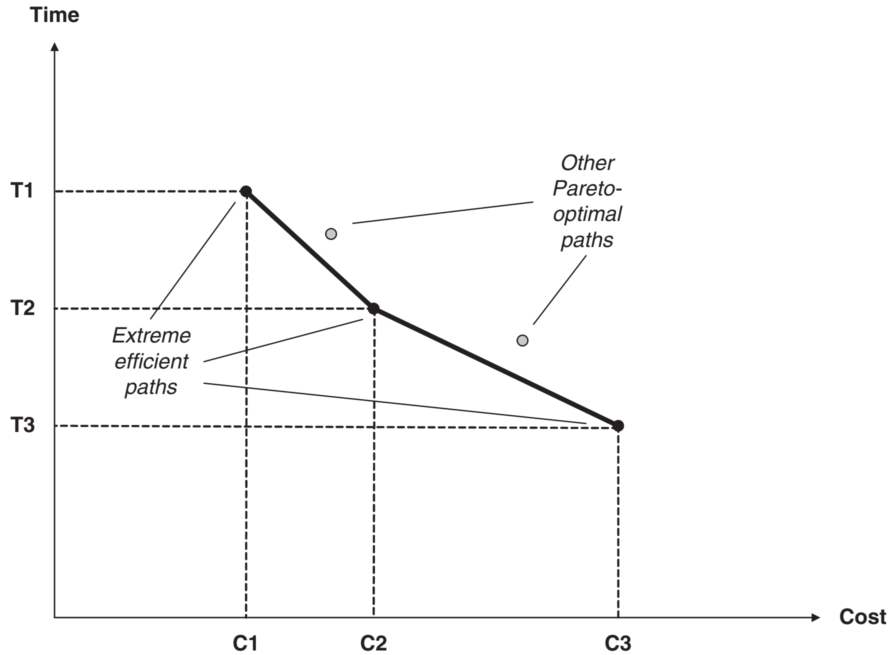

Figure 22. Extreme efficient paths.

The breakpoints ω_1, ω_2 can be calculated for the set of extreme efficient paths in such a way that the following condition holds:

$$\frac{C_1}{T_1} < \omega_1 < \frac{C_2}{T_2} < \omega_2 < \frac{C_3}{T_3} \qquad \text{(Equation 21)}$$

In the bi-criterion parametric optimum path-finding algorithm developed by Mahmassani, et al. (2005), the range of VOT values over which a particular efficient (time-dependent) tree (all-to-one) remains optimal for a given destination node (centroid) is determined. The ranges cover the continuum of possible VOT values. A major advantage of this procedure is that the solution and the computational effort are entirely independent of the shape of the underlying VOT distribution. In addition, considerable flexibility is afforded at the route choice/assignment stage because different distributions of VOT across the population could be used, and sensitivity analysis with regard to this distribution could be readily conducted. Furthermore, the evolution of VOT over time, through the effect of repeated experience in the system and preference shifts over time, can be accommodated in the assignment framework.

This parametric shortest path algorithm forms the backbone of a bi-criterion simulation-based dynamic assignment procedure that has been developed and tested by Lu, et al. (2006). The algorithm has been successfully applied as an extension to DYNASMART-P to a large corridor network, along I-95 connecting Washington, DC, to Baltimore.

The framework of this algorithm turns out to provide a very general solution to address heterogeneity not only in terms of VOT, but also in terms of value of reliability [e.g., in the specification of Small, et al. (2005) for route and departure time choice]. As such, Lu and Mahmassani (2007) have extended the framework to incorporate: (1) other choice dimensions, e.g., departure time; and (2) sensitivity to additional attributes, e.g., reliability and schedule delay (in a non-additive generalized cost structure).

The study team thus firmly believes that integration of advanced behavioral model constructs, that include the key short- and medium-term choice dimensions of users in response to dynamic pricing, congestion, and unreliability of travel time, with the network performance modeling side within reach using the simulation-based DTA platforms that have started to appear in practice. Because the bottleneck in applying the findings from behavioral models to forecasting the impact of pricing and other operational measures in actual networks lies on the network modeling side, and especially in its ability to handle very large networks with detailed time-varying link attributes, the study team proposes to push the boundaries on the extent of providing operational realism within state-of-the-art dynamic network modeling platforms. The work by Mahmassani, et al. (2005) provides a proven and highly promising direction to alleviate such constraints and achieve a greater extent of integration than previously envisioned as possible for large-scale networks.

Because our concern is with operational tools that could be used in practice as soon as possible, the development on the network side will consider integration within existing frameworks that have a base of application to real networks. The keen interest that agencies have for evaluation of pricing and other intelligent management strategies provides an opportunity for complementing the set of tools available to these agencies through the use of simulation-based dynamic modeling techniques. These may be used either as stand-alone or in coordination with the existing model system in use at these agencies.

5.3.3 Perspective of Using TRANSIMS for Highway Pricing Projects

The TRansportation ANalysis and SIMulation System (TRANSIMS) is a set of travel modeling procedures designed to meet the state DOTs' and MPOs' need for more accurate and more sensitive travel forecasts for transportation planning and emissions analysis. TRANSIMS is a microsimulation-based modeling environment that provides spatial and temporal resolution of activity and travel patterns at unprecedented levels for planning applications, investment decisions, and air quality conformity analysis. Because TRANSIMS is designed to simulate and track travel by individuals, the benefits to and impacts on different geographies and travel markets could be evaluated as well. Furthermore, TRANSIMS has the capability to evaluate highly congested scenarios and operational changes on highways and transit systems.

TRANSIMS is based on four primary modules:

- **Population Synthesizer** that creates list of individual households and persons,
- **Activity Generator** that estimates activities for households/persons and plans trips satisfying those activities,
- **Route Planner** that assigns trips to (multi-modal) time-dependent routes, and
- **Traffic Microsimulator** of all individual vehicles, transportation systems, and resulting traffic in a given study area.

Development of TRANSIMS was an important breakthrough in travel demand modeling, although there are still aspects and unresolved problems within the TRANSIMS framework that should be addressed in order to make the system operational and applicable for practical planning needs. At the time of original development in years 1995–2000, TRANSIMS differed from previous travel demand forecasting methods (4-step models) in its underlying concepts and structure. These differences include a detailed representation of persons and households; a consistent and continuous representation of time; time-dependent routing; and a person-based microsimulator. These advances are producing significant changes in the travel forecasting process.

From the perspective of today's state of the art and practice in travel demand modeling that has been moved significantly from the 4-step paradigm toward activity-based models since 1995, it is important to properly position TRANSIMS in the overall framework of progress made in the profession in the past 15 years, and to identify the most effective ways to integrate TRANSIMS into the modeling practice now. In particular, the following aspects of the relationship of TRANSIMS to other advance modeling practices should be understood:

- The first two components of TRANSIMS (Population Synthesizer and Activity Generator) directly correspond to the same components of microsimulation in an ABM. The progress made in the activity-based modeling field in this respect can be directly incorporated in TRANSIMS applications. In practical terms, TRANSIMS can be integrated with any of the existing activity-based models in a pilot application.
- The third and forth components of TRANSIMS (Route Planner and Traffic Microsimulator) relate to the mesoscopic and microscopic aspects of traffic network simulations. In particular, any of the mesoscopic tools described in the previous sub-sections can be considered for a route-planner (essentially route choice). The traffic microsimulator of TRANSIMS has most of the fundamental features comparable with the other traffic microsimulation algorithms (car-following rules, line changing rules, etc.). The unique feature of the TRANSIMS software that remains important is its ability to microsimulate traffic at a regional scale, achieved by an extensive multiprocessing.

From the travel demand modeling standpoint, the major component of TRANSIMS is the Activity Generator that predicts a list of activities (and consequently trips) for each household and person. This component corresponds to the Trip Generation stage in aggregate 4-step travel demand models and Individual Daily Activity-Travel Pattern in activity-based microsimulation models. The Activity Generator of TRANSIMS, however, follows a completely different modeling paradigm compared to the conventional models. Rather than model activity/travel agenda of households and persons explicitly by means of such functional forms as statistical regression or choice models that link the household composition and other independent variables to the list of activities, Activity Generator of TRANSIMS essentially expands the observed activity patterns by matching the modeled households to surveyed households in the base year.

Substitution of analytical and parametric modeling by the expansion-of-the-observed-behavior paradigm puts a great deal of importance on the matching method, since this method should incorporate the most important structural factors and dimensions defining the household travel behavior. This is done in TRANSIMS by means of the CART algorithm that allows for classification of the surveyed households into groups with similar travel behavior based on a predetermined set of criteria (for example, trip frequency, activity duration, travel time, etc.). While comparing the TRANSIMS Activity Generator to the conventional models (4-step and especially, activity-based) the following should be taken into account:

- The number of trips implemented by a household is not only a function of the household composition, but also a function of the density of potential attraction around the residential place, as well as its accessibility to attractions in a broader sense. In conventional models, this is accounted by introduction of area-type indicators and various accessibility measures into the regression models and choice utility functions. In the TRANSIMS framework, spatial variability of travel behavior can be taken into account by using zonal variables like residential density. However, there is a general problem with adding the spatial dimension to the CART algorithm. A really effective set of location-based categories could include around 10–20 types. Thus, a regional household survey of normal size (4–5 thousand households) would quickly wear very thin by using all demographic and spatial dimensions with a significant residual variation for end-nodes.
- Conventional demand models have interpolation and extrapolation properties by combining several variables in the utility expressions. Thus, if a high-income household with three workers and two children, residing in some particular location, has not been observed in the survey, it can be "interpolated" by combination of properties pertinent to three workers, two children, and the location. The "expansion-of-observed-behavior" paradigm does not have the interpolation ability and is applicable only in a case where the synthetic population is structurally close to the surveyed population. There is a similar extrapolation problem when forecasts should be done for a future year when one can expect a very different mix of households for some newly-built zones.
- Recent research on travel behavior has shown that there is a strong impact of the location of mandatory activities (work, school) on the number of non-mandatory activities and trips implemented by the person and entire household. In particular, longer commuting tends to reduce the number of other independent tours and trips. This has led to a significant re-consideration of the structure of contemporary demand models where trip/tour generation and distribution stages are now closely intertwined. While using travel time as a dependent variable may partially account for this factor, there is still a gap between generation of activities and their location in TRANSIMS.

Recognition of these problematic aspects has given rise to the integration of more flexible approaches to demand generation in first applications of TRANSIMS, basically borrowed from the recent experience with activity-based models. To date the TRANSIMS models have been tested with data from Dallas, Texas, and Portland, Oregon.

The Portland test case is important because it was the first time in which multi-modal microsimulation of traffic, using time-dependent paths, has been attempted at the regional level for a problem of this size. General objectives of the project were:

- To demonstrate how existing four-step model trip tables can be disaggregated by time of day, routed, and micro-simulated,
- To develop methods and a set of recommended practices for network construction, attribute variables, and stabilization methods,
- To demonstrate the feasibility of implementing relatively simple activity-based modeling components, using an adaptation of existing trip-based models,
- To develop a system of feedback between the time-dependent network service attributes and the demand-side activity-based model components,
- To develop and document methodologies for implementation as well as lessons learned in the process.

The conceptual design of the TRANSIMS-Portland modeling system is shown in Figure 23. TRANSIMS model included the four core components with some modifications. In particular, the Activity Generator included a tour-based location choice model, and a mode preference model was placed between the Activity Generator and multi-modal Router. In addition to the model core components, there are several paths for feedback in the design.

The Population Synthesizer can be termed an "unqualified success," as its fundamental design has been imitated by several subsequent activity-tour-based transportation and land use modeling projects. The population synthesizer uses three controlled attributes (household size, income, and age of head of household) and generates additional uncontrolled attributes for households sampled in the U.S. Census's Public Use Microdata Sample (PUMS). The study team demonstrated that this method provides a good fit to the distributions of uncontrolled attributes, such as worker status and automobile ownership.

The Activity Generator utilized the CART method to draw representative activity patterns directly from Metro's household interview survey, based on a match between survey households and those in the synthetic population. These activity patterns had all of the dimensions of the survey (travel party composition, activity purpose, time of day, location and travel mode). To resolve the problematic issues mentioned above, subsequent model steps were then applied in order to

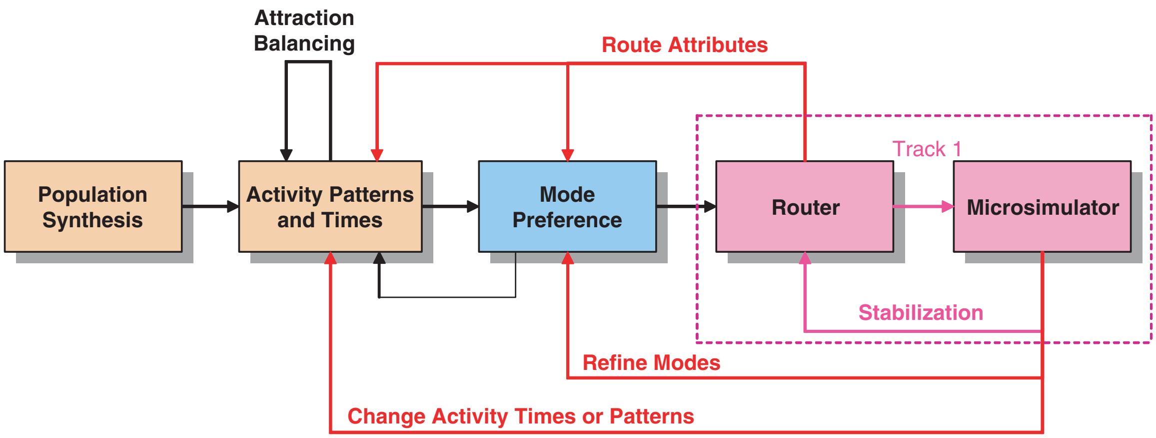

Figure 23. Conceptual design of TRANSIMS-Portland modeling system.

replace some of these activity pattern attributes with choices that are more probable for the synthetic traveler, taking into consideration the implied space-time constraints that their itinerary presents.

A subcomponent of the Activity Generator is a tour-based location choice module that selects the locations of activity stops in the pattern sequence and considers both the "size" of the opportunities at alternative activity locations as well as the impedance between activity stops and the travel impedance from activity stops to the home locations of the synthetic traveler ("rubber banding" method). The project team was able to demonstrate that the specification of an existing trip-based destination choice model could be borrowed and adapted to this tour-based modeling choice with the addition of just four calibration constants and district-level workplace attraction balancing, achieving surprisingly good fit at the aggregate level.

The mode preference model was designed to be applied at the tour level, borrowing a specification from Metro's existing trip-based model and using zonal aggregate skims. The design also featured a second stage in which a limited number of travelers who had both feasible automobile and public transit choices would make a more detailed comparison, using time-dependent highway and transit path data from the TRANSIMS Router.

A method was developed for calibrating the tour-level mode preference model using observed trip modes as target values. In addition, feedback methods were conceptualized and tested. Among these methods was the time-based comparison of routed paths with itinerary paths, the results of which may trigger feedback to prior model components (e.g., refine mode selection, choose new starting times, choose different activity location, choose a new activity pattern).

In general, TRANSIMS-Portland application has proven that a successful incorporation of activity-based demand modeling approach in the TRANSIMS framework is possible. It makes TRANSIMS a generally viable and potentially attractive framework for pricing projects where there is sufficient data to support it. FHWA plans several activities to support both the development of TRANSIMS and further research into TRANSIMS applications. TRANSIMS is made available under the NASA Open Source Agreement. For more information on TRANSIMS visit http://tmip.fhwa.dot.gov/transims.

5.4 Integration of Demand Model and Network Simulation

5.4.1 Essence of Equilibrium and Possible Feedback Options

Methods to integrate ABM and DTA through activity scheduling/rescheduling procedures will be specifically explored in the course of the SHRP 2 C04 and L04 projects. A preliminary conceptual framework for achieving individual level integration between an ABM and DTA is suggested in Figure 24. While conceptual schemes for inter-relating behavior and network models can be formulated, actual integration at an operational level entails considerable challenges, and judicious modeling and software decisions to enable such integration.

The key notion of integrated models is the need to achieve compatible and mutually consistent levels of analysis detail between the demand side on one hand, and the network modeling side on the other. Integrated models must retain the richness carried by the individual model components and not lose information (e.g., through aggregation) in the various transfers of information that take place within a model framework. For example, after generating an activity pattern in a tour-generation disaggregate process, assigning these outcomes in a trip-based static assignment loses much of the information provided in the behavioral model that could inform the route choice simulation.

Integrated modeling of behavior and network performance for the evaluation of pricing schemes is best achieved by a consistent and mutually compatible representation of the decision-making entities in the network. In other

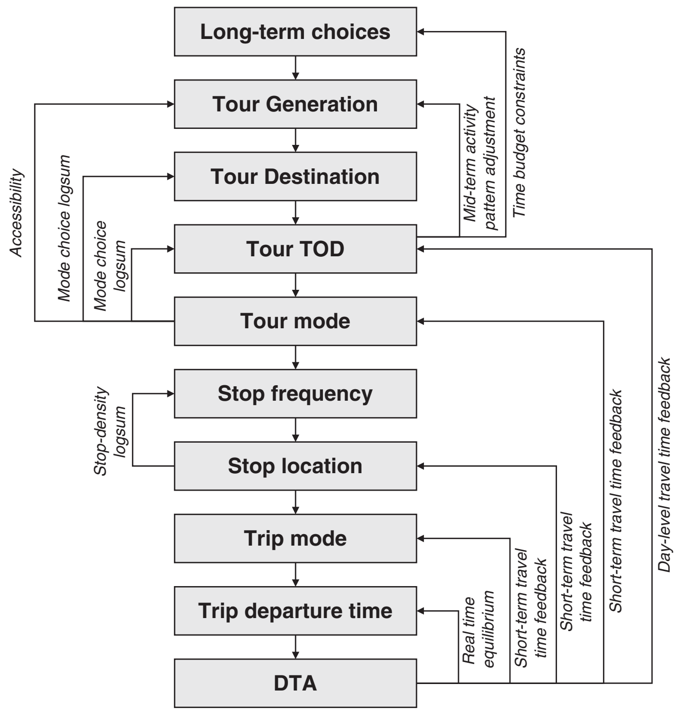

Figure 24. Integration of ABM and DTA.

words, the fact that individual particles are represented in micro-assignment techniques provides a natural integrating mechanism with the demand side. Hence, particle-based, or disaggregate DTA, is a central element in developing integrated approaches. An important mechanism is to allow the loading of entire trip chains onto the network instead of just individual trips. This capability was illustrated for a relatively small network (Abdelghany and Mahmassani 2003) in an integrated model of trip timing and activity sequencing that is solved to equilibrium consistently with a dynamic assignment of the resulting choices. For the evaluation of pricing schemes and reliability improving measures, incorporation of short-term adjustments in trip timing is a critical capability.

5.4.2 Incorporation of Reliability in Network Equilibrium

Incorporation of travel time reliability in the feedback mechanisms is not a trivial problem in application, since the travel time reliability measure in itself require several iterations with variable demand and supply conditions. The reliability measure can be introduced in the generalized cost function of route choice (in addition to average travel time and cost as described in the Appendix A, Section A.3.1). Then, the route generalized cost (or separate time, cost, and reliability skims) can be used in the mode choice and upper level models. This technique, however, would only address one iteration feedback of (previously generated) reliability on average travel demand. The fact that both demand and supply fluctuations affect reliability creates a certain complication. In other words, the equilibration scheme should incorporate the process of generation of reliability measure itself.

These issues represent a cutting edge research agenda. The recently started SHRP 2 L04 project "Incorporating Reliability Performance Measures in Operations and Planning Modeling Tools" will specifically address these aspects. The general suggested structure that could resolve these issues is presented in Figure 25. The key technical feature of this approach is that the very top and bottom components (average demand and average travel time) are preserved as they function in the conventional equilibration scheme while the reliability measures are generated by pivoting off the basic equilibrium point.

Distribution of travel times is essentially modeled as a composition of three sets of probabilistic scenarios: 1) demand variation scenarios, 2) network capacity scenarios, and 3) network simulation scenarios. Each set of scenarios has its own group of factors that cause variation. The final distribution of travel times is generated as a Cartesian combination of the demand, capacity, and simulation scenarios.

It is essential to have a static demand-supply equilibrium point (between the average demand and supply) explicitly modeled for two reasons, the need to:

- Define the basic travel demand patterns from which the variation (scenarios) can be pivoted off.

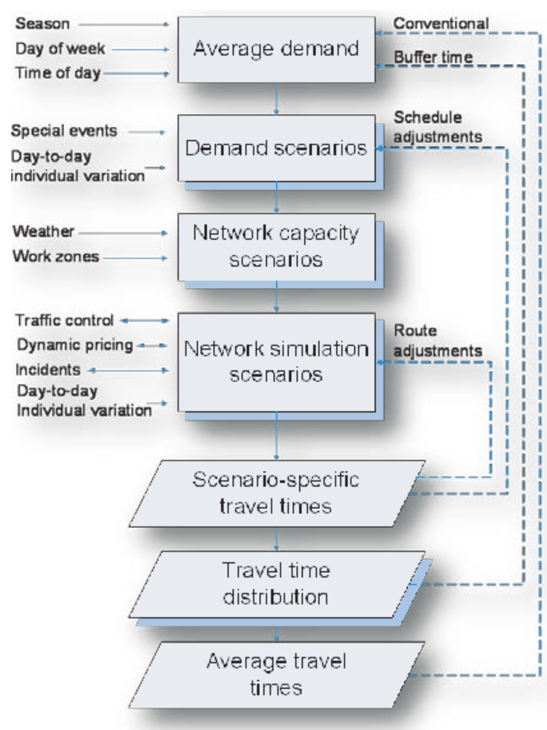

Figure 25. Feedback with reliability measures.

- Provide the background level of fragility of traffic flows from which the probability of breakdowns can be derived.

Average demand is a function of both average travel time and reliability (through measures like buffer time). It is assumed that average demand, and the corresponding equilibrium point, are simulated separately for each season (if seasonal variation is substantial), day-of-week (if there is a systematic variation across days of week), and time-of-day period conditions, though there is a linkage across the demand generation steps for different periods of a day (especially if an advanced Activity-Based model is applied). The demand fluctuation scenarios are created by application of several techniques (like Monte-Carlo variation) and auxiliary models (like special events model) described in the subsequent sections.

In addition to feeding back the resulted average travel times and reliability measures to the average demand generation stage (i.e., having a global feedback), two additional (internal) feedback options should be considered:

- First internal feedback of scenario-specific travel times through route choice adjustments in the network simulation procedure. In this feedback, travel demand, and network capacity is considered fixed. However, route choice can change from iteration to iteration because of the factors associated with traffic control, incidents, individual variation of driving habits, as well as dynamic real-time pricing. The network simulation can also incorporate probability of flow breakdown. In the course of the SHRP 2 L04 research, the corresponding network simulation algorithm and route choice feedback mechanism will be established first. Then, this module will be employed within the demand-supply equilibrium framework (second internal feedback and global feedback).
- Second internal feedback of travel time distributions (and any derived measure of reliability) to the demand scenario through schedule adjustments of trip departure times. In this feedback, the demand scenario in terms of trip generation, distribution, and mode choice is considered fixed while the trip departure time can change from iteration to iteration as the result of travel time fluctuations modeled by the network capacity and network simulation scenarios. The purpose of this feedback is to stabilize trip departure times for each demand scenario. This feedback is applied within the global equilibrium loop.

The details of demand generation process and its sensitivity to reliability measures depend on the type of travel demand model. The ABM framework represents a more promising counterpart to microscopic and mesoscopic network simulation models because of its more compatible temporal resolution. Advanced ABMs in practice already operate with 30–60 min demand slices, while traditional 4-step models operate with broad 3–4 hour periods. Additionally, 4-step models can only produce aggregate zone-to-zone flows. Thus, any demand response to reliability will be identical for all trips within the same segment. In contrast, ABMs are based on individual microsimulation. This opens a way to implement feedback on an individual level, where additional individual variation can be taken into account. Also, the utility coefficients in microsimulation models can be effectively randomized taking into account individual variation of VOT and VOR.

CHAPTER 6

Pilot Studies for Demonstration of Improved Tools

This chapter is focused on a detailed review and analysis of four model improvement case studies that were implemented in order to prepare for actual pricing studies. The following four studies and corresponding model improvement efforts are:

- Improvement of the San Francisco ABM for different pricing studies,
- Improvement of the New York ABM for (area) pricing study,
- Application of DTA for analysis of pricing in the Baltimore-Washington corridor, and
- Improvement of the Los Angeles 4-step model for different pricing studies.

These particular studies were chosen for this research since they included a substantial level and range of model improvements, designed and implemented to address variety of pricing forms and project types. The studies and model structures applied are characterized by a wide range of planning and modeling issues that illustrate the general modeling principles described in Chapter 4, and many of the advanced model features described in Chapter 5.

6.1 Improvement of the San Francisco ABM for Pricing Studies

6.1.1 General Model Structure and Phased Improvement

Model System Structure and Incorporation of Pricing

The San Francisco County Transportation Authority (SFCTA) received a grant from the FHWA Value Pricing Program in 2006 to study the feasibility of implementing congestion pricing in downtown San Francisco. Congestion pricing is the charging of user fees for drivers on congested routes or in congested areas, with goals of reducing congestion for those who choose to pay the fee and improving alternatives to driving during peak periods for those who choose not to.

SF-CHAMP is an ABM that has been used in practice in San Francisco for several years. The model structure is shown in Figure 26. Prices enter the model as network LOS variables, which are a product of skimming the network by each of five time periods (Early AM, AM Peak, Midday, PM Peak, and Night). The LOS variables are used directly in tour and trip mode choice, and peak spreading for auto trips. The LOS variables are represented as mode choice Logsums in destination choice and time-of-day choice models and in the full-day tour pattern model for work tours, where the destination is known. LOS variables are represented as destination choice Logsums for choices where the destination is unknown, such as generation of discretionary activities and auto ownership choice. The transformation of price into Logsums ensures that the sensitivities to price are based on appropriate traveler sensitivities to cost and preference for travel by auto versus other competitive modes as expressed in mode-specific constants and household/person variables. Because toll costs are skimmed from transport networks, the entire system must be iterated several times, with feedback of skims input to the next iteration of the models, in order for estimated demand to stabilize (converge). To reduce Monte Carlo variability, the entire system is run five times with several iterations of feedback within each run, and the results are averaged.

In order to support the San Francisco Mobility and Pricing Study, the SF-CHAMP model was extended to forecast the travel behavior of all residents of the 9-county Bay Area, rather than just residents of San Francisco County. The expansion allows all residents of the region to be modeled in a consistent manner using the more sophisticated structure of the SF-CHAMP model—an important enhancement for a study where a key market is persons living in other counties and traveling to downtown San Francisco.

In addition to the geographic expansion to the 9-county Bay Area, the models were enhanced to include the ability to

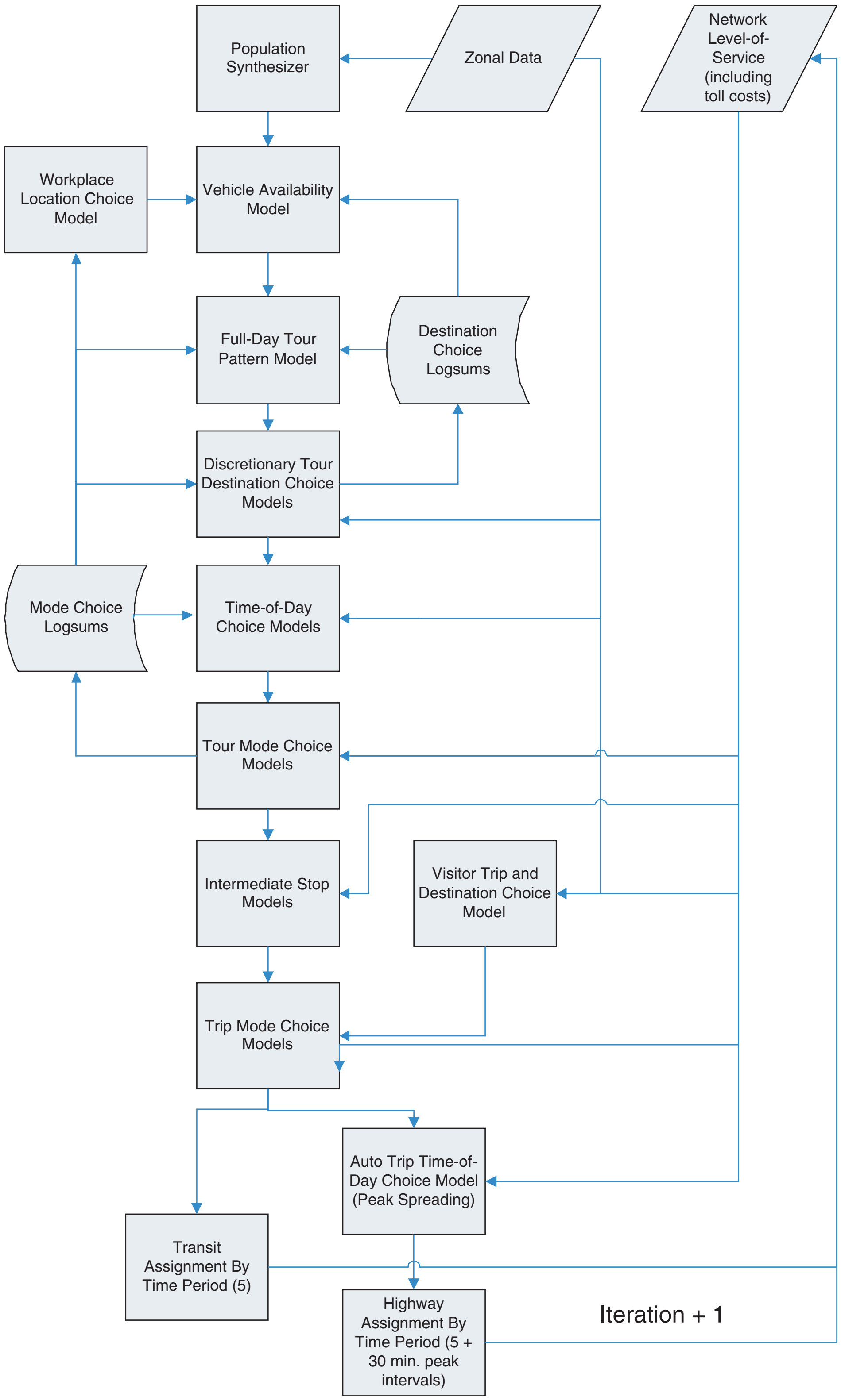

Figure 26. RPM-9 model structure.

evaluate cordon pricing and area pricing scenarios at all levels of the decision-making structure. Specifically, this includes the addition of a choice of whether or not to pay a toll to enter the pricing area, the use of a VOT distribution rather than average VOT, and supporting enhancements. After calibrating, these models were used for Phase 2 of the Mobility and Pricing Study.

A final set of Phase 3 models was then created to better capture time-of-day shifts expected due to pricing. The Phase 3 models incorporate the information gained from a stated preference survey of persons making auto trips to downtown San Francisco. After implementing these improvements, the model was calibrated to match observed data at a regional level, with a particular focus on San Francisco trips.

The resulting models are termed the 9-County Regional Pricing Model (RPM-9).

Generalized Cost Assignment in CHAMP 3

For initial study analysis, the one-county CHAMP 3 model was modified to use generalized cost highway path-building, rather than time-only path-building. The generalized cost function is:

$$GenCost = Time + 0.04 * \left(12 * Distance + Toll/Occupancy\right) \quad \text{(Equation 22)}$$

In this equation, the 0.04 factor converts from cost in cents to minutes, using an equivalent of $15/hour. The auto operating cost is 12 cents per mile, and toll costs are specified in cents. All costs throughout the model are in 1990 dollars or cents. The division of cost by auto occupancy is new in RPM-9 and allows for the sharing of costs among passengers. The auto operating cost is not divided by occupancy because doing so would force the model to predict higher shared ride shares for longer trips, a result that is not seen in the observed data.

Expansion to 9-County Area

The development of RPM-9 began by modifying the existing CHAMP 3 models to cover the entire 9-county Bay Area. In many cases, such as the application of mode choice models, the same models are applied and calibrated for the 9-county area, only with the removal of a restriction that they apply to only San Francisco residents. In some ways, this makes the entire model system simpler because there is no longer a need to combine the regional results from the MTC model with the SF-CHAMP results. However, to achieve this regional scope, there were a number of changes that needed to be made. Most of these changes involved resolving inconsistencies between the detailed data that are available only within San Francisco, and the more general data available for the entire 9-county area.

6.1.2 Model Structure Improvement for Choice of Tolls

In addition to the expansion to the 9-County area, the behavioral structure of the Phase 2 model was extended to include a choice of tolls. The model updates made as part of that extension are discussed in this section.

Networks

The highway networks are coded in equivalent manner as the networks for the Phase 1 CHAMP 3.1 models, with one additional field indicating if the toll should be treated as a "value toll" and included as a separate alternative in the choice models. Specifically, the network fields related to tolling are:

- TOLLEA_DA – Cost of tolls to single-occupant vehicles in the Early AM;
- TOLLEA_SR2 – Cost of tolls to shared-ride 2 vehicles in the Early AM;
- TOLLEA_SR3 – Cost of tolls to shared-ride 3+ vehicles in the Early AM;
- TOLLAM_DA – Cost of tolls to single-occupant vehicles in the AM Peak;
- TOLLAM_SR2 – Cost of tolls to shared-ride 2 vehicles in the AM Peak;
- TOLLAM_SR3 – Cost of tolls to shared-ride 3+ vehicles in the AM Peak;
- TOLLMD_DA – Cost of tolls to single-occupant vehicles in the Mid-Day;
- TOLLMD_SR2 – Cost of tolls to shared-ride 2 vehicles in the Mid-Day;
- TOLLMD_SR3 – Cost of tolls to shared-ride 3+ vehicles in the Mid-Day;
- TOLLPM_DA – Cost of tolls to single-occupant vehicles in the PM Peak;
- TOLLPM_SR2 – Cost of tolls to shared-ride 2 vehicles in the PM Peak;
- TOLLPM_SR3 – Cost of tolls to shared-ride 3+ vehicles in the PM Peak;
- TOLLEV_DA – Cost of tolls to single-occupant vehicles in the Evening;
- TOLLEV_SR2 – Cost of tolls to shared-ride 2 vehicles in the Evening;
- TOLLEV_SR3 – Cost of tolls to shared-ride 3+ vehicles in the Evening;
- VALUETOLL_FLAG – Binary flag indicating whether or not trips traversing this link should be included in the toll alternative in the choice models.

All costs are coded in 1990 cents. The value toll flag is important because it distinguishes between the congestion pricing tolls and the background tolls on the Bay Area bridges. Just because someone is willing to pay a toll to cross the Golden Gate Bridge does not necessarily mean that they are also willing to pay a toll to enter the downtown area. A trip is only included in the toll alternative if it traverses a link where both the value toll flag and the toll for that time period and auto occupancy are greater than zero. If the flag is set to zero, then the toll is still paid, but it is included in the utility equation of the no-toll alternative.

Highway shortest paths are built based on the generalized cost (Equation 22). Two separate sets of highway skims are built. The toll skims are allowed to use any link in the network, subject to the normal HOV restrictions. The no-toll skims are prevented from using links where the toll and the value toll flag are both greater than zero. The no toll skims include three tables: time, distance, and cost of bridge tolls. The toll skims include four tables: time, distance, cost of bridge tolls, and cost of value tolls. The value tolls need to be skimmed separately such that the availability of toll alternatives can be determined, and such that incremental value toll costs can be set to zero for area pricing scenarios.

Car Availability, Tour Generation, and Time-of-Day

No changes were necessary to the vehicle availability, tour generation, or time of day models in order to accommodate the revised behavioral structure. Changes were made to achieve better calibration results, however, that are discussed in that section.

Tour Destination Choice

The tour destination choice and workplace location choice models are integrated with the tour mode choice models, and use the mode choice Logsum as the primary measure of impedance. Therefore, no further changes were required for them to be sensitive to congestion pricing scenarios.

Tour Mode Choice

The tour mode choice models were re-structured to allow for a more realistic behavioral response to the types of scenarios that will be evaluated in the Mobility and Pricing Study. Figure 27 shows the tour mode choice nested structure used by CHAMP 3. This structure is limiting in two ways: First, there is no explicit choice of whether or not to pay the toll, and second it does not necessarily capture differences in cost or toll across auto occupancy. The auto driver alternative in CHAMP 3 is exposed to the drive-alone skims, and the auto passenger alternative is currently exposed to the shared ride 2 skims. In reality, some drivers would be exposed to shared ride skims, and some passengers would be exposed to shared ride 3+ skims. When the scope of the model was limited to San Francisco County without tolling, this was not an issue, but in a region that includes high-occupancy vehicle lanes and toll discounts for carpools, there are some cases where it is limiting.

To overcome these issues, RPM-9 uses the nested structure in Figure 28. This structure includes a choice of Drive Alone, Shared Ride 2, or Shared Ride 3+ for greater consistency with the skims. It also includes a choice of toll or no-toll as a subnest on each auto alternative. The nesting coefficients for the non-motorized, auto, and transit nests remain at 0.72, and the nesting coefficients on the toll nests are set to 0.50. The resulting product of the nesting coefficients at the lowest level is 0.36, a value consistent with what is typically observed in toll modeling. The utility equations for the toll and no-toll alternatives are the same as the driver and passenger utility equations in the existing model, except that they also include the costs of tolls. The coefficients on toll cost are set to the same as the coefficients other out-of-pocket costs.

The nature of the highway skims is such that the toll skims will include a valid path for all OD pairs, but the no-toll skims might not. That is, if it is impossible to reach a TAZ without paying a value toll, then the no-toll pathfinder will not find a path, and the no-toll alternative will not be available. While the toll skims will always have a valid path, the toll alternative

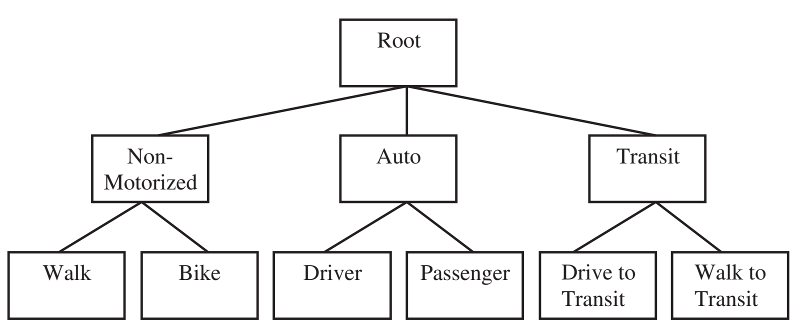

Figure 27. CHAMP 3 tour mode choice nested structure.

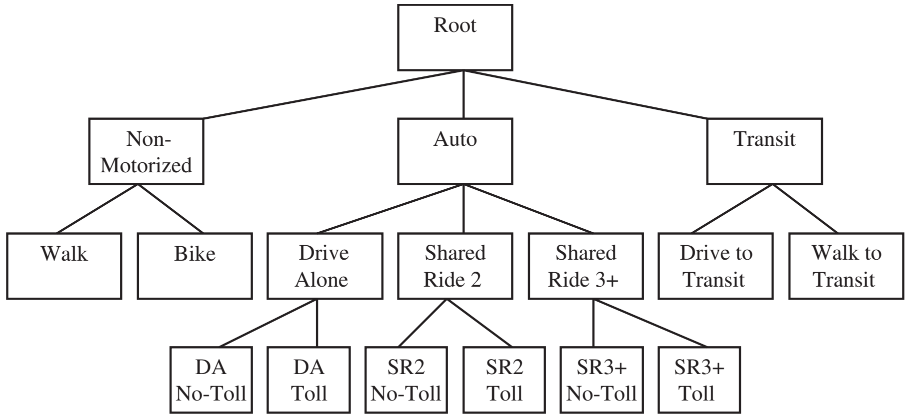

Figure 28. RPM-9 tour mode choice nested structure.

should only be available when toll is a distinct alternative. To meet these criteria, the following rules are defined:

- DA No-Toll is available as long as a valid DA path can be found;
- SR2 No-Toll is available as long as a valid SR2 path can be found;
- SR3+ No-Toll is available as long as a valid SR3+ path can be found;
- DA Toll is available if the DA value toll is greater than zero;
- SR2 Toll is available if the SR2 value toll is greater than zero; and
- SR3+ Toll is available if the SR3+ value toll is greater than zero.

These rules are in addition to the existing availability rules: DA not available if it is a 0-vehicle household or age is less than 16. For the congestion pricing scenario, it is expected that for most OD pairs, either the toll or the no-toll alternative will be available, but not both. The exception to this rule is trips that pass through the congestion pricing area but have the option of avoiding the toll and still reaching their destination. Even though the side-by-side choice of toll versus no-toll is not common, it is still important that the appropriate alternative be selected in the tour mode choice because that choice will serve as the basis for subsequent models.

Toll costs and parking costs are divided by auto occupancy to reflect the sharing of costs among all occupants. Auto operating costs are not shared among occupants, because doing so would result in a model that predicts higher carpooling rates for longer trips, a result not typically observed in reality.

The format of the skims also requires that the walk and bike travel times be a function of the distance in the toll skims, rather than the non-toll skims. This will ensure that travelers are not restricted from choosing the non-motorized modes because a toll is imposed.

Intermediate Stop Location Choice

The intermediate stop choice models previously used the extra time to a stop as the measure of impedance. This extra time is calculated as origin to stop time plus stop to destination time minus origin to destination time. In the CHAMP 3 models, the extra time is specific to the chosen tour mode. During the calibration of CHAMP 3, an extra distance term was introduced such that the models could be calibrated to the average observed trip distance without becoming too sensitive to changes in travel time.

For the RPM-9 models, the intermediate stop location choice model was further enhanced to consider the extra toll cost, both of bridge tolls and value tolls. The intermediate stop models use only the toll skims, such that any zone can be reached. With this approach, if the tour mode is toll, then an intermediate stop that would normally require a toll of the same cost can be reached for no additional cost. In the event that the intermediate stop alternative requires paying a value toll both on the origin to stop and on the stop to destination legs of the tour, then an addition cost is incurred. If the tour mode is no-toll, then an intermediate stop that involves paying a toll could still be reached, the cost of paying the toll would be included in the utility. This latter case dictates that individual trip modes can be toll trips, even though the main tour mode was originally chosen as no-toll.

Trip Mode Choice

With the restructuring of the tour mode choice model, the trip mode choice model receives one of six possible tour modes for auto trips: DA No-Toll, DA Toll, SR2 No-Toll, SR2 Toll, SR3+ No-Toll, or SR3+ Toll. The trip mode choice model assigns each trip in the tour a trip mode in one of the same six categories. It is not required that all trips on a tour have the same trip mode, or match the tour mode. The nested

Table 17. Trip modes allowed for each tour mode.

Trip Mode	Tour Mode									
	DA No-Toll	SR2 No-Toll	SR3+ No-Toll	DA Toll	SR2 Toll	SR3+ Toll	Walk	Bike	Walk-Transit	Drive-Transit
DA No-Toll	X			X						
SR2 No-Toll	X	X		X	X				X	X
SR3+No-Toll	X	X	X	X	X	X			X	X
DA Toll	X			X						
SR2 Toll	X	X		X	X				X	X
SR3+ Toll	X	X	X	X	X	X			X	X
Walk	X	X	X	X	X	X	X	X	X	X
Bike								X		
Walk-Local									X	X
Walk-Muni									X	X
Walk-Premium									X	X
Walk-Bart									X	X
Drive-Premium										X
Drive-BART										X

structure for the revised trip mode choice model is identical to the nested structure of the tour mode choice model shown in Figure 28. The upper level nesting coefficients are 0.7 and the toll nesting coefficients are 0.5.

Table 17 shows the availability constraints used to convert from tour to trip modes. The auto occupancy at the tour level represents the maximum auto occupancy, so at the trip level SR2 tours can have DA trips, but not vice-versa. These availability constraints are defined such that the choice of toll or no-toll at the tour level is non-binding. This non-binding approach is necessary for two reasons.

First, not all trips on a toll tour are expected to cross the toll cordon. For example, consider a commuter driving from Palo Alto to downtown San Francisco for work and paying the toll to enter the pricing area. The tour is clearly a toll tour, and the inbound commute is clearly a toll trip. If the toll is only paid on the inbound direction, then the return trip is a no-toll trip. If the commuter stops on the way home in Menlo Park for a softball game, the trip from Menlo Park to Palo Alto is a no-toll trip.

Second, it is possible for individual trips on no-toll tours to cross the toll cordon. Consider a commuter driving from the Sunset district to the Presidio for work. This commute does not enter the tolling area and is a no-toll tour. However, after work the traveler drives to the financial district to meet friends for happy hour. This stop is in the pricing area and subject to tolling, so that trip is a toll trip.

The trip mode choice model alternatives are also subject to the skim-based availability rules equivalent to the tour mode choice rules. Specifically, these are:

- DA No-Toll is available as long as a valid DA path can be found;
- SR2 No-Toll is available as long as a valid SR2 path can be found;
- SR3+ No-Toll is available as long as a valid SR3+ path can be found;
- DA Toll is available if the DA value toll is greater than zero;
- SR2 Toll is available if the SR2 value toll is greater than zero; and
- SR3+ Toll is available if the SR3+ value toll is greater than zero.

As in tour mode choice, these availability rules ensure that in most cases, either the toll or no-toll alternative will be available, but not both. Both might be available in cases where the trip neither starts nor ends in the pricing area, but has the option to go through it. In these few cases, forcing the tour mode to be toll to avoid penalizing travelers twice for paying the same toll might be considered.

The toll cost coefficients used in the trip mode choice model are the same as the out-of-pocket cost coefficients.

Highway and Transit Assignments

For each time period, the highway assignment models read the following eight person trip tables:

- DA;
- SR2;
- SR3+;
- Trucks and commercial vehicles;
- DA Toll;
- SR2 Toll;
- SR3+ Toll; and
- Trucks and commercial vehicles with toll.

After converting the trip tables to vehicle trips, these trip tables are assigned using a multi-class highway assignment. The impedance is the same generalized cost function used for skimming, which includes both the cost of bridge tolls and the cost of value tolls. Any HOV restrictions are maintained as is done in the current model. Beyond these HOV restrictions, the toll trip tables are able to traverse any links. The no-toll trip tables will be restricted from traversing links where the value toll flag is greater than zero, and the toll for that occupancy and period is greater than zero. These results are consistent with the paths resulting from skimming. Additional classes of users are introduced for the model's area pricing mode, as discussed in that section.

The introduction of toll nests did not warrant any changes to the transit assignment models.

Non-Resident Trips

Non-resident trips, including commercial vehicles, external trips, and visitor trips are not subject to the same behavioral framework as normal personal travel. Instead, for each of these components, a binary logit choice model was developed to split the trip tables into toll and no-toll trips. Visitors and external trips use a $15/hour VOT. Commercial vehicles use a $30/hour VOT.

Distributed VOT

The Phase 2 models were enhanced to include VOT distributions, rather than using fixed average VOT for each income class. In a mode choice model, value-of-time is not an explicit model coefficient, but implied from the ratio of the time coefficient and the cost coefficient. Therefore, there are three possible ways to incorporate a distributed VOT in a mode choice model—using a distributed time coefficient, using a distributed cost coefficient, or using distributed values of both.

The utility of money should vary with income, as well as with personal circumstances. It makes sense that a single person earning $60,000 per year would have a different utility for money than someone trying to raise a family of four on the same income. It also makes sense for those two individuals to have very different utilities of time, where one traveler may need to make it to his child's soccer game, and another may have no specific time restrictions. From a practical standpoint, however, it is not clear what greater effects varying the time coefficient might have, particularly on the user benefit calculations required for New Starts analysis. Since it is safer to vary only the cost coefficient, that approach is taken for RPM-9.

Structurally, a work VOT and a non-work VOT are selected for each individual when the work location choice model is run. These VOT are written with the person record in the output file. All remaining models read these VOT and use them in combination with the in-vehicle time coefficient, to calculate the cost coefficient for the model being run. In this way, each individual has a single VOT for work and a single VOT for non-work that are consistent across all models.

The method for determining VOT (in 1990 dollars) for each person is:

- Divide the household income by the number of full-time household workers plus half the number of part-time household workers. If there is less than one worker in the household, do not divide. The result is the household income per worker.
- Divide the household income per worker by 2,080 hours to get the average wage rate per worker for that household.
- Construct a log-normal VOT distribution where the mean is half the wage rate for that household, and the sigma is 0.25. Draw from this distribution to obtain the work VOT.
- Calculate the non-work VOT as 2/3 the work VOT.
- Impose a minimum of $1/hour and a maximum of $50/hour.
- For persons less than 18 years old, impose a maximum of $5/hour.
- An option is provided in RPM-9 to use the standard, average VOT for each income group. Table 18 shows a comparison of these averages, and the average of the distributed values. The model was calibrated using the distributed VOT, so it is not clear what effect the standard values would have on the calibration results.
- VOT distributions for different population and travel segments are shown in Figure 30 through Figure 35.

Table 18. Comparison of average distributed VOT with non-distributed.

Purpose	Income Range	Non-Distributed VOT (1989 $/hr)	Distributed VOT (1989 $/hr)
Work	$0-30k	$3.61	$3.66
	$30-60k	$10.82	$8.19
	$60k+	$18.03	$16.53
Non-Work	$0-30k	$2.40	$2.49
	$30-60k	$7.21	$5.46
	$60k+	$12.02	$11.45

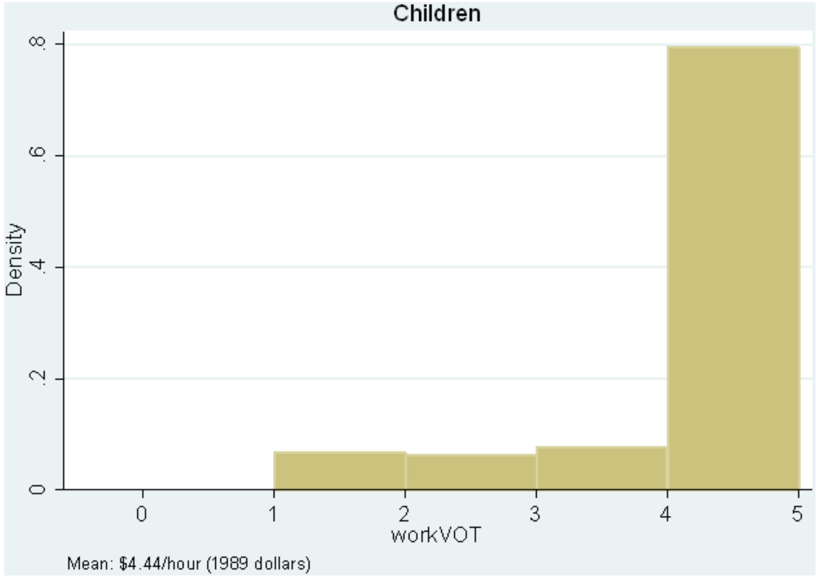

Figure 30. VOT distribution for children.

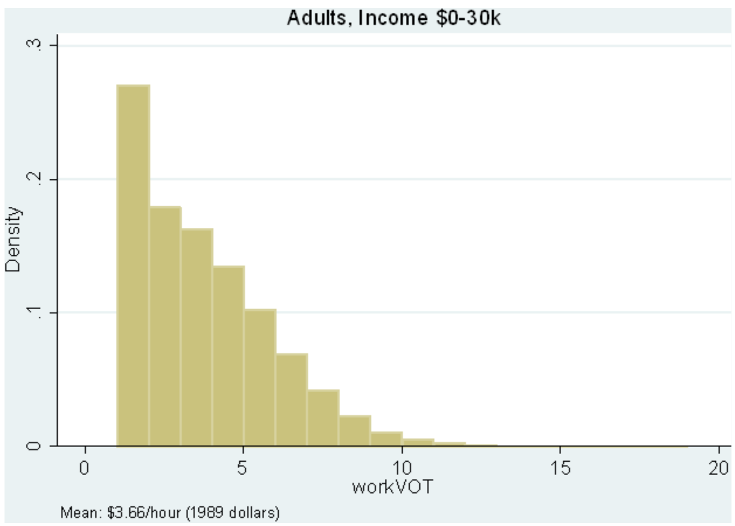

Figure 31. VOT distribution for adults in households with income $0–30k.

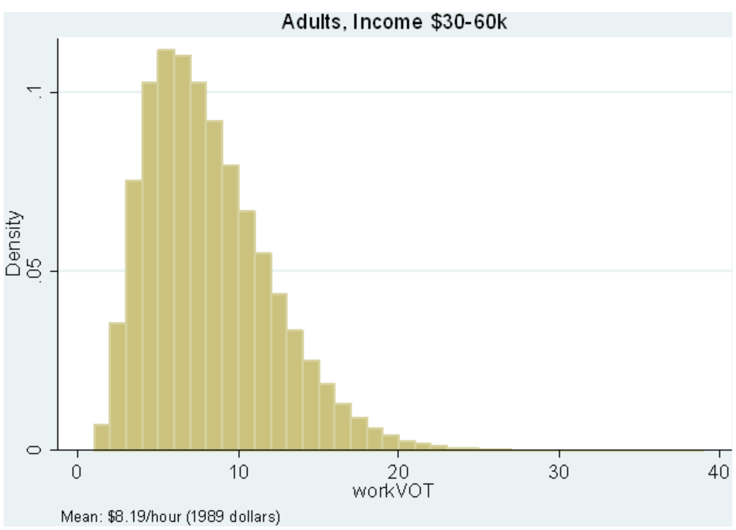

Figure 32. VOT distribution for adults in households with income $30–60k.

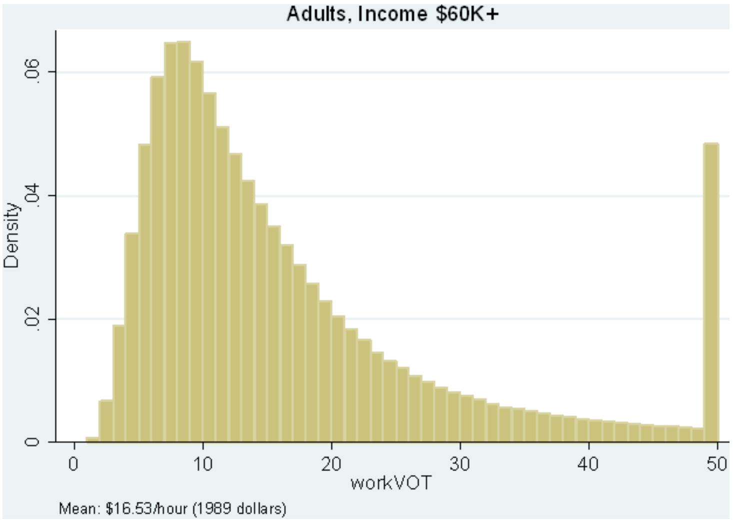

Figure 33. VOT distribution for adults in households with income $60k+.

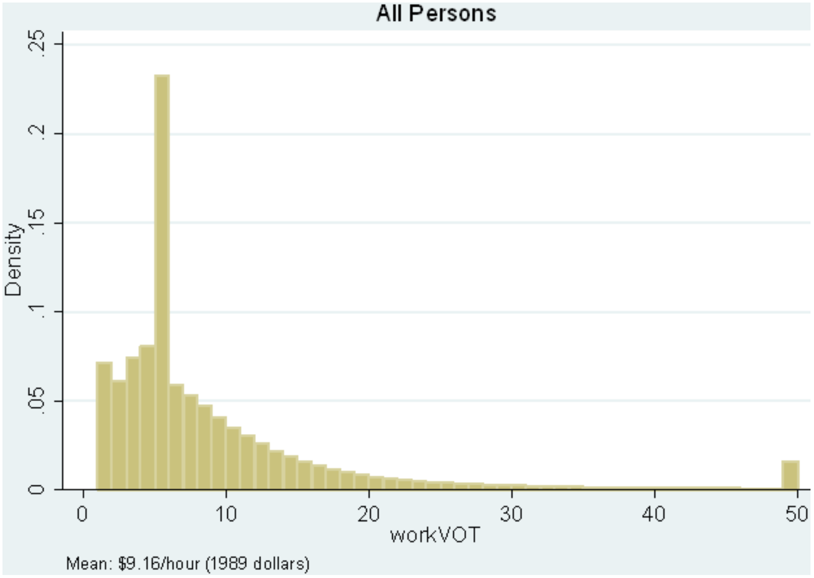

Figure 34. Work VOT distribution for all persons.

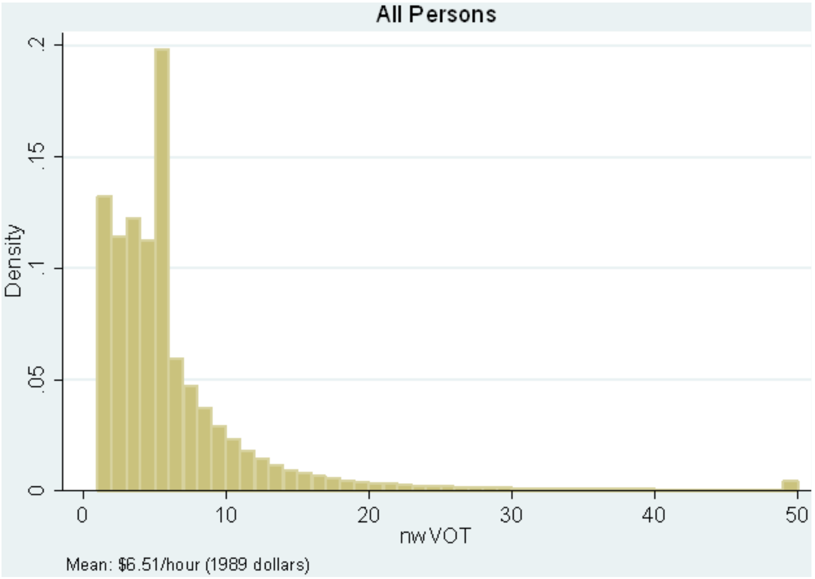

Figure 35. Non-work VOT distribution for all persons.

Area Pricing Logic

Two basic schemes are under consideration for how to operate a pricing system. A cordon approach would require that autos pay a toll any time they traverse a toll link. If a driver entered the pricing area three times in one day, he would be required to pay the toll three times. The second possible scheme is an area pricing approach: once the toll is paid by a vehicle, that vehicle can enter or exit the pricing area an unlimited number of times throughout the day. The mechanism to model the area pricing approach is discussed here.

A binary flag is included in each of the control files to specify if the area pricing mode should be used. If set to zero, the standard cordon pricing method is used. The model does not allow for a mix of the two approaches; it is one or the other.

The basic approach is that tours are sorted first in priority order, then in chronological order. The first time a traveler enters the pricing area, she must pay the full toll. For all subsequent travel, there is no toll charged. Changes to the individual models for area pricing are outlined below.

Workplace Location Choice. The workplace location decisions are assumed to be at the top of the hierarchy, so there is no difference from the cordon pricing mode.

Tour Generation. The tour generation models are responsible for writing the tour records in priority order for each person. The work or school tour is always first, followed by all other tours in chronological order.

Tour Mode and Destination Choice. The tour mode and destination choice program read the tours in priority order, as written by tour generation. The program stores a variable to keep track of when the person ID changes. Within the tours made by a single person, if any previous tour has chosen a toll mode, a flag is set indicating that the value toll was already paid. If this flag is true, the cost of value tolls in the toll alternative is zero. The rules of operation are:

- First (highest priority) tour of the day sees the full toll cost.
- If a toll mode is chosen, subsequent tours for that same person have the value toll cost coefficient set to zero. This means that he can go anywhere, for zero additional toll. The coefficient is changed instead of the cost itself, because the toll cost is used to determine if the toll alternative is available. If the toll cost > 0, then the alt is available.
- If a person has already paid and the toll alternative is available (with zero toll cost), the non-toll alternative becomes unavailable. The non-toll alternative is unavailable because it is dominated. There is no reason to incur extra time avoiding toll links if there is no need to.

Intermediate Stop Location Choice. The intermediate stop location models read the already paid flag created by the tour mode choice models and apply the logic:

- If a tour has already paid, the toll cost coefficient is set to zero. Intermediate stops on that tour can stop anywhere for no additional charge.
- If tour has not already paid, but the tour mode is toll, then the toll cost coefficient is set to zero, and intermediate stops can occur anywhere for no additional charge. This is distinct from the case above, because the first tour of the day, where the toll must be paid at the tour level.

Trip Mode Choice. In trip mode choice, the individual trips on each tour are processed chronologically. The costs are treated normally until the first trip is found that pays the toll. After that point, the value toll costs are zero. Switching is allowed at the trip mode choice level, either from a toll tour mode to a no-toll trip mode, or from a no-toll tour mode to a toll tour mode. The specific logic for area pricing in trip mode choice is:

- If the tour is coded as already paid and a toll alternative is available, then any no-toll alternatives are not available, and the value toll cost coefficient is set to zero.
- For the first tolled tour of the day (toll tour mode, but already paid is false), the individual trip paying the toll is identified. Each trip is processed in the order that they occur. The initial trip/trips see the full cost until one chooses a toll trip mode. Subsequent trips are given a value toll cost coefficient of zero and treated as having already paid.
- Following the choice of modes, any auto trips that have already paid the toll are segregated into separate trip tables such that they can be assigned separately.

Non-Resident Trips. The non-resident trip tables are split into toll, non-toll, and already paid, just like the residents. The toll/no-toll choice uses simple logit models, where the VOT is $15/hour for external and visitor trips, and $30/hour for commercial trips.

In these aggregate models, it is not possible to explicitly track which trips have paid and have not. Instead, the cost coefficients are divided by the average number of times that the same traveler is expected to enter the pricing area in a day. Lacking any observed data, the model uses the following assumptions:

- External travelers enter once per day,
- Visitors enter twice per day, and
- Commercial vehicles enter twice per day.

Note that these entries are only the number of inbound trips, assuming that exiting the pricing area is free. Following the choice of the toll or no-toll alternative, the toll trips are split into two trip tables for those who have to pay the toll in assignment, and those who have already paid it. This split is done by dividing by the number of entries per day.

Assignment. For consistency with the choice models, four additional user classes are introduced to the highway assignment process, bringing the total to 12. The new classes are:

- DA Already Paid;
- SR2 Already Paid;
- SR3+ Already Paid; and
- Trucks and Commercial Vehicles Already Paid.

These new classes are necessary to avoid further penalizing the vehicles that have already paid the toll. The methods for assigning the trip tables are:

- No Toll trips are assigned using the full cost and are not allowed to use any links with a value toll on it.
- Toll trips are assigned using the full cost, but are permitted to use any links.
- Already paid trips are assigned with zero cost of any value tolls and are permitted to use any links.

Feedback Implementation

Previous CHAMP models did not include feedback from assignment to the demand models. They were just run once, based on pre-skims created from assigning MTC trip tables. This approach was adequate for many applications, but is limiting for the Mobility and Pricing Study. A goal of congestion pricing is to reduce congestion. While travelers with a low VOT are less likely to drive to the pricing area, some travelers with high VOT may be more likely to drive to the pricing area if the travel time savings compensate for the cost. The only way to account for this effect is to feed the travel times from the final assignment back to the skimming process and re-run the models. The details of the RPM-9 feedback approach are described here.

Several research presentations on the topic of feedback were reviewed. Each involves some empirical tests for a specific model system and attempts to evaluate what approaches work well for that model. The goal is a method that converges to a stable result in a relatively small number of iterations. The presentations discuss three main topics:

- How to measure convergence,
- How to combine iterations to achieve convergence, and
- How many iterations to run.

Slavin, et al. (2007) found that averaging link flows using the method of successive averages seems to work well. Boyce, et al. (2007) advocated averaging trip tables instead of link volumes, and found that a constant weight on each new iteration works well. Gibb and Bowman (2007) worked on the Sacramento model and used an approach where they started with a small sample in the demand models for early iterations and increased the sample sizes with later iterations. Vovsha, et al. (2008) advocated averaging both trip tables and network volumes based on the experience with the New York model. The approaches presented found generally good convergence in the range of 4-10 iterations, with declining returns for increases in the number of iterations. They all emphasized that their results are not necessarily transferable and that they should be tried with a specific model system to see what works best.

Given this information, the following approach was implemented for RPM-9. The approach may be modified as the model is tested and used if its behavior warrants.

1. Call all of the initialization scripts, and run the first assignment using MTC trip tables (implemented in runModel.bat).
2. Run an iteration of the demand models and assignments, given a specified iteration number, weight for combining the previous and next iterations, and sample rate (implemented in runIteration.bat). Each iteration includes the following steps:
   - Each iteration runs everything from the highway skims through the highway assignment.
   - The core models are run with the specified sample rate. They are run six times and averaged, since there is little incremental cost given the distribution across multiple machines.
   - At the end of the iteration, the link volumes of the resulting networks are averaged with the link volumes on the input network using the weights specified.
   - A report is written (to feedback.rpt) showing the differences in the assignment results and the differences in the trip tables.
   - The averaged networks are renamed to serve as the basis for skimming for the next iteration, and the trip table is copied for comparison after the next iteration.
   - All other files are over-written during the next iteration.
3. RPM-9 runs a fixed number of iterations. Using a fixed number should make scenarios more comparable if results fluctuate a bit from iteration to iteration. It runs four iterations with the parameters shown in Table 19.
4. On the first iteration, there is zero weight given to the previous assignment, because it is based on the MTC trip tables, not the SF-CHAMP trip tables. On the final iteration, the networks are still averaged, but the final assigned networks are kept.

Table 19. Averaging parameters for each feedback iteration.

Iteration	Sample Rate	Weight for Previous Link Volumes	Weight for Current Link Volumes
1	8	0	1
2	4	0.5	0.5
3	2	0.67	0.33
4	1	0.75	0.25

6.1.3 Model Estimation and Structural Changes

After the interim Phase 2 models were completed, the RPM-9 was further enhanced to more realistically capture travelers' time-of-day responses to pricing, an important consideration for the study team. At the same time, the tour generation models and vehicle availability models were modified to account for the potential suppression of trips due to pricing, and the VOT distributions were estimated from stated preference survey data.

SP Survey

In July and August 2007, Resource Systems Group administered a survey of travelers driving to downtown San Francisco. The SP survey was designed to help understand traveler's response to a potential entry fee into the downtown area. A total of 663 respondents completed a series of experiments, where they traded off cost, shifted their trip time, or changed to transit. The full report is available in RSG (2007).

Model Sequencing

The sequencing of time-of-day choice within the travel models is a classic chicken-and-egg problem. When choosing a time-of-day, one might expect that travelers would consider the travel time between their origin and destination for the mode they have chosen. For example, auto trips might be likely to shift out of the peak due to congestion, but transit trips might be likely to shift into the peak due to the higher frequency of transit service. Accounting for this would require knowledge of both mode and destination. Similarly, when choosing a mode, travelers might consider their origin, destination, and departure time. Finally, when choosing a destination, travelers may be sensitive to mode and departure time.

One approach to resolving this issue would be to build a joint mode, destination, time-of-day choice model. Such a model, however, would have a large number of alternatives, and likely be unwieldy and difficult to calibrate. Another good approach, and the one used here, is to assert a priori logical sequencing of choices, and to use Logsums from downstream models in the upstream choices. The project team believes that the most logical sequencing of these three choices within the RPM-9 framework is:

1. Destination choice,
2. Time-of-day choice, and
3. Mode choice

To accomplish this sequencing, the time-of-day choice model uses mode choice Logsums for the time-of-day alternatives being considered. The destination choice model could use time-of-day Logsums as a measure of impedance between zones, but this would break the traditional understanding of how a destination choice model works and enter a level of theoretical abstraction with which the project team was not comfortable. Instead, the destination choice model works by starting from initial simulated times-of-day for each tour and choosing a destination by considering the mode choice Logsums for that initial time-of-day. The time-of-day model then replaces the initial time-of-day with the actual chosen time-of-day. The only purpose of the initial simulated time-of-day is to provide a basis for destination choice, so the details of how those are determined are not particularly important. In this case, the old time-of-day model from CHAMP 3 is run, which provides a simulated distribution equivalent to the actual distribution. In this way, the chicken-and-egg problem is resolved and the models operate in a consistent manner.

The final sequencing of all models is:

1. Choose a workplace location, assuming an AM peak departure, PM peak return, and autos greater than or equal to workers.
2. Choose the vehicle availability, considering the destination choice Logsum at home, at work, and the mode choice Logsum between home and work.
3. Run tour generation, with consideration for the destination choice Logsum at home, at work, and the mode choice Logsum between home and work.
4. Determine the initial simulated time-of-day using the CHAMP 3 time-of-day model.
5. Choose primary destinations for non-work tours, considering the initial simulated time-of-day and the mode choice Logsum.
6. Choose the tour time-of-day for all tours, considering the chosen destination, and mode choice Logsums.

7. Choose the tour mode, considering the chosen destination and chosen time-of-day.
8. Choose locations for any intermediate stops.
9. Run trip mode choice given previously chosen primary and intermediate destinations, previously chosen times-of-day, and the previously chosen tour mode.
10. Assign highway and transit trips.
11. Run the trip time-of-day model (explained in more detail below) to allocate auto trips to more detailed sub-periods.

Tour Time-of-Day Choice

For each tour, the tour time-of-day choice model chooses the departure time from home, and the departure time from the primary destination. The time periods used are the five periods consistent with the skims:

- Early AM (EA): 3:00-5:59 AM,
- AM Peak (AM): 6:00-8:59 AM,
- Midday (MD): 9:00 AM-3:29 PM,
- PM Peak (PM): 3:30-6:29 PM, and
- Evening (EV): 6:30 PM – 2:59 AM.

The return time period must be the same as or later than the departure time period. Therefore, the model has 15 alternatives:

- EA to EA,
- EA to AM,
- EA to MD,
- EA to PM,
- EA to EV,
- AM to AM,
- AM to MD,
- AM to PM,
- AM to EV,
- MD to MD,
- MD to PM,
- MD to EV,
- PM to PM,
- PM to EV, and
- EV to EV.

This structure is equivalent to the old time-of-day models, except that it is applied for all tours, not just for the primary tour of the day. Tours are scheduled first in priority order, then in temporal order. Therefore, if there is a work or school tour, that is scheduled first, followed by any other tours, then any work-based sub-tours. If there is more than one other tour, they are scheduled in the order they occur in the initial simulated times-of-day. Secondary tours are subject to the time constraints imposed by previously scheduled tours, thus preventing any overlap. For example, if a work tour has already been scheduled for the AM to PM, then another tour that is being scheduled can occur in the AM to AM or the PM to PM or the PM-EV, but it cannot occur in the MD to PM or EA to EV because that would conflict with the work tour. Sub-tours must be within the bounds of their parent tour.

Trip Time-of-Day Choice

The trip time-of-day model determines a detailed departure time for each auto trip. Within the peak periods, the resolution is half-hour periods. Outside of the peaks, more aggregate periods are used. In addition to the highway travel time and cost for each sub-period, the model considers the amount of shift from the desired departure time.

This model structure corresponds to the format of the stated preference survey, where respondents were asked about a recent trip they made to downtown San Francisco, and what they would do if prices were imposed for different time periods: shift before the pricing period, shift after the pricing period, or switch to transit. For example, if the desired departure time is 8:00 AM, and the alternative being considered is a 9:00 AM departure, then the shift is 60 minutes.

Figure 36 shows the effect of time shifts on the utility function.

When the trip time-of-day model was implemented within the RPM-9 model stream, it is run after the trip mode choice model, not jointly with mode choice as in the estimation above. It is run using half-hour periods in the peaks, a one-hour buffer at the edge of the peaks, and more aggregate periods in the off peaks. The temporal alternatives are:

- EA300: 3:00–4:59 AM,
- EA500: 5:00–5:59 AM,
- AM600: 6:00–6:29 AM,
- AM630: 6:30–6:59 AM,
- AM700: 7:00–7:29 AM,
- AM730: 7:30–7:59 AM,
- AM800: 8:00–8:29 AM,
- AM830: 8:30–8:59 AM,
- MD900: 9:00–9:59 AM,
- MD1000: 10:00–10:59 AM,
- MD1100: 11:00 AM–1:29 PM,
- MD130: 1:30–2:29 PM,
- MD230: 2:30–3:29 PM,
- PM330: 3:30–3:59 PM,
- PM400: 4:00–4:29 PM,
- PM430: 4:30–4:59 PM,
- PM500: 5:00–5:29 PM,
- PM530: 5:30–5:59 PM,
- PM600: 6:00–6:29 PM,
- EV630: 6:30–7:29 PM, and
- EV730: 7:30 PM–2:59 AM.

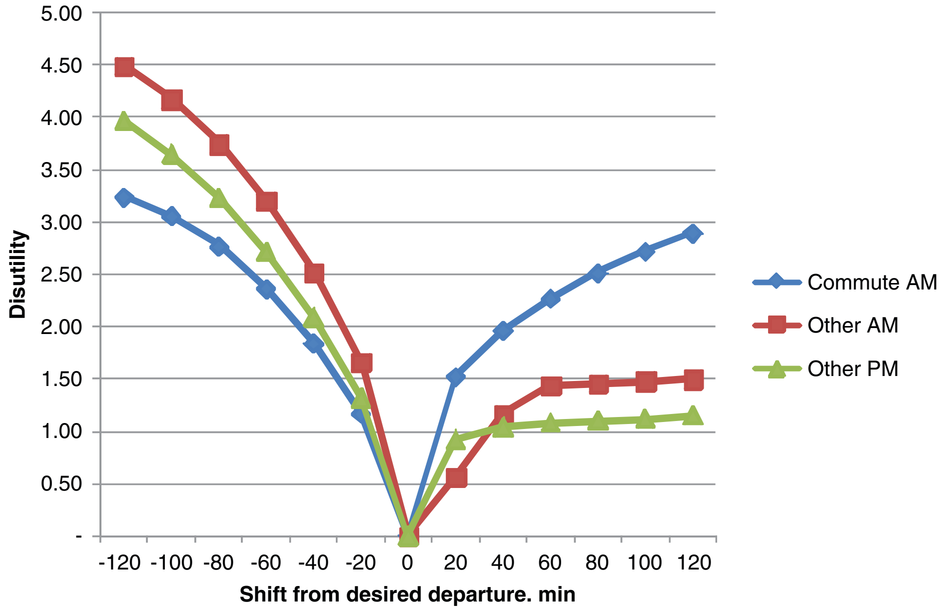

Figure 36. Effect of time shift on utility.

The model considers the tour time-of-day, and requires that the chosen trip time-of-day be within 1 hour of the tour time. For example, a trip whose tour time is AM peak can choose EA500, any alternative within the AM peak, or MD900.

To deal with the shift variables appropriately, a desired departure time is chosen for each trip from the observed distribution of departure times within each main period. Once this desired time is chosen, then a shift can be calculated for any alternative.

Travel times for each alternative are derived by:

1. Starting from the loaded highway networks output from assigning trips for the five main periods.
2. Factoring the main period volumes into sub-period volumes using constant factors on all links, derived from traffic counts.
3. Factoring the main period tolls into sub-period tolls using factors specified by the user. This allows the user to model a higher toll for the peak-of-the-peak.
4. Skim the shortest paths for each sub-period based on these factored networks.

The detailed temporal distribution for factoring is derived from traffic counts, as shown in Figure 37. Hourly traffic counts were available on state highways from Caltrans, and 15 minute counts were available for a cordon around the pric-

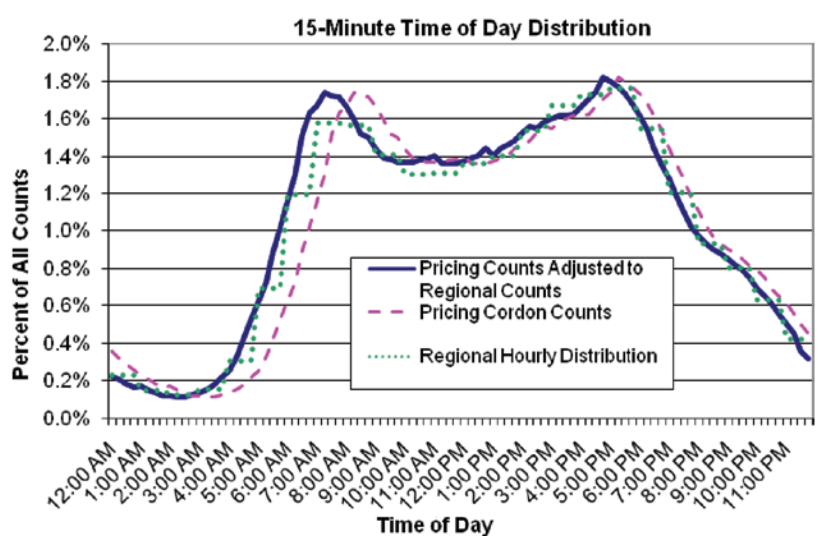

Figure 37. Diurnal traffic count distribution.

ing area. The downtown counts were shifted somewhat from the regional counts, so the detailed downtown area counts were adjusted to better match the regional distribution.

VOT Estimation

The SP data were also used to estimate VOT distributions for use throughout the model stream. This was done by estimating a joint mode and departure time choice model, except with mixed logit, rather than nested logit. Mixed logit is important in this case because it allows the user to estimate a distribution on a coefficient, rather than just the mean value. In this case, a distribution was estimated on the travel time variable, asserting a lognormal form. The cost coefficients are estimated as standard, nondistributed coefficients segmented by income. The resulting model is shown in Table 20. The most important result of this estimation is the mean and median VOT shown at the bottom of the table.

When the estimated VOT distributions are plotted as lognormal functions the curves are the shapes shown in Figure 38. These distributions are used in RPM-9 and replace those used in the Phase 2 models.

6.1.4 Model Calibration

After implementing the structural changes, RPM-9 was calibrated to match observed data for the 9-county area.

Table 20. Trip time-of-day mixed logit estimation results.

Variable	Coef.	Std. Err.	z Parameter	Prob > z	95% Interval Conf. (lower & upper bounds)	
Mean						
cost0_30	-0.2884	0.0456	-6.33	0.000	-0.3777	-0.1990
cost30_60	-0.1968	0.0193	-10.20	0.000	-0.2346	-0.1590
cost60_100	-0.1661	0.0151	-11.02	0.000	-0.1956	-0.1365
cost100p	-0.1349	0.0119	-11.33	0.000	-0.1582	-0.1115
shift_earl~r	-0.0126	0.0012	-10.85	0.000	-0.0149	-0.0103
shift_later	-0.0206	0.0022	-9.53	0.000	-0.0248	-0.0164
delay_1_5	-0.0127	0.0062	-2.07	0.039	-0.0248	-0.0007
delay_1_10	-0.0050	0.0063	-0.79	0.430	-0.0173	0.0073
transitWalkTime	-0.0307	0.0044	-6.95	0.000	-0.0393	-0.0220
transitDriveTime	-0.0307	0.0111	-2.75	0.006	-0.0525	-0.0088
transitFreq	-0.0166	0.0071	-2.34	0.019	-0.0304	-0.0027
transitXfers	-0.2434	0.0889	-2.74	0.006	-0.4176	-0.0693
transitDrive	-0.4426	0.1639	-2.70	0.007	-0.7637	-0.1214
bart	-0.0180	0.1659	-0.11	0.914	-0.3432	0.3072
caltrain	0.2834	0.1889	1.50	0.133	-0.0868	0.6537
muniMetro	-0.0851	0.1653	-0.52	0.607	-0.4091	0.2388
prepeak	0.2987	0.0891	3.35	0.001	0.1241	0.4733
postpeak	-0.5271	0.1013	-5.20	0.000	-0.7257	-0.3286
transitAlt	-0.2223	0.2014	-1.10	0.270	-0.6170	0.1725
travel_time	-3.9231	0.2338	-16.78	0.000	-4.3813	-3.4649
Standard Deviation						
travel_time	0.8709	0.3215	2.71	0.007	0.2408	1.5010
Ratios to Mean In-Vehicle Time						
Walk Time	1.06					
Drive Time	1.06					
Transfers	8.42					
Wait Time	3.49					
Constants						
Prepeak	-10.34					
PostPeak	18.24					
Transit	7.69					
Bart	0.62					
CalTrain	-9.81					
Muni Metro	0.34					
Time Coefficient Statistics						
Median	-0.01978		exp(coef)			
Mean	-0.0289		exp(coef + sd^2/2)			
Standard Dev	-0.03079		mean * sqrt(exp(sd^2) -1)			
VOT by Income Group		**Median**	**Mean**			
0-30k		$4.12	$6.01			
30-60k		$6.03	$8.81			
60-100k		$7.15	$10.44			
100k+		$8.80	$12.86			

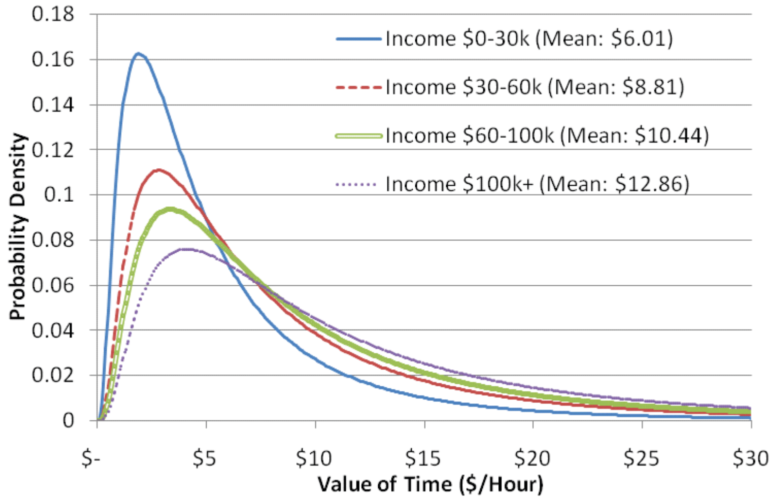

Figure 38. VOT distributions estimated from mixed logit.

The following section discusses the calibration process, final model coefficients, and comparisons to observed data.

The calibration targets were derived from the 2000 Bay Area Travel Survey (BATS 2000). They are generally in the same format as the targets used to calibrate CHAMP 3, but are not restricted to only San Francisco residents.

An extended set of traffic counts was used to validate the highway assignment results. The previous CHAMP 3 count database included 1,091 counts, all within San Francisco. An extended database was created with an additional 617 counts in the remaining eight counties. These counts are from the Caltrans hourly count database, for the years 1998 through 2000. SFCTA staff coded each count to the network links.

Additional observed transit data were provided by MTC, and are the same as those used to calibrate the 2000 base year for the MTC model. These data include boarding counts for each transit operator in the region.

Previous (CHAMP 3) calibration efforts focused on mitigating the initial under-prediction of highway volumes at a system-wide level. Building upon that successful calibration, the RPM-9 calibration moved to the next level, and focused on calibrating to bridge volumes and screenline volumes by time-of-day. In mitigating this issue, a number of modifications were made to the model system:

- Updated the factors used to convert from the total period volume to the hourly volume within the period based on recent traffic counts. Table 21 shows the revised peak hour percentages used for assignment.
- To balance the above change, and maintain appropriate congested travel speeds, introduced an adjustment factor of 1.2 applied as a product to the volumes in the volume-delay functions.
- Upgraded Embarcadero, Sunset, and Great Highway to super-arterials, reflecting divided medians and lower cross traffic.
- Converted Golden Gate Bridge and Bay Bridge from Area Type 3 (urban) to Area Type 1 (CBD), reflecting their narrow lanes and lower speed limits.
- Converted the Bay Bridge Toll Plaza to Facility Type 5 (ramp), reflecting a lower capacity at the plaza.
- Shifted commercial vehicle and internal-external trips in the markets that cross the Bay Bridge or Golden Gate Bridge out of the peak periods.

6.1.5 Conclusions

The SCFTA case study demonstrates how an ABM can provide clear advantages over trip-based models in the analysis of pricing policies. The limitations of trip-based models (lack of policy sensitivity and insufficient market segmentation) can be overcome with more advanced models such as SF-CHAMP. There are, however, a number of issues that remain to be addressed by ABMs in practice. First, this model, like most ABMs, relies on static equilibrium high-

Table 21. Revised peak-hour percentages for assignment.

Period	Percent in Peak Hour
EA	46.3%
AM	34.8%
MD	15.4%
PM	33.7%
EV	17.3%

way assignment algorithms. It is common knowledge that such techniques fail to adequately address congestion due to their lack of ability to reflect queuing. One of the advantages of priced facilities (particularly dynamically priced facilities) is that they offer more reliable travel times than competing congested facilities where the variability of travel time can be quite onerous. We need better tools to reflect reliability and address the value of reliability on travel decisions. The impacts of pricing on long-term choices such as vehicle ownership, workplace location, residential location, and ultimately firm location need to be better understood. Most ABMs are based on cross-sectional data and unable to fully capture the long-term behavior associated with the introduction of pricing policies. Hopefully as more policies become implemented, more data will be available to improve this critical aspect of travel demand models.

6.2 Improvement of the New York ABM for Manhattan Area Pricing Study

6.2.1 Objectives of the Study

Area Pricing Concept in New York

This section reviews the demand modeling that has been done with adaptations of the New York ABM for the planning and analysis of New York City's PlanNYC and its congestion pricing component in particular. The modeling of a Congestion Pricing Zone (CPZ), or a proposed area pricing concept for the Manhattan CBD similar to the London pricing scheme, began with work done for the New York City Partnership in 2005 and evolved in the subsequent modeling in support of the development of the City of New York's long range transportation investments plan or "PlanNYC 2030" in 2006-2007. In this work, and in the subsequent Pricing Commission review phase mandated by the New York state assembly its approval of the City's submittal of an Urban Partnership Agreement grant application in mid-2007, the new York ABM was adapted and refined to assess congestion reduction and other transportation impacts associated with various proposed pricing options, as well as for alternative strategies aimed at achieving similar levels of congestion reduction for travel to, from, and within Manhattan.

The nature and variety of pricing forms and policies considered in the study represented a real challenge from the modeling standpoint. To accomplish this, a number of modeling enhancements and refinements to the standard New York ABM platform were developed and applied to support the estimation of impacts on different traveler markets and various transportation system performance measures. These modeling improvements allowed for better understanding of the likely behavioral responses to the changes in road pricing and congestion levels associated with Manhattan congestion management programs.

The congestion pricing, tolling, and other congestion mitigation strategies that required evaluation and modeling for New York City's planning comprised a fairly wide range and challenging set of transportation policies and actions as described in the next section. The modeling and evaluation of these pricing alternatives and other policies needed to address a spectrum of related transportation issues, within the complexity of the New York Metropolitan Region, including many that are unique in comparison to the other metropolitan regions. In particular, the following aspects were of primary importance:

- Transit service to and from Manhattan is extremely developed from most areas of the region. The current transit share in commuting to and from Manhattan is close to 80%. As such, transit represents a very good alternative to the auto for commuters and other travelers to Manhattan, but since most of the transit lines are already crowded in peak hours, very little transit capacity is available to accommodate additional riders who might be influenced to switch from driving due to congestion pricing.
- Existing auto commuters to the CBD represent a special market that needs to be well understood before any policy could be seriously considered. Some of them (although not the majority) may be considered "captive" users for either of two reasons. For most of the existing auto commuters, surveys have shown that employer and other subsidies are prevalent with respect to parking cost, tolls, and vehicle operating cost, making the use of a car compelling. In addition to these drivers, the most substantial share of auto commuters to CBD comes from "outer boroughs" of New York City, where transit service from these areas is the most limited, without walk to subway or commuter rail options.
- Residence of commuters and other travelers to Manhattan is important since some other pricing policies are differentiated by the place of residence. From this point of view, three major segments could be distinguished: 1) residents of Manhattan who contribute to intra-Manhattan reverse commuting out of Manhattan, 2) residents of other four New York City boroughs who contribute to relatively short commute trips to Manhattan, and 3) residents of outer suburbs from four states (New York, New Jersey, Connecticut, and Pennsylvania) who contribute to longer commute trips to Manhattan.

Congestion Pricing Zone (CPZ)

Geographically, the Manhattan CPZ was defined as part of Manhattan South of 60th Street; see Figure 39. This definition

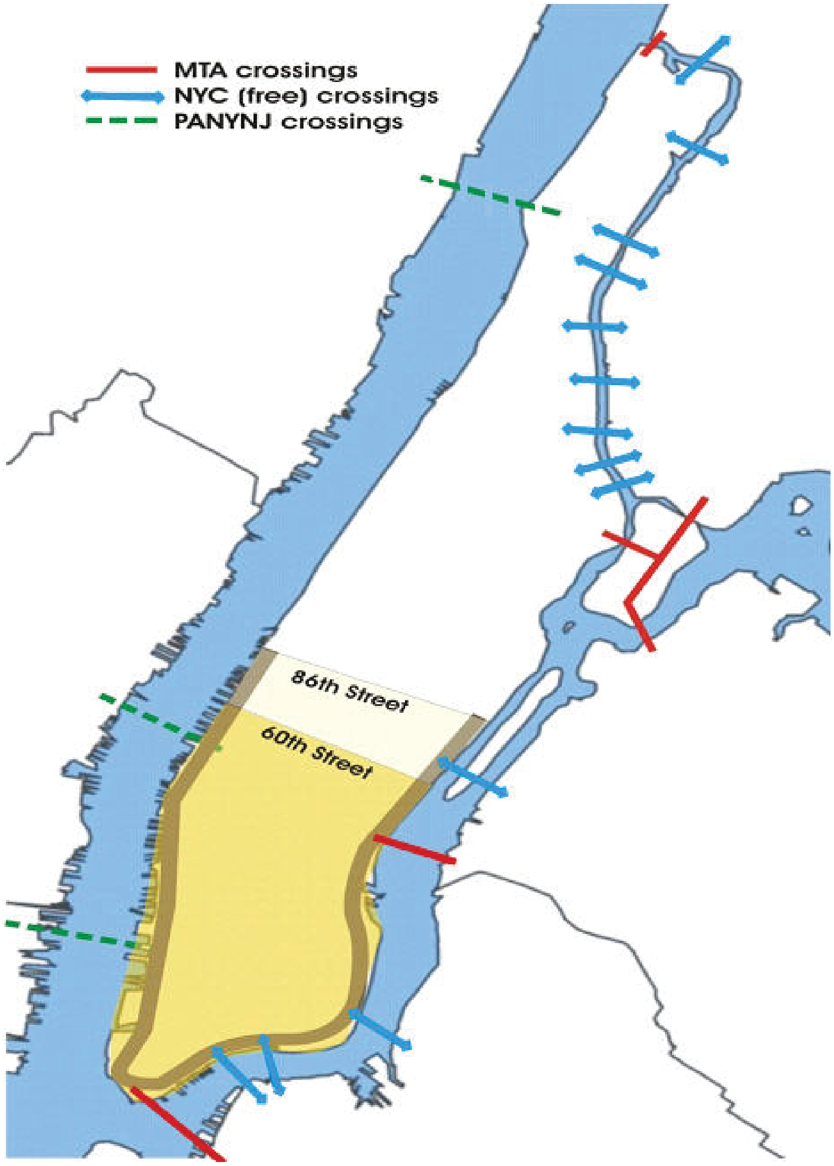

Figure 39. Manhattan CPZ and existing bridges and tunnels.

was more conservative compared to the previously implemented (preliminary) study where the border was at the 86th street. The CPZ has several portals (bridges and tunnels) connecting it to the rest of the metropolitan region. They can be grouped in the following way:

- Tolled bridges and tunnels of the Metropolitan Transit Authority (MTA),
- Tolled bridges and tunnels of the Port Authority of New York and New Jersey (PANYNJ), and
- Free bridges of the New York City (NYC).

In addition to the set, there are the Harlem River bridges that are not directly connected to CPZ, but are still relevant choices for some travelers to and from Manhattan.

6.2.2 Modeled Options for Area Congestion Pricing

Main Area Pricing Options and Other Strategies Modeled

The study considered a wide spectrum of pricing forms and policies where each scenario was defined as a combination of the following main characteristics:

- Type of charge. Alternatives included daily fee paid once a day regardless of the number of trips to CPZ (i.e., daily permit) and (recurrent) toll paid for each trip.
- Rate charged. Alternatives were formulated in terms of the amount charged, flat versus variable tolls by time of day, pricing schedule (12 hours, 24 hours, etc.), and toll off-

set (full or partial credit) for travelers who already paid a creation toll on one of the MTA or PANYNJ tolled crossings. Sub-alternatives included surcharges for non-EZ-pass vehicles (based on license plate reads) and surcharges for taxi trips.

- Northern boundary of CPZ. Alternatives included 86th St. and 60th St.
- Policy for intra-zone trips. Alternatives included free, discounted, and full-fee options for staying in CPZ.
- Policy for through trips. Alternatives included providing a free peripheral route around CPZ on FDR Drive and Rt. 9A or charging on it.
- Trip direction charged at cordon crossings. Alternatives included 2-way (inbound and outbound) tolls and 1-way (inbound only) tolls.
- Differentiation by vehicle type. Alternatives included different specific toll schemes for trucks and taxis compared to the base fee for auto.

In the course of the study, several additional pricing and congestion-mitigation strategies were formulated and required modeling:

- Higher tolls on existing tolled Manhattan crossings (MTA and PANYNJ).
- Introduce tolls on the currently free Manhattan bridges. Alternatives included a subset of four East River free bridges or all Manhattan bridges (including Harlem River and Henry Hudson).
- License Plate Rationing. Alternatives included different ways to impose prohibitions on entry to CPZ by vehicle license plate number. They included either 10% or 20% of vehicles for each day.
- Parking Policies. Alternatives included reduction in free parking permits for City employees (targeted zones in CPZ) and elimination of Manhattan resident parking tax rebates.

The main characteristics of the CPZ scheme are summarized in Table 22. The initial plan has undergone a substantial revision with regard to such characteristics as the North boundary, direction of charge, imposing of intrazonal charge, providing a free periphery, charging taxis, and license plate rationing.

Modeling Challenges Associated with Area Pricing

The ABM developed for the New York Metropolitan Transportation Counsel (NYMTC) and first deployed for planning in 2001 was used as the modeling platform for the area pricing study. Some of the pricing forms studied could be addressed adequately with little or no modification of the model, due to the structural advantages of the NYMTC ABM and its ability to model individual household, person, and tour/trip records in the microsimulation fashion. For those pricing features that required new methods to be introduced, the ABM structure allowed for the addition of incremental improvements in a natural and consistent way. For example, for the license plate rationing options, in which the number of vehicles in each household is modeled endogenously and auto availability for each member of the household is explicitly evaluated in the mode choice model, it was possible to introduce new controls to test these strategies that mirror the logic of actual travel decision-making, in this case focused on the initial stage of modeling intra-household car allocation and subsequent use by affected households. In this sense, the ABM and the microsimulation implementation of it contributed both to the generation of more reliable estimates of impacts than a conventional aggregate model could, as well as offered the ability for the planner to report and explain these responses logically, and in considerable detail for specific travel markets of concern, e.g. low-income population, residents of specific neighborhoods, and tour types.

Another important advantage of the NYMTC ABM is that it considers travel tours as units for mode, destination, and time-of-day choice decisions. This ensures realism and consistency of the modeled choices. It is fundamentally different from the trip-based models that do not recognize internal linkages across the trips in the same tour and can result in conflicting choices of modes and destinations for different trips made by

Table 22. Characteristics of the CPZ.

Characteristic	Initial plan	Final recommendation
Daily fee or toll per trip	Daily fee	Daily fee
Duration	12 hours (6 AM – 6 PM)	12 hours (6 AM – 6 PM)
Flat or variable & amount	Flat $8	Flat $8
North boundary	86th St.	60th St.
Direction of charge	2-way	In-bound
Intrazonal charge	Yes	No
Through trips	Free periphery	No free periphery
Toll offset	Yes	Yes
Taxis	Free	$1 trip charge
License Plate Rationing surcharge	None	Yes 1$

the same person as parts of the same tour. In the context of area pricing, this consistency of the NYMTC ABM was of primary importance since it allowed for capturing impacts of pricing applied for one time-of-day period (for example, the AM peak period) on the other periods of the day (for example, PM when the return commuting mostly occurs).

Aside from the ABM issues, special network methods were also developed to address the single fee policy feature of area congestion pricing, i.e., a one-time charge or permit to travel to or within the charged zone for some designated period of time, in contrast to the simple toll transaction-based charges that are easily implemented, for both network skimming and assignment by means of toll link attributes. While a full and logical implementation to address this unique aspect of an area charging fee would be possible in the ABM structure that operates with entire day individual patterns, due to time and budget limitations, a simple scaling of cordon link fee tolls, reflecting daily trip frequencies for different tour types, was applied.

A related, but even more difficult issue, was the need to consider and credit tolls paid on existing tolled crossings into Manhattan, such as those operated by PANYNJ and MTA. For example, in some scenarios, the policy to be tested might be an $8 cordon fee, but with the $5 EZ-pass toll paid at the Lincoln Tunnel credited, the effective cost for a driver using the tunnel to enter the CPZ would be only $3. Using link-based tolls with the standard highway network procedures found in existing modeling platforms requires various configurations of dummy links for these toll increments associated with crossing the cordon and reflecting the upstream tolls. Corresponding procedures were developed, generally resulting in a realistic representation of the policy with respect to costs that travelers would consider in their destination, mode, and route choice. A more robust implementation may be the application of node to node based toll algorithms, not yet tested in this application.

As part of this work, aspects of the available data and elements of the modeling technology that could be further refined to increase the precision and level of confidence of the forecasts have been identified. These included more specific methods of representing and modeling a complex system of cordon fees and tolled crossing credits, as well as time-of-day choice model sensitive to tolls and congestion levels, and responsiveness to specific parking policies and pricing. These additional enhancements could be implemented within the New York ABM and could serve to further increase levels of confidence in the planning forecasts, as well as to possibly support an investment grade level of T&R forecasting and analysis.

6.2.3 Structure of the NYMTC ABM

General Model System Structure

The NYMTC ABM represents an advanced structure that is based on tour-based and activity-based modeling principles applied in a micro-simulation fashion. This model allows for detailed and behaviorally realistic analysis of traveler responses to pricing.

The NYMTC ABM structure is presented in Figure 40 [see also NYMTC (2004) for a more detailed technical description]. It has four major modules applied consecutively with possible feedbacks involving all or some of the modules:

- Tour generation that includes household synthesis, auto ownership, and tour frequency choice models,
- Tour mode and destination choice that includes pre-mode choice between motorized and non-motorized travel, primary destination choice, entire tour mode combination choice, stop-frequency choice, and stop-location choice,
- Time-of-day choice and pre-assignment processor that include tour time-of-day allocation for outbound and inbound directions, and aggregation tours and stops micro-simulation results to mode and time-of-day period trip tables,
- Traffic and transit network simulations (assignments) that are implemented by mode and vehicle class, by time-of-day periods.

The first three modules are implemented as fully-disaggregate micro-simulation procedures working with individual records for the synthesized population (households, persons, tours). The last module is currently based on standard aggre-

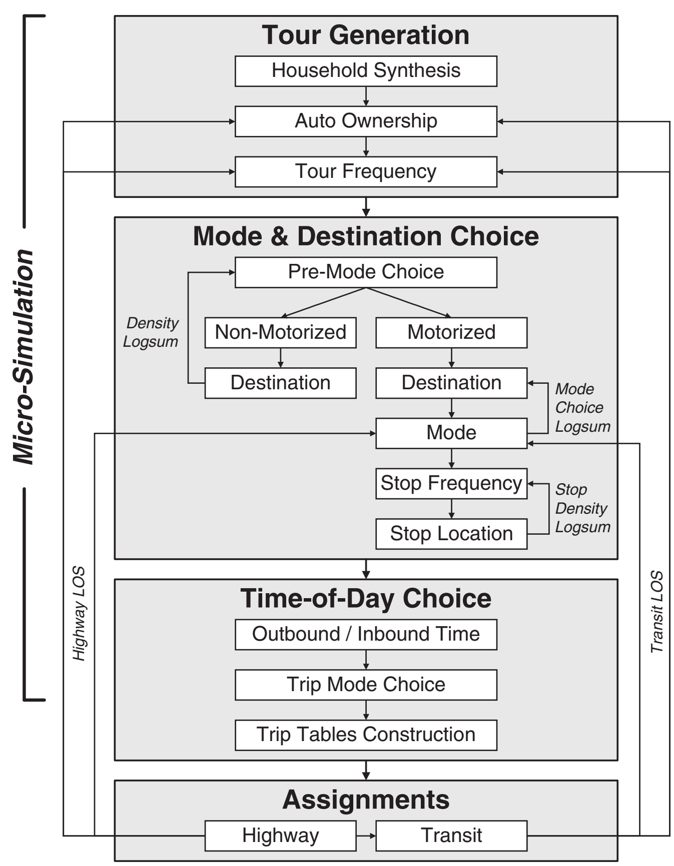

Figure 40. Structure of the NYMTC ABM.

gate (zone-to-zone) assignment algorithms. The application software supports numerous feedbacks to be implemented until equilibrium is reached. LOS skims after the last stage can be fed back to the mode and destination module, as well as to the tour-generation components through accessibility indices.

The tour-generation module of NYMTC ABM model consists of three successive models that include a household population synthesizer, an auto-ownership model, and a tour-frequency choice model. The household synthesis is based on the predetermined socio-economic controls (number of households, population, labor force, and income) for each zone. The auto ownership choice model is applied for each household and is sensitive to the household characteristics and residential zone accessibility by auto and transit respectively. The tour-frequency model is implemented at the person level. There are three person types and six travel purposes that yield 13 tour frequency models taking into account that children cannot make tours to work, at work or university tours; and non-working adults cannot make tours to work or at work. Each model is essentially a multinomial logit construct having three choice alternatives (no tours, one tour, two or more tours). The set of the tour-frequency models is ordered and linked in such a way that choices made for some purposes and household members have an impact on the other choices of the same person, as well as for the other household members.

The mode and destination module starts with a pre-mode choice step, where each tour is assigned to either motorized or non-motorized mode of travel. Density of non-motorized attractions is essentially a log-sum from the subsequent destination-choice model for non-motorized travel with individual attractions available in a 3-mile radius around the tour origin. If the motorized option is chosen, then the motorized branch of the algorithm is activated. First the mode and primary destination choice for the entire tour is modeled (without intermediate stops). It can be thought of as a nested structure where destination choice comes at the upper level of the hierarchy, while mode choice is placed at the lower level conditional upon the destination choice.

The motorized destination choice model has been calibrated by eight purposes (six original purposes with additional subdivision of work tours by three income categories). In the microsimulation framework, the destination choice model is applied as a doubly constrained construct (either fully constrained or relaxed constrained). Constraining the destination ends is achieved by removing the chosen (taken) attraction from the zonal size variable after each individual tour simulation. For fully-constrained mandatory purposes (work, school, university), an entire attraction unit is removed. For relaxed constrained non-mandatory purposes (maintenance, discretionary, at work), only a part (0.5) of the attraction unit is removed.

The mode-choice model has been estimated for six purposes as a nested logit construct with differential nesting depending on the purpose. In most cases, drive-alone and taxi modes proved to be in separate nests, while transit and shared-ride mode were nested in different combinations.

In the next stage of the motorized branch of the application, intermediate stops are modeled conditional upon the chosen mode and primary destination for the tour. Stops are modeled by means of two linked choice models: stop frequency and stop-location. The stop-location model includes a zonal stop-density size variable that is similar to the attraction size variable. The composite log-sum from the stop-location model is used in the upper level stop-frequency model.

The stop-frequency model has been calibrated for six purposes as a multinomial logit construct. After having considered observed stop frequencies from the survey (it was found that an absolute majority of tours do not have more than one stop on each leg of the tour (90-95%, depending on the tour purpose), a decision was made to limit the number of choice alternatives to the following four: 1=no stops on either outbound or inbound direction; 2=one outbound (from home) stop leg, no inbound (return home) stops; 3=no outbound stops, one inbound stop, and 4=one stop on each direction.

The stop-location choice model is also a multinomial logit construct. Similar to the destination-choice model, the stop-location model requires a procedure for selecting a limited subset of relevant zones (for both model calibration and application) in order to reduce the computational burden. For the stop-location model, however, both the OD of the tour are known from prior processing, thus effective rules were applied to build a spatial envelope that reflects the observed stop patterns.

The current version of the NYMTC ABM has a simple time-of-day model based on a set of predetermined time-of-day distributions segmented by travel purpose, mode, and destination area. One of the identified for further enhancement of the NYMTC ABM includes replacement of the time-of-day distribution with a time-of-day choice model sensitive to person, household, and LOS variables. Currently, time-of-day allocation is followed by trip-level mode choice (in most cases predetermined by the entire-tour mode) and a pre-assignment processing procedure that aggregates the microsimulation results and constructs mode-specific and period-specific trip tables.

Segmentation and Level of Network Details

The basic version of NYMTC ABM, which was used as the platform for the model improvements implemented for the pricing analysis, has the following main structural dimensions:

- Eleven travel modes (drive alone, shared ride-2, shared ride-3, shared ride-4+, transit (including bus, subway, and ferry) with walk access, transit with drive access, commuter rail (with transit feeder lines) with walk access, commuter rail with drive access, taxi, school bus (for tours to school only), and walk (the only non-motorized mode),

- More than 100 population segments including a Cartesian combination of three household income groups (low, medium, high), four household car-sufficiency groups (without cars, cars fewer than the number of workers, cars equal to workers, cars greater than workers), and three person types (worker, non-working adult, child),
- Six travel purposes including work, school, university/college, household maintenance (shopping, banking, escorting children, visiting a doctor), discretionary activity (leisure, entertainment, visiting relatives and friends, eating out), and non-home-based sub-tours originated and ended at work (as a special segment),
- Two freight traffic components that are characterized by a distinctive value of time and willingness to pay: heavy trucks with 3+ axles and light trucks (commercial vehicles) with 2 axles.
- Four time-of-day periods (AM peak 6:00–10:00, midday 10:00–16:00, PM peak 16:00-20:00, and night 20:00–24:00, 0:00–6:00).
- Six vehicle classes applied in the multi-class highway assignment including SOV, HOV-2, HOV-3+, light trucks and commercial vehicles, heavy trucks, and external auto trips to, from, and through the region are allocated by vehicle occupancy.

The New York Region (28 counties in New York, New Jersey, and Connecticut) has a very large and complex transportation network that is a substantial modeling challenge in development of the NYMTC ABM [see NYMTC (2004) for more details]. To address this, the highway network has the following main dimensions and characteristics:

- Very large size including 4,000 traffic zones and 52,800 links of the following major types: 4,950 high-level limited access (highway, freeway) facilities, 26,385 major arterials, 10,765 collector and other (local) facilities, 10,694 centroid and external connectors;
- Unidirectional/dualized coding;
- Conflated network geography and topology based on detailed GIS street network;
- Classified by 21 link types for specification of lane capacities, free-flow speeds, and volume-delay functions; and
- Includes high-occupancy-vehicle lanes and numerous existing toll facilities.

6.2.4 Application Assumptions and Model Adjustments for Area Pricing

Within the limited time framework of the recent planning feasibility stage of the area pricing study, the NYMTC ABM was applied in a simplified version with limited functionality across several dimensions compared to the potential functionality that the ABM microsimulation framework could provide. The main simplifying assumptions and limitations of the applied approach are discussed.

Fixed Transit LOS

The transit network, line itineraries, and frequencies, as well as other components of transit LOS, were considered fixed and were not improved across the compared alternatives. As the London area-pricing experiment has shown, the LOS on bus lines was significantly improved as the result of congestion relief, which made transit an even more attractive option in the presence of road tolls. This important additional feedback would be included in the model structure in a next stage of study. Another important factor is that the New York transit system has also reached the capacity limit for many lines serving CBD in the peak periods. Thus, additional modal shift from private auto to public transit should be accompanied by a realistic enhancement of the transit system and consideration of the LOS problems that stem from the train congestion and crowding in transit vehicles. As one policy option, the revenue generated from the area pricing could be effectively used for cross subsidizing the transit improvements. This aspect would also be considered in a next stage of study.

Fixed Time-of-Day Distributions

The current time-of-day model was used with no specific improvement. The current time-of-day model is based on a set of predetermined distributions developed for expected departure time and duration of activity for various travel segments. Although the developed set of distributions is very detailed (more than 60 different combinations are considered by travel purpose, mode, and destination), and is characterized by a very good statistical fit to the observed data and traffic counts, it (in its current form) is not sensitive to pricing and does not include toll or any other travel cost variable that would explain the choice. Development of a new version of the time-of-day choice model that will include pricing as an explanatory variable is underway. For this current stage of the study, travel impacts of pricing were captured mostly with respect to the destination choice, mode choice, and route choice.

Simplified Use of Certain LOS variables

The available basic version of the mode and destination choice models used time-of-day-specific LOS variables (travel time and cost) in a simplified way. Mode and destination choice for mandatory activities (work, school, and university) were based exclusively on the AM peak travel times and cost (reversed commuting in the PM period was assumed to have exactly the same LOS). Contrary to that, mode and destination

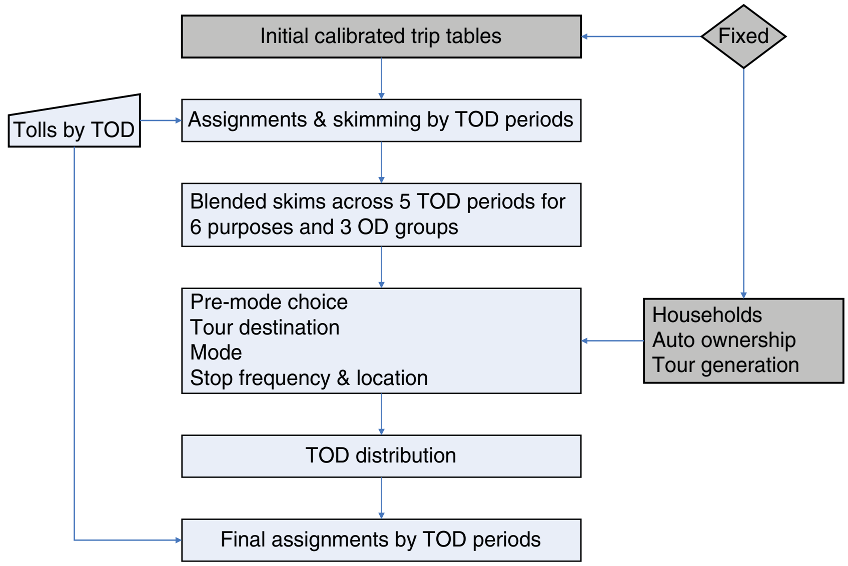

Figure 41. New York ABM application for pricing studies.

choice for non-work travel purposes (maintenance, discretionary, and also at-work) was based exclusively on the Midday off-peak travel times and cost. As a result of this simplification, pricing applied in the AM or Midday period with the basic version of NYMTC ABM would directly affect the mode and destination choice, as well as subsequent route choice in the assignment procedures for these periods. Pricing applied in the PM and Night period, however, would mostly affect route choice in these periods with no direct impact on the mode and destination choice. To overcome these limitations at the current stage, several modifications to the basic version were made. In particular, highway skims for each travel purpose were blended according to the actual mix of time-of-day distributions for each travel segment. Bi-directional tolls were introduced in the destination choice and mode choice utilities.

Model Application Scheme

The model application scheme is shown in Figure 41. The scheme was applied for the base year scenario (without area pricing) and then to the alternative pricing scenarios. Each pricing scenario was simulated for the entire day under regular workday conditions and travel behavior.

The model chain for each pricing scenario started with the same fixed set of initial calibrated trip tables, list of synthetic households with the predicted number of autos owned by each household, and list of travel journeys (tours) generated by each household and person. These components were simulated once for the base scenario without tolls, and then re-used for simulation of each of the pricing scenarios to ensure comparability of the results across scenarios. The basic chain of models that were re-run for each scenario included: initial assignment and skimming, mode and destination choice, time-of-day distribution, and final assignments (route choice).

The base version of the NYMTC ABM was refined in terms of time-of-day choice periods applied for network simulation and LOS variables. The standard 4-hour PM period (4:00 PM – 8:00 PM) was split into two 2-hour periods: 4:00 PM – 6:00 PM and 6:00 PM–8:00 PM. This was essential for modeling pricing alternatives with charging time between 6:00 AM and 6:00 PM. This resulted in five time-of-day periods instead of the original four.

For traffic simulation and skimming of tolls, a combination of network and matrix techniques was employed (see Table 23).

For trips from the outside areas to CBD, as well as for traversal trips from outside to outside areas that cross CBD, pricing charges were skimmed from the link tolls coded for each entry on the cordon line. For internal trips within the pricing

Table 23. Representation of tolls in area pricing scheme.

Trip origin	**Trip destination**	
	In the pricing area	**Outside the pricing area**
In the pricing area	Imputed toll in the skim matrix	
Outside the pricing area	Network skim (cordon crossing)	Network skim (cordon crossing)

area, link tolls cannot be applied, so for these trips the charge was imputed to the corresponding part of the matrix skim. Trips from CBD to outside areas were not tolled according to the area-pricing concept described earlier. Technically, trips within the pricing area and outgoing trips from the pricing area are distinguished by the time threshold for free driving in CBD (5 min or so). It is assumed that for trips from CBD outside, 5 min will be enough to reach the cordon line.

For each travel purpose in daily models of destination choice and mode choice, blended highway skims across all time-of-day periods weighted by the actual time-of-day distribution were applied. Transit skims are impossible to blend in general because of the discrete nature of transit availability parameters. Transit skims for each travel purpose were chosen based on the most representative time-of-day period for each purpose (AM for Work, University, and School; Midday for Maintenance, Discretionary, and At-Work) as implemented in the base version of the NYMTC ABM.

In order to model toll offsets assumed in certain pricing scenarios with credits for tolls paid at the existing PANYNJ and MTA tolled facilities, special dummy links connecting the existing facility to the pricing area with reduced fees were introduced.

Special provisions were made for better modeling taxi trips, which represent one of the major sources of traffic in the Manhattan CPZ. The pricing options evaluated included differential charging policies applied to taxis (from a full exemption to reduced or even full charge). For this reason, taxis were singled out as a special segment at the network simulation stage. Trip tables for taxis were added as a separate vehicle class to multicall assignments in addition to the existing six vehicle classes, which made seven vehicle classes.

Modeling of Daily Fee

One of additional advantages of the advanced micro-simulation approach essential for daily area pricing is that it allows for a proper scaling of the charge for those travelers (and associated vehicles) that implement multiple trips to and from the pricing area in the course of the day. At the current stage of the study, average scaling factors for each time-of-day period were applied. The following scaling factors were calculated based on the average observed number of trips to the priced area per individual for each period when the given trip occurs:

- AM peak – 0.92
- Midday – 0.87
- PM peak – 0.88
- Night – 0.93

These adjustment factors were applied for all link toll values in the network, as well as for the imputed parts of the toll skim matrices for the corresponding period of a day. Overall, adjustment factors proved to be close to 1. This means that most of the auto travel to, from, and within the pricing area is associated with a only one tour (by vehicle) per day. This is quite reasonable for trips to and from CBD. For internal trips within the pricing area, it should be noted that the majority of them are made by transit and non-motorized modes. Thus, two or more auto tours of the same person are rarely made by auto.

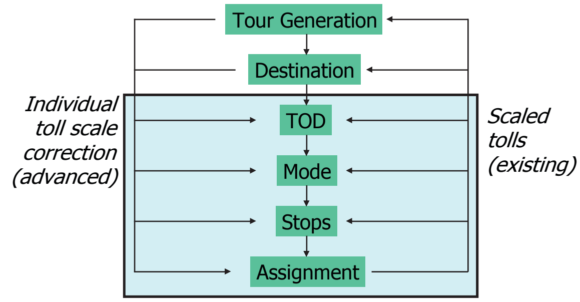

Figure 42. Daily area pricing equilibrium.

Micro-simulation with calculation of the scaling factors for each person (vehicle) individually is the next stage of study. A more advanced approach is shown in Figure 42 on the left side compared to the currently applied scaling factors (on the right side).

The advanced approach is based on individual scaling coefficients calculated for each person based on the actually implemented number of trips to CPZ as modeled at the previous iteration. The individual toll scale can take a value of 1, ½, ⅓, . . . $1/n$, depending on the number of trips (n) to CPZ made by the modeled person in the micro-simulation process. These individual scales affect tour and trip time-of-day choice and mode choice, as well as route choice in the assignment procedure. This technique can be most effectively incorporated within the iterative equilibrium framework where several inner iterations are implemented with a fixed set generated for each person and fixed destination for each tour.

6.2.5 Application Assumptions and Model Adjustments for License Plate Rationing

License plate rationing is a travel management policy that represents a challenge to modelers. The essence of license plate rationing is that a certain percentage of vehicles (10% or 20%) are subject to a no-drive to CBD ban based on the last digit of license. This type of policy cannot be addressed with a 4-step model, but an advanced micro-simulation framework opens a way to effectively model it.

The corresponding modeling technique essentially falls into the general category of individual parameter variation, one of the most powerful advantages of micro-simulation. In contrast to the aggregate 4-step models where any variation in parameters requires an explicit segmentation of the entire trip table by all combined categories, micro-simulation allows for any variation in individual parameters, either in the form of predetermined categorized segmentation or randomly drawing from a distribution accounting for situational variability. It can be incorporated at practically no cost in terms of model complexity. The individual parameter variation technique can be applied to any behavioral parameter used in the demand model. For example, it can be applied to VOT as described in the San Francisco ABM application for pricing studies in Section 6.1.

In the context of license plate rationing, the individual parameter variation principle is applied through the Household Auto Availability model (see Figure 43).

In the micro-simulation model run, for each household some cars are randomly tagged as unavailable for travel to CPZ based on the rationing policy that defines the probability of disabling a car. This affects the household car sufficiency variable (number of cars minus number of workers) that has a strong impact on mode choice, as well as on choices of frequency and location of intermediate stops for the given tour. In the model application at this stage assume there is no impact on tour frequency choice and primary tour destination choice. This makes the comparison across scenarios easier since the same subset of tours with the destination in CPZ that are affected by the rationing is fixed.

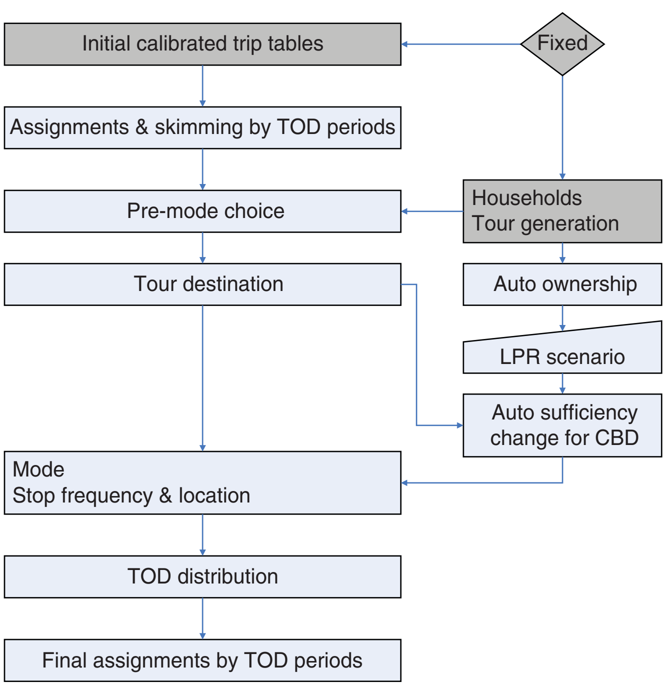

Figure 43. New York ABM application for license plate rationing.

Using a household car-sufficiency variable rather than person-car availability allows for an accounting of interchangeable vehicle allocation and use within the household. A behavioral aspect of license plate rationing that is not currently modeled (and yet to be explored) is whether the travelers could adjust their weekly schedules in view of this policy and re-plan their trips to CPZ on the days where their cars are available.

6.2.6 Aggregation of Model Output for Analysis

The NYMTC model provides a very detailed output of the micro-simulation procedure where all activities and travel are described for each of the 20 million persons residing in the region. At the current stage of the study, several aggregate statistics that are of primary importance for analysis of the area pricing impacts and comparison across pricing alternatives are the focus. The calculated aggregate measures can be broken into two main categories:

- Network-based statistics that are skimmed from the network simulations (traffic assignments)
- Matrix-based statistics that are calculated based on the produced OD trip tables

Each of the groups of measures (network-based and trip-table-based) is initially calculated for each of the five time-of-day periods (AM, Midday, early PM, later PM, and night) and then summarized for the entire day. The network-based statistics provide insights into traffic impacts and conditions. They are complemented by the trip-table-based statistics that describe the mode and destination choice impacts including transit modes and activity participation levels by destination.

The network-based statistics are calculated for each of the 14 super-zones defined for the project. Additionally, it was decided to single out such important and critical network facilities as the bridges and tunnels connecting the Manhattan CBD area with the other NYC boroughs and New Jersey, which formed a 15th group, as well as a cordon line (periphery) to form a 16th group. This allowed for tracing impacts on pricing, specifically on the modes congested bottleneck facilities, as well as for analysis of possible consequences of the free-periphery scenarios on congestion along the cordon line itself. The resulting 16 basic network components were mutually exclusive and collectively exhaustive with respect to the regional geography, and they constituted one of the main levels of analyses for which a set of reports was routinely produced for each model scenario analysis. These reports also were used as inputs to the analysis of the environmental impacts. In addition to the predefined 16 basic network parts, some smaller local sub-network components were analyzed to provide examples of area pricing impacts in different parts of the region. The network-based statistics were also segmented by vehicle types (SOV, HOV2/taxi, HOV3+, external autos, trucks, and commercials). The following characteristics were calculated for each of the 16 geographical components of the network and by each of the vehicle types:

- Total vehicle miles traveled (VMT)
- Total vehicle hours traveled (VHT)
- Average speed (miles/hour) as a ratio of VMT to VHT
- Total revenue generated from toll facilities coded as toll links (except for intra-CBD charges)

The matrix-based statistics were calculated for each of the 14×14=196 OD pairs between super-zones. This allowed for detailed level of analysis of modal shifts and impacts on the total and mode-specific number of trips made to each destination. These statistics were also used to provide inputs to the analysis of area-pricing impacts on commercial activity and development in CBD. The mode trip tables produced by the adapted NYMTC model are segmented by seven highway vehicle types (SOV, HOV2/taxi, HOV3+, trucks, commercials, eternals, and taxis) and four transit modes (transit with walk access, transit with drive access, commuter rail with walk access, and commuter rail with drive access). The following characteristics were calculated for each of the 196 OD pairs and 10 modes:

- Number of trips;
- Mode share (number of trips made by the mode divided by total number of trips); and
- Total revenue generated from area pricing not coded as toll links (intra-CBD charges).

However, even the aggregate super-zone level for both network-based and matrix-based statistics provide a great level of detail that is useful for professional analysis, but is too stratified for presentation of the area-pricing impacts to a wider audience. Further aggregation was needed to provide focused insights into the most important aspects of area pricing and comparing across the pricing alternatives. This additional level of aggregation included the following segments:

- For network-based statistics:
  - Entire regional network
  - CBD (pricing area)
  - Bridges and tunnels between CBD and the other areas
  - Cordon line (periphery)
- For matrix-based statistics:
  - Total regional trips
  - Trips to CBD

In additional to the basic outputs described above that were automatically generated for each pricing alternative, several additional reports were generated to highlight some specific features of the scenarios studied. One of them included area pricing impacts on mode choice for work commuters to CBD segmented by income group. This was especially useful to provide a preliminary monitor for equity-related issues associated with highway pricing. Other useful measures were obtained from the tabulation of revenue generated by area pricing versus revenue generated by the existing toll facilities in the region. This was useful to illustrate the overall revenue balance in the region including (possible) negative impacts of the pricing applied in CBD on patronage of the existing toll facilities. Additionally, several useful statistics such as time-average time-saving per auto commuter trip were calculated by combining network-based and matrix-based data.

6.2.7 Technical Lessons Learned

Variable Bi-Directional Tolls

From the experience of modeling different pricing options with the NYMTC BPM, an important general issue has emerged that could only partially be resolved at this preliminary stage of study since it was not in a focus of the area pricing study itself. This issue relates to how, within an ABM framework, to properly model tolls collected in both directions of travel when the tolls are differentiated by time-of-day and directions. This is increasingly a realistic situation, especially with newer forms of pricing like dynamic pricing, where toll rates and schedules are flexible and demand-responsive.

Consider a scenario where in the outbound (from home) direction (to CBD) commuters have to pay $5 in the AM peak period and $3 in the off-peak period, while in the inbound direction (from CBD) they have to pay $4 in the PM peak period and $1 in the off-peak period. In reality, and depending on the combination of outbound and inbound time-of-day periods, the travelers will have to pay either $9 or $7 or $6 or $4 for the round trip. The differential cost will affect traveler choices including route choice, mode choice, time-of-day choice, and destination choice (if flexible). Only route choice in the highway network can be considered independent by directions. The other choices are essentially based on the entire-tour time and cost.

However, it is difficult to ensure that all sub-models of the travel model would see the true toll value for each demand segment. With a trip-based 4-step model, it is impossible to ensure a reasonable level of behavioral realism across choices of mode, time-of-day, and destination. A trip-based 4-step procedure essentially breaks tours into disconnected outbound and inbound trips that are considered independently. Depending on the time-of-day period and direction the model will apply tolls of $5, $3, $4, or $1. The true toll values of $9 or $7 or $6 or $4 for the round trip can never be applied. With a tour-based ABM, it is still a non-trivial task to ensure a full consistency across all travel dimensions, but a much more realistic approximation can be achieved. Behavioral realism in this context is primarily achieved by a tour-level bi-directional time-of-day choice and mode choice that consider all possible combinations of outbound and inbound tolls. It is also essential to implement traffic simulations with the corresponding level of temporal resolution (1 hour or even less) to inform the time-of-day choice model on the variable toll rates and congestion levels.

Toll Differentiation by Payment Type and Individual Discounts

Another important general issue relates to the proper incorporation of various toll discounts by payment type (including cash, EZ-pass, and transponder that are substantially differentiated in the pricing policies of the toll facilities in the New York region), individual discounts for residents of the pricing zone and/or low-income people, as well as different credit-based pricing forms and employer-provided reimbursement policies with respect to tolls and parking. From the modeling perspective, all these measures and policies result in the need to consider multiple segments of the traveling population, each with different actual tolls experienced and perceived. It is (in principle) impossible to address these segments with an aggregate 4-step model.

The ABM micro-simulation platform, however, provides a solution to the multitude of possible actual tolls with individual discounts. It can be done through the individual parameter variation technique that was successfully applied for license plate rationing and probabilistic VOT. Individual parameter variation can be used in a similar way for all types of payment media and individual discounts if their distribution is known and can be parameterized for the modeled population. The ability to incorporate probabilistically distributed parameters is one of the most powerful features of micro-simulation. The alternative to individual parameter variation (and the only possible way with aggregate 4-step models) is an explicit model segmentation approach that quickly runs into an infeasible number of segments.

6.2.8 Conclusions

The NYMTC ABM is a powerful, flexible, and adaptable tool for modeling various pricing scenarios. Most of the pricing forms modeled in the framework of the current study would have been impossible to evaluate with an aggregate trip-based 4-step model. In the preliminary study, as well as in future possible studies, the multiple advantages of the ABM structure for modeling highway pricing scenarios can be exploited in terms of the following categories of model features:

- Tour-based structure that is essential for the full accounting, in a consistent and coherent way, of tolls collected in both directions by TOD periods. This is, however, conditional upon a level of temporal resolution that would match the details of pricing schedules. Network simulations and modeled time-of-day periods of the standard NYMTC ABM version were modified to match those of the pricing strategies. In particular, the broad 4-hour PM period that is specified as 4:00 PM–8:00 PM in the base version of the NY ABM was broken into two sub-periods: 4:00 PM–6:00 PM and 6:00 PM–8:00 PM. Since variable pricing schemes are frequently a focus of pricing studies, it is essential to have a large set of period-specific simulations, ideally, hourly assignments or a full-day DTA, in order to address different pricing schedules.
- Micro-simulation of individuals that allows for the probabilistic variation of individual parameters including: VOT, car rationing by license plate, toll discounts associated with different payment types and/or population groups. In addition to this aspect of micro-simulation model processing, a fully disaggregate structure of the model output proves to be extremely convenient for the reporting, analysis, and evaluation of the pricing scenarios, in particular the screening of winners and losers, and for equity analysis across different population groups.
- Entire day individual activity pattern that provides a consistent modeling of non-trip based pricing options such as a daily area pricing fee. In this regard, some advanced model equilibration schemes can be considered that incorporate individual-level scaling for multiple trips to the priced area. The essence of the advanced approach is that the toll scaling can be linked to the modeled number of trips to the priced area made by each person.

6.3 Modeling User Response to Pricing with DTA: Baltimore-Washington Corridor

6.3.1 Description of the Study

Analysis and prediction of user response to highway pricing in conjunction with integrated corridor management strategies requires application of a new generation of demand modeling and network analysis tools. This study describes the development and application of a multidimensional simulation-based dynamic micro-assignment system that incorporates individual trip-maker choices of travel mode, departure time, and route in multimodal urban transportation networks. These travel choice dimensions are integrated in a stochastic utility maximization framework that considers multiple user decision criteria such as travel time, travel money cost (i.e., road toll and transit fare), schedule delay, as well as travel time reliability. Based on a multidimensional network representation, an efficient time-dependent least-cost path algorithm is adapted to generate an intermodal route choice set that recognizes time-dependent mode transfer costs and feasible mode transfer sequences. A case study based on a large-scale multimodal transportation network adapted from the Baltimore-Washington corridor is presented in this section to illustrate capabilities of the methodology and provide insight into the potential benefit of the integrated congestion management strategies.

In order to attain the potential of integrated congestion management strategies, it is essential to have tools and methods that are responsive to the needs of the problem environment and to the opportunities offered by emerging ITS technologies. It is essential that these methods be based on an integrated platform representation of the various components of the corridor transportation system, and that it provides seamless movement of vehicular and person flows across these components. Such representation cannot be achieved by juxtaposition of models developed separately for individual system elements, but must be built on a common network framework. Furthermore, these methods should be dynamic and capture the variation of flows over the course of the day, thereby requiring a rich representation of mode and departure time choice decisions of trip-makers. To generate a realistic route choice set in multimodal networks, the path-finding algorithm should be able to realistically account for several practical aspects such as park-and-ride options, waiting at switching places, turning movements at traffic intersections, as well as feasible mode transfer sequences. Moreover, as the fundamental demand input for applying simultaneous dynamic departure time and route choice models, travelers' preferred departure (arrival) time pattern should be estimated and updated using available data sources to support sound evaluation of demand management strategies in actual transportation networks.

To meet these challenges, this study describes the development and application of a multidimensional simulation-based dynamic micro-assignment modeling approach for multimodal urban transportation networks. The next section provides a problem statement, followed by discussion of its conceptual framework and underlying traveler decision model for joint mode and departure time choice. After addressing multimodal network representation issues and presenting an iterative solution algorithm for solving the dynamic trip assignment problem, this study proposes a two-stage procedure to estimate the unobserved preferred arrival time pattern information. Various capabilities of the advanced traffic analysis system are illustrated using a large-scale multimodal network along the Baltimore-Washington corridor.

6.3.2 Problem Statement

The following notation is used to represent variables in the problem formulation and solution algorithm:

i = origin zone index, $i \in I$
j = destination zone index, $j \in J$
m = travel mode index, $m \in M$
T = total duration for which assignments are to be made (analysis period)
τ = departure time interval index, $\tau = 1, 2, \ldots, T$
PAT = preferred arrival time interval index, $PAT = 1, 2, \ldots, T$
t = aggregation time interval index
k = superscript for path
$r_{i,j,PAT}$ = number of travelers from origin i to destination j with the preferred arrival time interval PAT
$r_{i,j}^{\tau}$ = number of travelers from origin i to destination j with the departure time interval τ
$r_{i,j,PAT}^{\tau,m,k}$ = number of travelers from origin i to destination j with the preferred arrival time interval PAT, departing in time interval τ with mode m and route k
$V_{i,j,PAT}^{\tau,m,k}$ = systematical disutility for an alternative from origin i to destination j with the preferred arrival time interval PAT, departing in time interval τ with mode m and route k
$GT_{i,j}^{\tau,m,k}$, $TT_{i,j}^{\tau,m,k}$, $TC_{i,j}^{\tau,m,k}$, $TTSD_{i,j}^{\tau,m,k}$ = path generalized travel time, travel time, travel money cost (e.g. road toll and transit fare) and travel time reliability (in terms of standard deviation), respectively, from origin i to destination j departing in time interval τ with mode m and route k
$AAT_{i,j,PAT}^{\tau,m,k}$, $SD_{i,j,PAT}^{\tau,m,k}$, $SDE_{i,j,PAT}^{\tau,m,k}$, $SDL_{i,j,PAT}^{\tau,m,k}$ = actual arrival time, schedule delay, early schedule delay and late schedule delay, respectively, of an alternative from origin i to destination j with the preferred arrival time interval PAT, departing in time interval τ with mode m and route k
$\Pr_{i,j,PAT}^{\tau,m,k}$ = probability of individual from origin i to destination j with the preferred arrival time interval PAT choosing alternative (τ,m,k)

Consider an urban transportation network $G(N,A)$ consisting of $|N|$ nodes, $|A|$ directed arcs, multiple origins $i \in I$, and destinations $j \in J$. The analysis period of interest, taken as the planning horizon T, is discretized into small intervals $1, \ldots, T$. The time-dependent zonal demand $r_{i,j,PAT}$ over the study horizon represents the number of individual travelers from zone i to zone j with preferred arrival time (PAT). Information on existing transit service in the network is also given, with M denoting the set of available modes. Three modes are considered in this study: drive alone, shared ride, and transit. The transit system, which includes train and BRT, is modeled in terms of its routes and stop locations, scheduled departure times at the starting terminal, the operating fare structure, and the parking cost at the park-and-ride facility. For a home-to-work intermodal trip, commuters first park their cars at park-and-ride stations and then ride a train or a bus to work place. An alternative in the travelers' choice set is considered as a path k that departs from origin i at time τ to destination j by mode m, which has a preferred arrival time PAT. With no loss of generality, the following discussion focuses on home-based intermodal commuters who drive alone on the first segment of their trips.

6.3.3 Conceptual Framework

Multidimensional Simulation-Based Dynamic Micro-Assignment System

The dynamic traveler assignment problem in multimodal transportation networks consists of determining the number of travelers for each alternative and the resulting temporal-spatial loading of vehicles. To this end, several models are systematically integrated to address emerging challenges in the deployment and use of DTA methodologies to support ICM planning and operations decisions. The system features the following three components: (1) traffic simulation (or supply) component, (2) traveler behavior component, and (3) path processing and traveler assignment component. A traffic simulator, namely DYNASMART-P (Mahmassani 2001), is used to capture the traffic flow propagation in the traffic network and evaluate network performance under a given set of intermodal, departure time, and route decisions made by the individual travelers. Given user behavior parameters, the traveler behavior component aims to describe travelers' mode, departure time, and route selection decisions in a stochastic utility maximization framework with multiple evaluation criteria. The third component is intended to generate realistic route choice sets and to perform stochastic network loading for solving the traveler assignment problem.

Figure 44 depicts the multidimensional simulation-based dynamic micro-assignment conceptual framework. The detailed implementation steps of this framework can be found in Zhou, et al. (2008). These can be summarized as follows:

- **Step 1:** Prepare network flow pattern and performance (congestion, reliability, pricing, and schedule delay), as well as traveler individual characteristics (user's preference on time, schedule delay, and mode);
- **Step 2:** Generate alternatives based on generalized costs obtained from Step 1 and augment into a multidimensional choice set based on a time-dependent intermodal least-cost path algorithm;
- **Step 3:** Determine an auxiliary choice probability based on a discrete choice model (e.g., logit-based model) for each traveler to find his/her alternative from a multidimensional choice of mode, departure time, ridesharing, and route combinations;

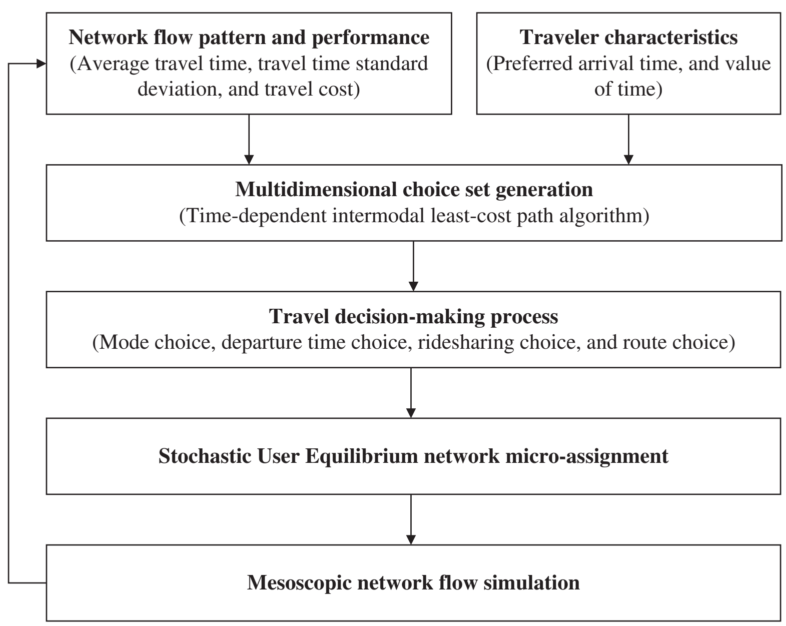

Figure 44. Conceptual framework for multi-dimensional network model.

- **Step 4:** Select alternatives following SUE conditions based on a micro-assignment approach;
- **Step 5:** Obtain network flow pattern and performance using a mesoscopic network simulation tool and feedback to Step 1 until an equilibrium network flow pattern is reached.

Multidimensional Choice Process

To investigate a wide range of integrated congestion management strategies in a multimodal corridor, it is essential to use a rich and policy-sensitive representation of traveler behavior. This study uses a discrete choice model to represent a stochastic joint traveler departure time, mode, and route choice process. An empirically calibrated model of departure time choice has been adapted to explicitly account for several important attributes of travel alternatives, including travel time, early and late schedule delay, and travel time reliability. To extend the above model to allow mode choice options, mode-specific constant terms $Const_m$ are added into the utility function to incorporate all of the characteristics of the traveler and the travel mode not explained by modeled variables. The mode-specific dummy variables are estimated based on a data set from a household activity survey conducted in the study area.

For each traveler with *i, j, PAT,* the systematic disutility equation is

$$V_{i,j,PAT}^{\tau,m,k} = Const_m + \alpha_1 * GT_{i,j}^{\tau,m,k} + \alpha_2 * SDE_{i,j,PAT}^{\tau,m,k} + \alpha_3 * SDL_{i,j,PAT}^{\tau,m,k} \qquad \text{(Equation 23)}$$

where α_1, α_2, α_3 are disutility coefficients for generalized travel time, early schedule delay, and late schedule delay, respectively.

Variability of travel time is an important measure of service quality for travelers, and reliability of travel time is a measure of many ICM benefits, such as HOV and HOT strategies. Thus, a realistic travel decision model should incorporate the reliability criterion. Recall that a common way of linking travel cost with travel time in a utility function is through VOT. Similarly, VOR can be used to quantify travel time reliability. This study considers the travel time standard deviation (TTSD) as a measure of reliability, so the travel reliability equals to TTSD×VOR in terms of dollar cost. To facilitate the conversion of travel time reliability and the interface of the mode choice model with the shortest path calculation, this study combines the path travel time (TT), travel money cost (TC), and travel time reliability into a generalized travel time (GT) term, that is,

$$\begin{aligned} GT_{i,j}^{\tau,m,k} &= TT_{i,j}^{\tau,m,k} + \left(TC_{i,j}^{\tau,m,k} + TTSD_{i,j}^{\tau,m,k} * VOR\right)/VOT \\ &= TT_{i,j}^{\tau,m,k} + \left(TC_{i,j}^{\tau,m,k} + TTSD_{i,j}^{\tau,m,k} * \beta * VOT\right)/VOT \\ &= TT_{i,j}^{\tau,m,k} + TC_{i,j}^{\tau,m,k}/VOT + TTSD_{i,j}^{\tau,m,k} * \beta \end{aligned} \qquad \text{(Equation 24)}$$

where β is reliability ratio defined as

$$\beta = \frac{VOR}{VOT} \qquad \text{(Equation 25)}$$

The travel time standard deviation measure in this study is defined as the standard deviation of the path travel time for paths departing at different travel time aggregation intervals but within the same departure time interval. The aggregation interval refers to the time interval over which travel time and cost measures are averaged and used by the time-dependent shortest path algorithm to calculate the shortest path tree. Given a path *k* with mode *m* from the shortest path calculation module, time-dependent link travel time, turning delay, mode-switching delay from simulation results, this proposed system computes the mean path travel time and the corresponding standard deviation for path *k* at departure time interval τ by backtracking path *k* from its origin and evaluating experienced path travel times for different departure times within the same departure time interval τ.

Depending on the specification of the distribution of the random utility component, a stochastic joint mode, departure time, and route choice model could lead to a wide range of probability forms, such as a path-size logit model in the context of multimodal route choice and an ordered generalized extreme value model in the context of departure time choice. By assuming random error terms are independently identically distributed Gumbel variables, the choice probabilities for each alternative (τ, *m, k*) corresponds to the usual unordered multinomial logit choice function:

$$\Pr_{i,j,PAT}^{\tau,m,k} = \frac{Exp\left(V_{i,j,PAT}^{\tau,m,k}\right)}{\sum_{\tau}\sum_{m}\sum_{k} Exp\left(V_{i,j,PAT}^{\tau,m,k}\right)} \qquad \text{(Equation 26)}$$

Note that more elaborate model forms and structures could be used, because the approach is fully micro-based at the individual traveler level. The use of a standard MNL form entails no loss of generality of the procedure.

Network Representation and Intermodal Path Finding Algorithm

In this study, a single integrated multidimensional network is used to represent multimodal networks with the following link types: regular non-toll links, regular toll links, HOV links, HOT links, and transit links. A transit link could be further classified as a regular bus, BRT, or rail link. For each link, a travel-cost vector and a travel-time vector are defined to specify the cost charged and travel time, respectively, for travelers with mode *m* traversing this link departing at time interval *t.* Travel time on auto links are generated from traffic simula-

Table 24. Link pricing schemes for different modes of travelers.

Travelers	Regular link	Regular toll link	HOV link	HOT link	Transit link
Drive Alone	0	Toll	∞	Toll	∞
Shared Ride	0	Toll	0	0	∞
Intermodal	0	Toll	∞	Toll	Fare

tion. The simulator uses a hybrid (mesoscopic) approach to capture the dynamics of vehicular traffic flow, thus vehicles (passenger cars and buses in this study) are moved individually according to prevailing local speeds, consistent with macroscopic flow relations on links. On the other hand, travel time of a rail link is predetermined by the given train timetable, and the travel time of BRT along a link equals the travel time of the corresponding auto link(s) on which passenger cars and buses are simulated.

To designate certain types of links for travelers using different modes, a link pricing structure is imposed as shown in Table 24. Specifically, drive alone travelers are not allowed to use HOV links, and they need to pay tolls for driving on HOT links. Shared ride passengers can use regular links, HOV, or HOT links without paying any toll, and they are charged only on regular toll links. Only park-and-ride travelers can use transit links by paying fares, and the auto-mode users in the traffic assignment process are not allowed to access transit links.

In calculating shortest paths in transportation networks, a traffic movement penalty dimension can be added into the network structure to efficiently model time-dependent turning delay and movement prohibitions. Based on an efficient network representation technique for intermodal shortest path calculation, this study also uses the movement penalty dimension to capture switching delay at mode transfer points. Specifically, the waiting time for an intermodal traveler is the time between his/her arrival at the terminal and the arrival of the next train/bus that serves the chosen transit line, and the waiting time is associated to a turning penalty from an auto link to its subsequent train/BRT link.

Another important task in intermodal shortest path calculation is how to generate viable transfer mode sequences. For example, park-and-ride travelers for home-to-work trips in the morning need to park their cars before riding the transit system, so walking to their final destinations is the only alternative left after they get off buses/trains. In this case, mode sequences such as auto→transit→auto and transit→auto are infeasible for this type of morning commuter.

Figure 45 illustrates the network representation used in this study for generating candidate feasible routes for the above type of commuter. This simple network contains auto and transit links in parallel along the corridor from origin *i* to destination *j*. For mode transfer movements, only allowed ones are displayed, such as 1→2→3, 2→4→5, 4→6→7. Three transit→auto transfer movements, 3→4→6, 5→6→8, 7→8→9, are disabled. These movements might be enabled when calculating feasible routes for other types of travelers. Without preventing these movements, the paths calculated from the shortest path algorithm might contain non-feasible mode sequences as discussed above. To generate park-and-ride route choice set, the candidate routes must end with transit links in the network. To this end, the movement from auto links to the destination zone connector is not permitted when calculating shortest paths for park-and-ride travelers, and a feasible path has to use transit links to reach the centroid of the final destination zone. Specifically, movements 6→8→*j*, 8→9→*j* are prevented; movement 7→8→*j* is allowed and must be incorporated in any viable path to destination *j*.

After setting up the necessary movement costs, the above intermodal network representation allows travelers to select alternative park-and-ride sites to reach the final destination, corresponding to path *i*→2→4→5→6→7→8→*j* using transfer node 4 and path *i*→2→4→6→7→8→*j* using transfer node 6 in the example. In addition, a transit-only path is also available, *i*→2→3→4→5→6→7→8→*j*, and connectors at the OD ends can be viewed as walking arcs.

Given time-dependent link travel times and movement turning delays as a result of the traffic simulation, time-dependent link costs, and mode-transfer delays, a deterministic time-dependent shortest path algorithm is used to find time-dependent least-cost paths between each OD pair for each mode at each departure time interval. When calculating cost for each mode, the link pricing and movement penalty schemes in the network are reset accordingly for mode-specific restrictions.

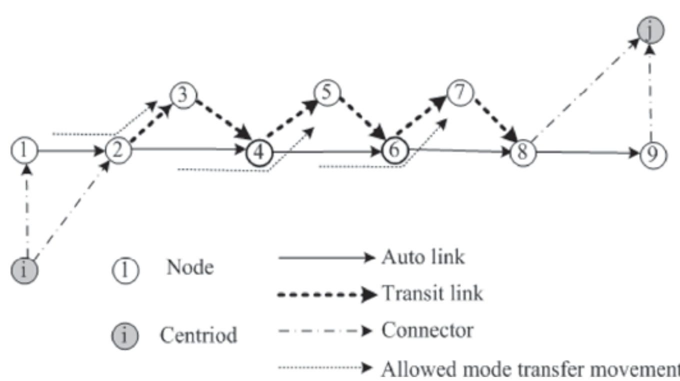

Figure 45. Intermodal network representation for park-and-ride trips.

6.3.4 Multidimensional Dynamic Stochastic User Equilibrium Formulation

Daganzo and Sheffi (1977) defined the SUE condition in urban transportation networks as follows: no user can reduce his/her perceived travel time by unilaterally changing routes. To incorporate travelers' behavior in joint mode, departure time, and route choice, the SUE condition is extended to the dynamic context for multimodal network and define time-varying multimodal stochastic user equilibrium as follows:

Definition 1: DMSUE
For each OD pair (o,d), and for each preferred arrival time *PAT*, no traveler can reduce his/her perceived generalized travel cost/disutility by unilaterally changing mode, departure time, or route.

An alternative, i, in the travelers' choice set, I, consists of a route k that departs from origin o at time τ to destination d by mode m with preferred arrival time *PAT*. Based on the weak law of large numbers, a choice probability $\Pr_i$ can be obtained through alternative flow r_i, $\forall\, i \in I$, divided by total OD demand, $q_{o,d,PAT}$, as shown in Equation 27:

$$\Pr_i = \frac{r_i}{q_{o,d,PAT}}, \forall i \in I \qquad \text{(Equation 27)}$$

The choice probability, $\Pr_i$, $\forall\, i \in I$, is generally defined as a function of the network path flow pattern r. Since a mathematical representation of traffic flow dynamics and an analytical path cost function of network flows are not readily available in the DTA context, this study applies the simulation-based approach by using a mesoscopic network traffic simulator to evaluate a given network flow pattern and to obtain corresponding average experienced travel time, travel time standard deviation, terminal transfer times, and costs.

The time-varying SUE condition can be stated mathematically as:

$$r_i = q_{o,d,PAT} \times \Pr_i(r), \forall i \in I \qquad \text{(Equation 28)}$$

Therefore, the time-varying SUE problem of interest can be formulated as the following fixed point problem that is a dynamic extension of the fixed point formulation technique typically adopted for static SUE Models:

$$r^* = q \times \Pr(r^*) \qquad \text{(Equation 29)}$$

By solving the resulting system of nonlinear equations, a set of alternative flows r^* is found, which is also the solution of the time-varying SUE problem (i.e., r^* would satisfy the condition stated in Equation 28). However, explicit solution of these equations is not typically undertaken for large networks, for which it would not be practical. Alternatively, iterative solution procedures (along the lines of Figure 44) are commonly used for this purpose.

6.3.5 Solution Algorithm

Figure 46 presents a heuristic iterative procedure for solving the stochastic intermodal dynamic traveler assignment

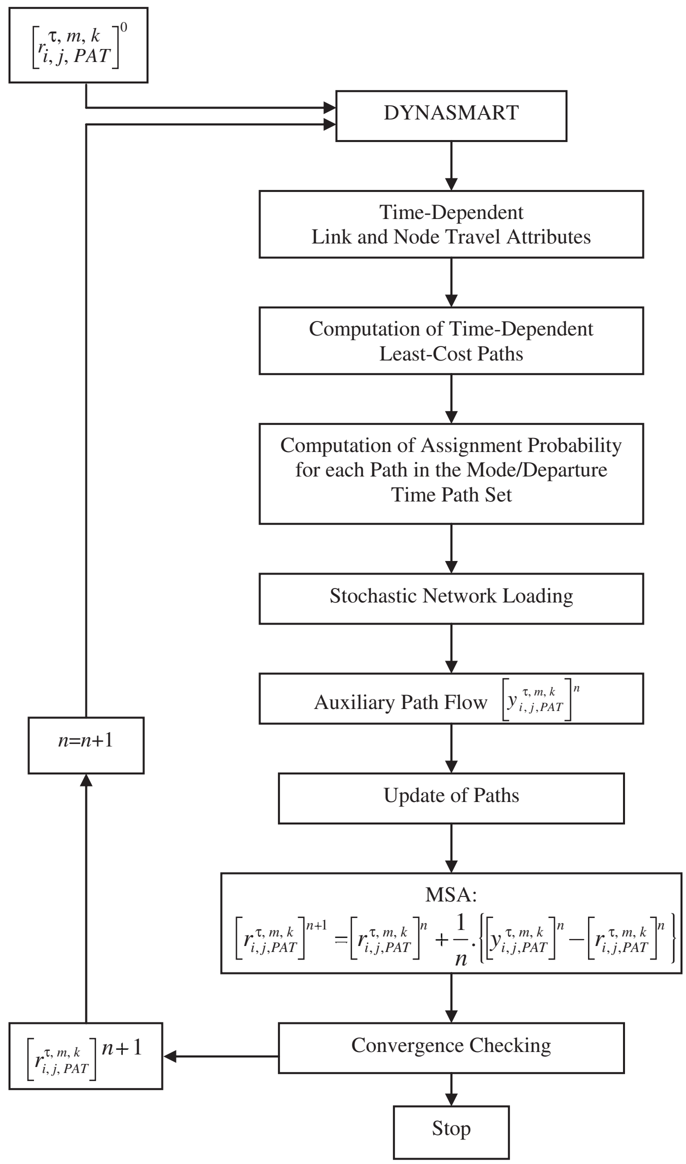

Figure 46. Solution algorithm for stochastic user equilibrium DTA.

problem with joint intermodal and departure time choice. The procedure adds the intermodal path choice dimension to the current algorithm of DYNASMART-P. The main steps of the solution algorithm are:

Step 0: Initialization

Let iteration number n=1. Based on a set of initial link and node travel attributes, find an initial feasible shortest path set for each mode and each departure time in the multimodal network. Perform a stochastic network loading using the paths set. Generate the set of mode-departure time-path flow solution $\left[r_{i,j,PAT}^{\tau,m,k}\right]^{n=1} \forall i,j,PAT$.

Step 1: Traffic simulation

Under the set of mode, departure time, and path assignment $\left[r_{i,j,PAT}^{\tau,m,k}\right]^{n}$, simulate the assigned vehicles between each OD pair for each departure interval τ and each mode m.

Step 2: Computing time-dependent intermodal shortest paths

Use the given transit schedule to determine the mode-transfer delay. Given time-dependent link travel time, travel cost (including link tolls and transit fares), and mode-transfer delay, the intermodal time-dependent least-cost path algorithm finds the minimum cost path in the multi-dimensional network for each feasible mode sequence at each departure time between the trip origin i and the destination j.

Step 3: Path probability calculation

Given path travel time and travel cost, calculate the schedule delay and travel times reliability associated with each path. Compute the utility of choice alternatives and determine the corresponding probabilities based on the multinomial logit choice model (Equation 27). This generates the auxiliary mode-path flows $\left[y_{i,j,PAT}^{\tau,m,k}\right]^{n}$.

Step 4: Update of path assignment

Use a predetermined move size from the method of successive average (MSA) to find the new departure time mode-path flow pattern:

$$\left[r_{i,j,PAT}^{\tau,m,k}\right]^{n+1} = \left[r_{i,j,PAT}^{\tau,m,k}\right]^{n} + \frac{1}{n}\cdot\left\{\left[y_{i,j,PAT}^{\tau,m,k}\right]^{n} - \left[r_{i,j,PAT}^{\tau,m,k}\right]^{n}\right\} \quad \text{(Equation 30)}$$

Step 5: Convergence criterion

Check the number of cases N for which

$$\left|\left[r_{i,j,PAT}^{\tau,m,k}\right]^{n+1} - \left[r_{i,j,PAT}^{\tau,m,k}\right]^{n}\right| \le \delta.$$

If $N < \Omega$, convergence is achieved, where δ and Ω are pre-specified parameters.

If convergence is attained, stop. Otherwise, set $n = n + 1$ and go to Step 1.

6.3.6 Estimation of Preferred Arrival Time (PAT) Pattern

The preferred arrival time pattern estimation problem aims to find PAT pattern $r_{i,j,PAT}$ for each OD pair (i,j) using a two-stage procedure. Given historical OD demand information and archived link measurements, the first stage estimates time-dependent vehicular OD demand matrix. The estimated dynamic vehicular OD demand matrix is loaded into a DTA program to generate a network path flow pattern, describing average travel time $TT_{i,j}^{\tau}$, travel cost $TC_{i,j}^{\tau}$, and travel time reliability $TTSD_{i,j}^{\tau}$ from origin i to destination j departing at time interval τ. The estimated vehicular OD demand matrix at the first stage is converted to a time-dependent traveler OD demand matrix $r_{i,j}^{\tau}$ by considering the existing mode shares in the study area.

Given estimated travel time, cost, and schedule delay from the first stage, the second stage utilizes a departure time choice probability function to calculate the probability of travelers from OD pair (i,j) with preferred arrival time PAT choosing departure time τ:

$$\Pr_{i,j,PAT}(\tau) = \frac{Exp\left(V_{i,j,PAT}^{\tau}\right)}{\sum_{\pi} Exp\left(V_{i,j,PAT}^{\tau}\right)} \quad \text{(Equation 31)}$$

This gives the following measurement equation:

$$r_{i,j}^{\tau} = \sum_{PAT} r_{i,j,PAT} \times \Pr_{i,j,PAT}(\tau) + \varepsilon_{i,j,\tau} \qquad \forall i,j,\tau \quad \text{(Equation 32)}$$

where $\varepsilon_{i,j,\tau}$ is the error term in estimating the PAT pattern from the given departure time pattern.

If preferred arrival time probability information $\overline{\Pr}_{i,j,PAT}$ is available from historical survey data or other planning applications, then a linkage can be established between the unknown PAT distribution pattern and the target PAT pattern.

$$\overline{\Pr}_{i,j,PAT} = \frac{r_{i,j,PAT}}{\sum_{PAT} r_{i,j,PAT}} + \xi_{i,j,PAT} \qquad \forall i,j,PAT \quad \text{(Equation 33)}$$

where $\xi_{i,j,PAT}$ is the error term in estimating the PAT pattern from historical information.

To find the number of trips from zone i to zone j with the preferred arrival time interval PAT, an optimization problem can be constructed to minimize (1) deviation between estimated and target realized departure time patterns and (2) deviation between estimated and target preferred arrival time probability. By assuming the above random error terms are independently normal distributed with zero mean, the objective function can be expressed in terms of least-square combined deviations, leading to the optimization problem:

$$\text{Min}\sum_{i,j,\tau}\left(\sum_{PAT} r_{i,j,PAT}\times \Pr_{i,j,PAT}(\tau)-r_{i,j}^{\tau}\right)^2 + w\sum_{i,j,PAT}\left(\frac{r_{i,j,PAT}}{\sum_{PAT} r_{i,j,PAT}}-\overline{\Pr}_{i,j,PAT}\right)^2$$

$$\text{s.t. } r_{i,j,PAT}\geq 0,\ \forall i,j,PAT \qquad \text{(Equation 34)}$$

Several multi-objective optimization techniques can be applied here to determine the weight w, and standard nonlinear optimization algorithms, such as the projected gradient algorithm, can be applied to solve the nonlinear optimization problem. The proposed PAT pattern estimation problem has $|I|\times|J|\times T$ unknown variables, and for each OD pair, the mapping function (Equation 31) can provide T linear measurements. However, the choice probability vector $\Pr_{i,j,PAT}(\tau)$ could be correlated to each other at different departure times. To identify a unique solution and reduce estimation uncertainty, it is necessary to add a priori information about the PAT pattern.

6.3.7 Experimental Results

Scenario Design

Figure 47 depicts the test network used in this study, which consists primarily of the multimodal corridor network between Washington, DC and Baltimore, MD. This network includes two interstate freeways, namely Interstate 95 and Washington-Baltimore Parkway (MD 295), part of state highway U.S. Route 29 and U.S. Route 1 as well as part of the MARC train system.

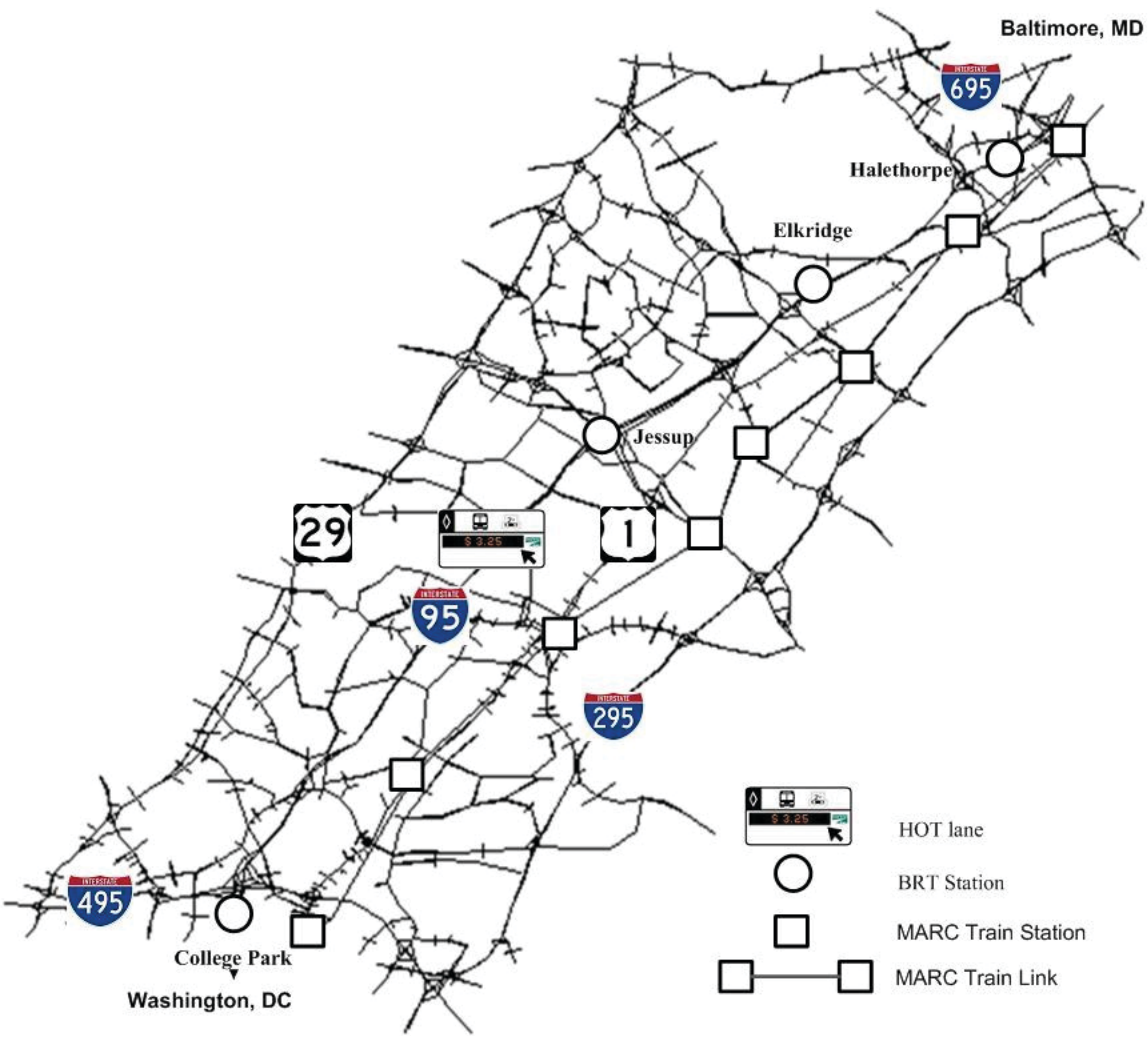

Figure 47. CHART corridor network with MARC train system and BRT on HOT lanes.

The corridor network contains 111 OD demand zones, and the corresponding zonal scheme is extracted from an existing transportation planning data set that covers the Greater Washington, DC area. The dynamic OD demand table in the study network is calibrated using a historical static planning OD table and archived time-dependent link flow observations, and the resulting OD trip distribution pattern shows high volume of OD trips along corridors I-95 and MD 295 in the study area. Two transit systems were considered in this study. One is the MARC Train—Camden Line between Washington, DC and Baltimore, MD; the other one is a hypothetic BRT system running on hypothetic HOT lanes along the I-95 from Baltimore, MD to Washington, DC. The planning horizon is selected to cover the morning peak period (4:00 AM to 11:00 AM) with the first two hours as a warm-up period and last hour as the clean-up period. In the experiments, the departure time interval is set to 15 minutes. The VOT is $20.00/h, and the reliability ratio is 1.31.

To evaluate congestion management strategies targeting intermodal choice and departure time choice, there are 12 scenarios in this study shown in Table 25.

The do-nothing case (Scenario 0) is defined as the following:

(1) Departure time pattern is generated based on estimated PAT pattern and travel time from One-Shot simulation results;
(2) Mode share is generated from mode-specific travel time from one-shot simulation results;
(3) No BRT on the HOT lanes.

Scenarios 1–3 are defined to test different ICM strategies, i.e., mode choice, departure time choice, and joint mode and departure time choice. Scenarios 4–6 are designed for BRT on HOT lane with different ICM strategies. Scenarios 7, 10, and 11 introduce various BRT operational strategies under ICM strategies such as accessibility, fare, and frequency policies. Scenarios 8–9 test peak spreading policy under ICM strategies. Scenario 12 shows peak spreading and toll policies under ICM strategies.

Two sets of BRT access point schemes are considered in the experiment:

- Limited access: Point-to-point express line, no intermediate stop (Scenarios 4–6, and 9–12); and
- Adequate access: Routing line with two intermediate stops at Elkridge and Jessup (Scenario 7).

Two sets of BRT frequencies are designed in the experiments:

- Low frequency: 5 minutes headway (Scenarios 4–7, 9–10, and 12); and
- High frequency: 2 minutes headway (Scenario 11).

There are three kinds of monetary cost in experiments:

- HOT Toll: toll for drive along using HOT lanes is 40 cents/mile for Scenarios 1–11, and 80 cents/mile for Scenario 12;
- Driving Cost: driving cost is 30 cents/mile (in terms of gas, repairs, maintenance, and depreciation); and
- Transit Fare: fare for BRT and Train is $2.00 per passenger for Scenarios 4–7, 9, and 12, and $4.00 per passenger for Scenarios 10–11.

To compare the results and demonstrate the user travel behavior in response to highway pricing under integrated congestion management strategies among different cases, the Measures of Effectiveness (MOE) of interest are:

- Average travel time,
- Average schedule delay,
- Average travel time standard deviation,
- Average utility,
- Mode share, and
- Departure pattern.

Networkwide MOE and critical OD pair MOE are used in experimental analysis. The critical OD pairs include six OD pairs along the I-95 corridor that starts from Baltimore and ends at Washington, DC. The MOE at critical OD pairs can be used to evaluate the performance of the BRT line on HOT lanes along the I-95 corridor and the intermodal choice-related ICM strategies.

PAT Estimation and Flexible Work Hour Policy

Figure 48 shows the networkwide average travel time and arrival time pattern from the assignment results and the estimated PAT pattern for the entire network, based on the proposed estimation method with a target PAT pattern. The unit of travel time is minute, and the PAT and arrival time distributions are re-scaled to fit into the same figure.

Clearly, network travel time significantly increases after 7:30 am, and the realized arrival time pattern increases smoothly and reaches the peak at 8:00 am. In contrast, the estimated PAT has a slowly changing pattern with its peak at 8:30 am. The estimated PAT pattern is quite sensitive to the temporal distribution of the target PAT pattern, since the realized departure times only contain limited information about the unobserved departure time choice process. More importantly, desirable arrival times are determined by complex activity choice and activity scheduling processes; estimating PAT patterns still calls for more data collection and demand modeling effort in order to provide accurate target PAT information based on actual survey samples.

Table 25. Scenarios for congestion management.

Scenario #	Scenario	Mode choice	Departure time choice	Peak spreading	HOT Toll	BRT line	BRT access points	BRT Fare	BRT Frequency
0	Do-nothing case (imperfect information to users, limited knowledge)								
1	Information and HOT use (mode choice)	Yes			Low				
2	Demand management strategies with estimated PAT (departure time choice)		Yes		Low				
3	Integrated congestion management targeting HOT use with estimated PAT (joint mode and departure time choice)	Yes	Yes		Low				
4	BRT + Information and HOT use (same as 1 + BRT)	Yes			Low	Yes	Limited	Low	Low
5	BRT + Demand management strategies with estimated PAT (same as 2 + BRT)		Yes		Low	Yes	Limited	Low	Low
6	BRT + Integrated congestion management targeting HOT use with estimated PAT (same as 3+ BRT)	Yes	Yes		Low	Yes	Limited	Low	Low
7	BRT + Integrated congestion management targeting HOT use with estimated PAT (same as 3+ BRT + more BRT access points)	Yes	Yes		Low	Yes	Adequate	Low	Low
8	Integrated congestion management targeting HOT use with estimated PAT+ peak spreading (same as 3 + peak spreading)	Yes	Yes	Yes	Low				
9	BRT + Integrated congestion management targeting HOT use with estimated PAT + peak spreading (same as 3+BRT+peak spreading)	Yes	Yes	Yes	Low	Yes	Limited	Low	Low
10	BRT + Integrated congestion management targeting HOT use with estimated PAT + Transit fare policy (same as 3 + BRT + increased fare)	Yes	Yes		Low	Yes	Limited	High	Low
11	BRT + Integrated congestion management targeting HOT use with estimated PAT + Transit fare and frequency policy (same as 3 + BRT + increased fare and frequency)	Yes	Yes		Low	Yes	Limited	High	High
12	BRT + Integrated congestion management targeting HOT use with estimated PAT + peak spreading + Increased HOT toll (Same as 3 + BRT + peak spreading + increased HOT toll)	Yes	Yes	Yes	High	Yes	Limited	Low	Low

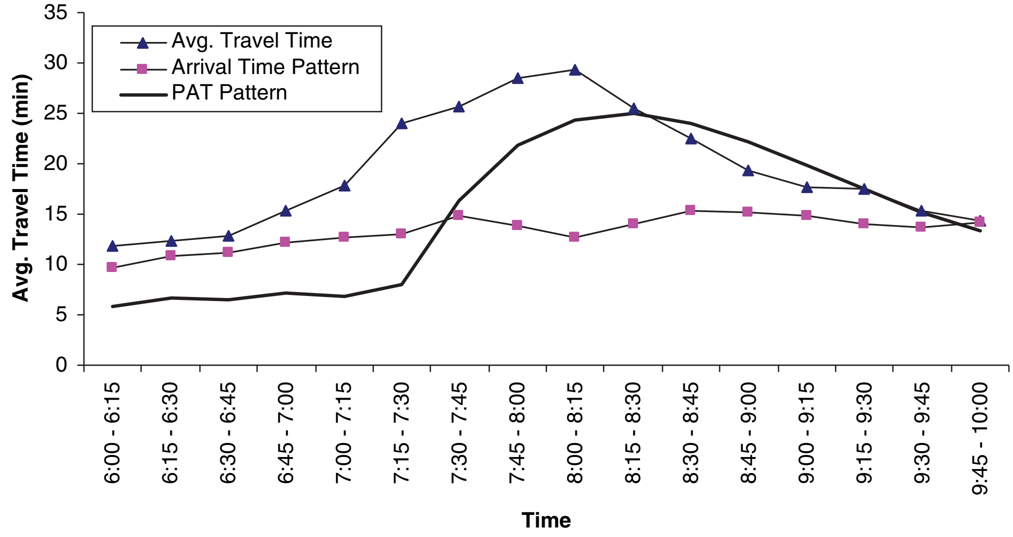

Figure 48. Estimated network-wide PAT pattern.

The PAT pattern above is estimated in a fixed work hour condition, where the travel time comes from the one-shot simulation results. To further investigate more aggressive demand spreading strategies, generate a PAT pattern by assuming a more flexible work hour policy as shown in Figure 49.

Analysis of Experimental Results

This section shows MOE (Table 26), improvement (Table 27), and traveler choice behavior for critical OD pairs and network-wide for each scenario (Figures 50 and 51).

Based on these results, the following observations can be made regarding the critical OD pairs. ICM strategies such as demand management, multimodal information dissemination that targets modal choice, especially HOT and HOV use, as well as peak spreading, have good potential to improve the cost and reliability of travel, by reducing travel time as well as allowing users to exert greater control over their travel schedules. Additionally, the hypothetical BRT line on HOT lanes considered in this corridor can serve travel demand for the critical OD pairs of interest, especially between the Baltimore and Washington, DC, areas, as it attracts a considerable number of travelers to the

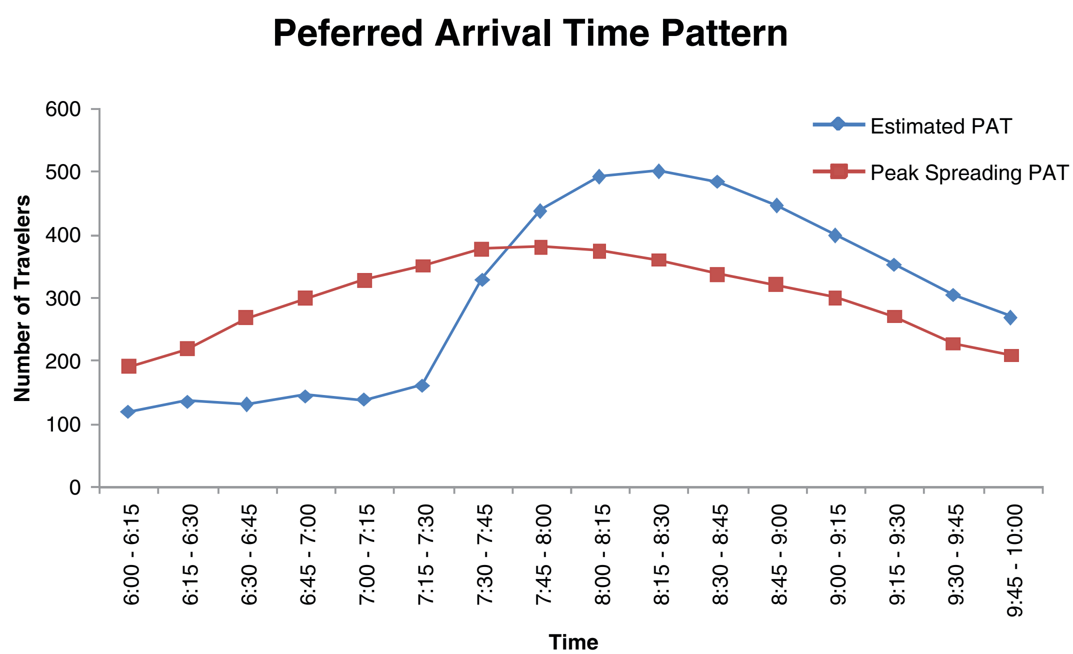

Figure 49. Preferred arrival time pattern with flexible work hours.

Table 26. MOE for critical OD pairs.

Scenario #	Scenario	Avg Travel Time (min)	Avg Schedule Delay (min)	Avg Travel Time Std Dev	Avg Utility
0	Do-nothing case (imperfect information to users, limited knowledge)	89.7	56.0	32.7	33.5
1	Information and HOT use (mode choice)	73.2	41.0	24.9	25.8
2	Demand management strategies with estimated PAT (departure time choice)	69.0	40.0	31.2	24.7
3	Integrated congestion management targeting HOT use with estimated PAT (joint mode and departure time choice)	65.8	36.6	27.7	23.1
4	BRT + Information and HOT use (same as 1 + BRT)	51.8	38.9	17.6	19.2
5	BRT + Demand management strategies with estimated PAT (same as 2 + BRT)	58.0	37.4	28.4	20.8
6	BRT +Integrated congestion management targeting HOT use with estimated PAT (same as 3+ BRT)	52.3	35.7	22.8	19.2
7	BRT + Integrated congestion management targeting HOT use with estimated PAT (same as 3+ BRT + more BRT access points)	61.4	43.3	27.8	23.0
8	Integrated congestion management targeting HOT use with estimated PAT+ peak spreading (same as 3 + peak spreading)	59.3	39.4	12.6	22.3
9	BRT + Integrated congestion management targeting HOT use with estimated PAT + peak spreading (same as 3+BRT+peak spreading)	50.9	37.6	18.6	19.8
10	BRT + Integrated congestion management targeting HOT use with estimated PAT + Transit fare policy (same as 3 + BRT + increased fare)	60.5	39.1	30.5	21.8
11	BRT +Integrated congestion management targeting HOT use with estimated PAT + Transit fare and frequency policy (same as 3 + BRT + increased fare and frequency)	58.5	36.5	29.8	20.8
12	BRT + Integrated congestion management targeting HOT use with estimated PAT + peak spreading + Increased HOT toll (Same as 3 + BRT + peak spreading + increased HOT toll)	49.5	40.7	16.2	20.9

Table 27. MOE for critical OD pairs (% improvement).

Scenario #	Scenario	Avg Travel Time (min)	Avg Schedule Delay (min)	Avg Travel Time Std Dev	Avg Utility
0	Do-nothing case (imperfect information to users, limited knowledge)				
1	Information and HOT use (mode choice)	18.4%	26.8%	23.9%	23.0%
2	Demand management strategies with estimated PAT (departure time choice)	23.1%	28.6%	4.6%	26.3%
3	Integrated congestion management targeting HOT use with estimated PAT (joint mode and departure time choice)	26.6%	34.6%	15.3%	31.0%
4	BRT + Information and HOT use (same as 1 + BRT)	42.3%	30.5%	46.2%	42.7%
5	BRT + Demand management strategies with estimated PAT (same as 2 + BRT)	35.3%	33.2%	13.1%	37.9%
6	BRT +Integrated congestion management targeting HOT use with estimated PAT (same as 3+ BRT)	41.7%	36.3%	30.3%	42.7%
7	BRT + Integrated congestion management targeting HOT use with estimated PAT (same as 3+ BRT + more BRT access points)	31.5%	22.7%	15.0%	31.3%
8	Integrated congestion management targeting HOT use with estimated PAT+ peak spreading (same as 3 + peak spreading)	33.9%	29.6%	61.5%	33.4%
9	BRT + Integrated congestion management targeting HOT use with estimated PAT + peak spreading (same as 3+BRT+peak spreading)	43.3%	32.9%	43.1%	40.9%
10	BRT + Integrated congestion management targeting HOT use with estimated PAT + Transit fare policy (same as 3 + BRT + increased fare)	32.6%	30.2%	6.7%	34.9%
11	BRT +Integrated congestion management targeting HOT use with estimated PAT + Transit fare and frequency policy (same as 3 + BRT + increased fare and frequency)	34.8%	34.8%	8.9%	37.9%
12	BRT + Integrated congestion management targeting HOT use with estimated PAT + peak spreading + Increased HOT toll (Same as 3 + BRT + peak spreading + increased HOT toll)	44.9%	27.3%	50.5%	37.6%

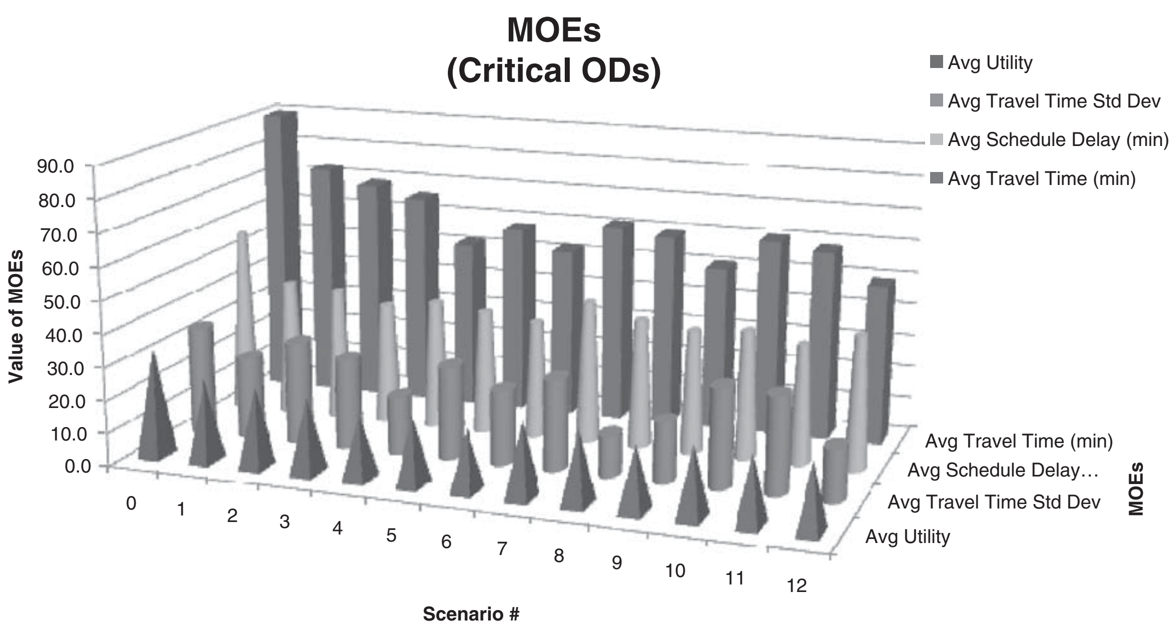

Figure 50. MOEs for critical OD pairs.

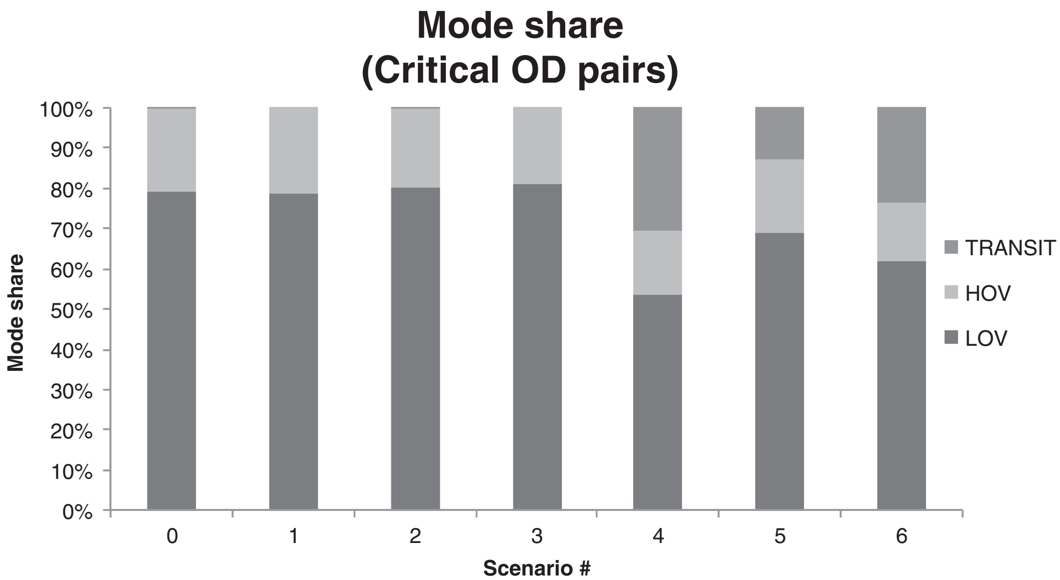

Figure 51. Mode shares of different choice dimensions for critical OD pairs.

transit mode; however, many of those may be diversions from HOV users. In conjunction with demand spreading strategies, the BRT line with more access points improves travel time, travel time reliability, and utility for critical OD pairs between Baltimore and Washington, DC.

Figure 52 and Figure 53 along with Tables 28 and 29 provide network-wide MOEs. Clearly, the benefit of targeted ICM strategies could be greater for certain OD pairs than for others, depending on relative location and corridor orientation, hence the higher rate of benefit for selected critical OD pairs. If many OD pairs do not have access to transit or HOV options, network-wide mode shares exhibit small changes, even though selected OD pairs might experience meaningful impacts. BRT lines with a sufficient number of access points, in conjunction with demand spreading strategies, can significantly improve the network-wide system performance under the present assumptions.

Figure 54 through Figure 62 show the mode-specific departure patterns for critical OD pairs to represent users' choice of mode, departure time, and route in response to highway

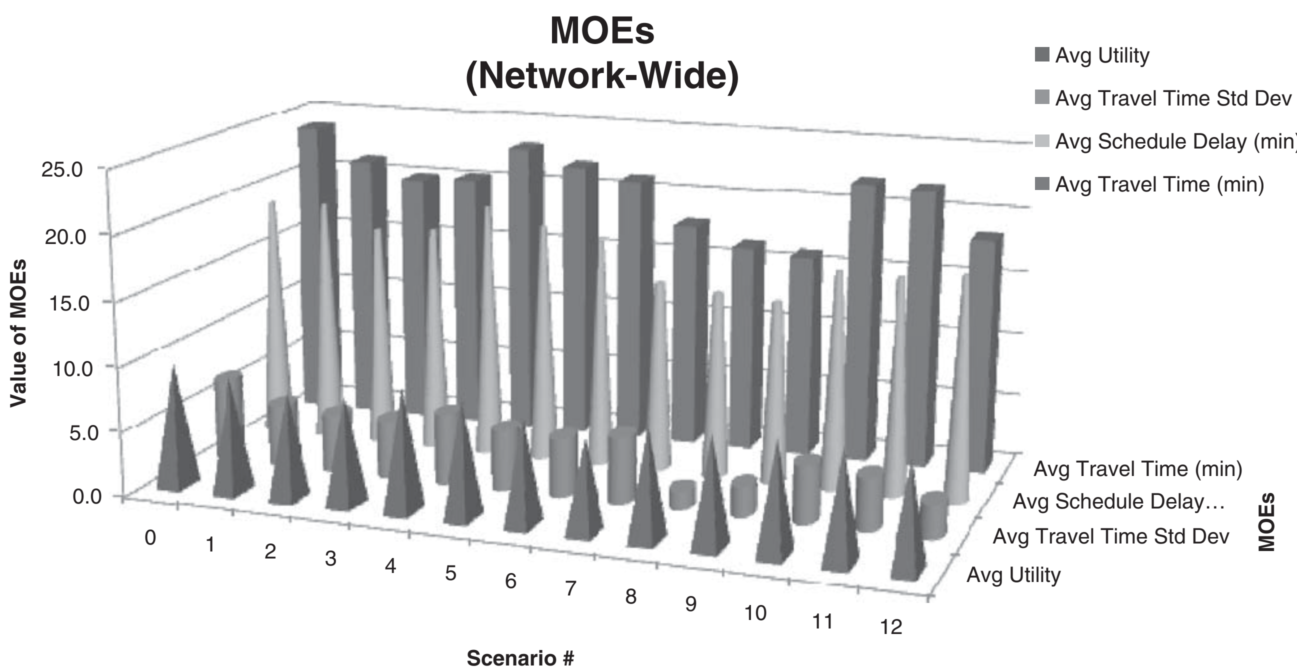

Figure 52. MOE comparison for network-wide.

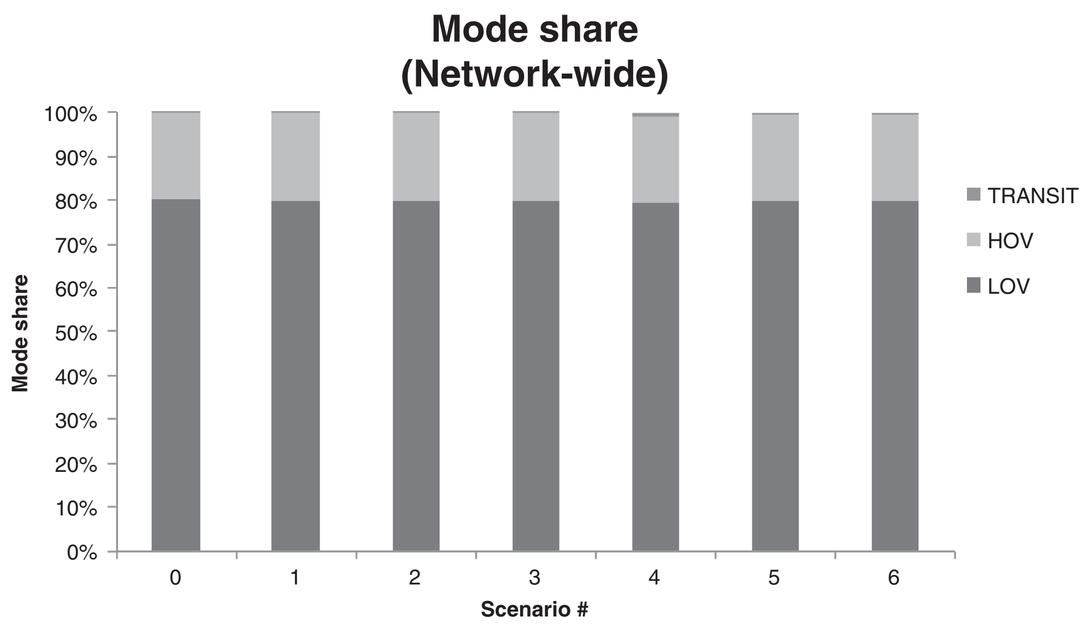

Figure 53. Mode shares of different choice dimensions for critical OD pairs.

Table 28. Network-wide MOE for different intermodal and demand spreading strategies.

Scenario #	Scenario	Avg Travel Time (min)	Avg Schedule Delay (min)	Avg Travel Time Std Dev	Avg Utility
0	Do-nothing case (imperfect information to users, limited knowledge)	23.7	18.8	6.4	9.6
1	Information and HOT use (mode choice)	21.2	18.9	4.8	9.0
2	Demand management strategies with estimated PAT (departure time choice)	20.0	17.2	4.5	8.3
3	Integrated congestion management targeting HOT use with estimated PAT (joint mode and departure time choice)	20.3	17.5	4.5	8.4
4	BRT + Information and HOT use (same as 1 + BRT)	23.1	19.7	5.5	9.6
5	BRT + Demand management strategies with estimated PAT (same as 2 + BRT)	21.9	18.5	4.7	9.1
6	BRT +Integrated congestion management targeting HOT use with estimated PAT (same as 3+ BRT)	21.1	17.7	4.5	8.7
7	BRT + Integrated congestion management targeting HOT use with estimated PAT (same as 3+ BRT + more BRT access points)	17.8	14.7	5.1	7.2
8	Integrated congestion management targeting HOT use with estimated PAT+ peak spreading (same as 3 + peak spreading)	16.4	14.3	1.5	8.6
9	BRT + Integrated congestion management targeting HOT use with estimated PAT + peak spreading (same as 3+BRT+peak spreading)	16.0	14.0	2.4	8.5
10	BRT + Integrated congestion management targeting HOT use with estimated PAT + Transit fare policy (same as 3 + BRT + increased fare)	22.1	16.8	4.5	8.6
11	BRT +Integrated congestion management targeting HOT use with estimated PAT + Transit fare and frequency policy (same as 3 + BRT + increased fare and frequency)	21.9	16.7	4.1	8.5
12	BRT + Integrated congestion management targeting HOT use with estimated PAT + peak spreading + Increased HOT toll (Same as 3 + BRT + peak spreading + increased HOT toll)	18.4	17.2	2.7	8.2

Table 29. Network-wide MOE % improvement.

Scenario #	Scenario	Avg Travel Time (min)	Avg Schedule Delay (min)	Avg Travel Time Std Dev	Avg Utility
0	Do-nothing case (imperfect information to users, limited knowledge)				
1	Information and HOT use (mode choice)	10.5%	-0.5%	25.0%	6.3%
2	Demand management strategies with estimated PAT (departure time choice)	15.6%	8.5%	29.7%	13.5%
3	Integrated congestion management targeting HOT use with estimated PAT (joint mode and departure time choice)	14.3%	6.9%	29.7%	12.5%
4	BRT + Information and HOT use (same as 1 + BRT)	2.5%	-4.8%	14.1%	0.0%
5	BRT + Demand management strategies with estimated PAT (same as 2 + BRT)	7.6%	1.6%	26.6%	5.2%
6	BRT +Integrated congestion management targeting HOT use with estimated PAT (same as 3+ BRT)	11.0%	5.9%	29.7%	9.4%
7	BRT + Integrated congestion management targeting HOT use with estimated PAT (same as 3+ BRT + more BRT access points)	24.9%	21.8%	20.3%	25.0%
8	Integrated congestion management targeting HOT use with estimated PAT+ peak spreading (same as 3 + peak spreading)	30.8%	23.9%	76.6%	10.4%
9	BRT + Integrated congestion management targeting HOT use with estimated PAT + peak spreading (same as 3+BRT+peak spreading)	32.5%	25.5%	62.5%	11.5%
10	BRT + Integrated congestion management targeting HOT use with estimated PAT + Transit fare policy (same as 3 + BRT + increased fare)	6.8%	10.6%	29.7%	10.4%
11	BRT +Integrated congestion management targeting HOT use with estimated PAT + Transit fare and frequency policy (same as 3 + BRT + increased fare and frequency)	7.6%	11.2%	35.9%	11.5%
12	BRT + Integrated congestion management targeting HOT use with estimated PAT + peak spreading + Increased HOT toll (Same as 3 + BRT + peak spreading + increased HOT toll)	22.4%	8.5%	57.8%	14.6%

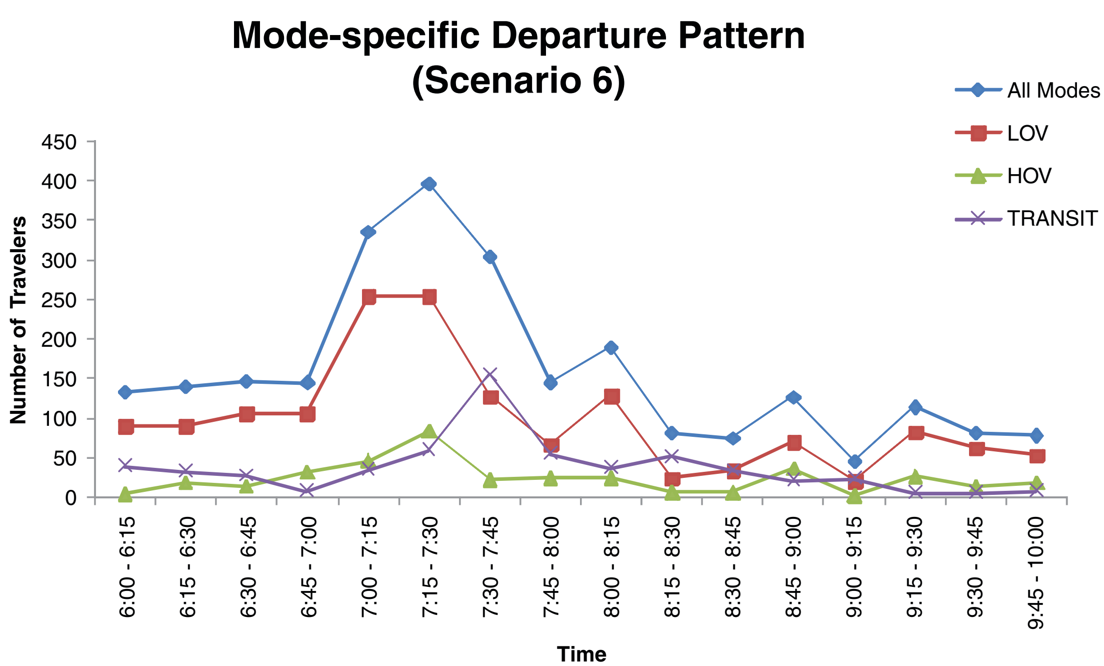

Figure 54. Mode-specific departure pattern for critical OD pairs – Scenario 6.

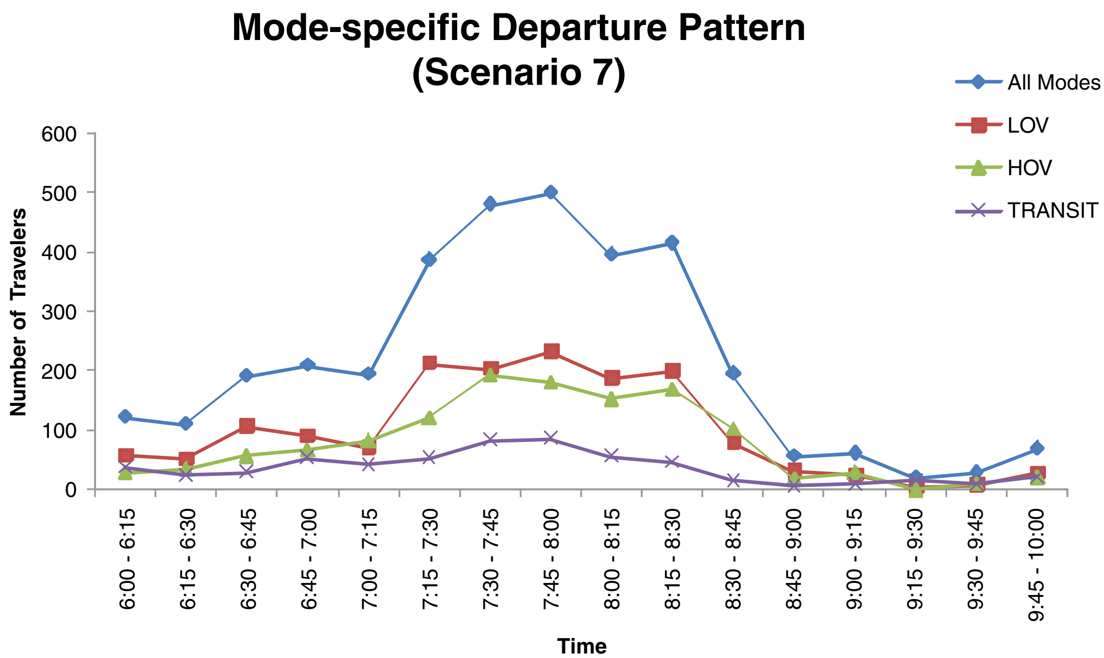

Figure 55. Mode-specific departure pattern for critical OD pairs – Scenario 7.

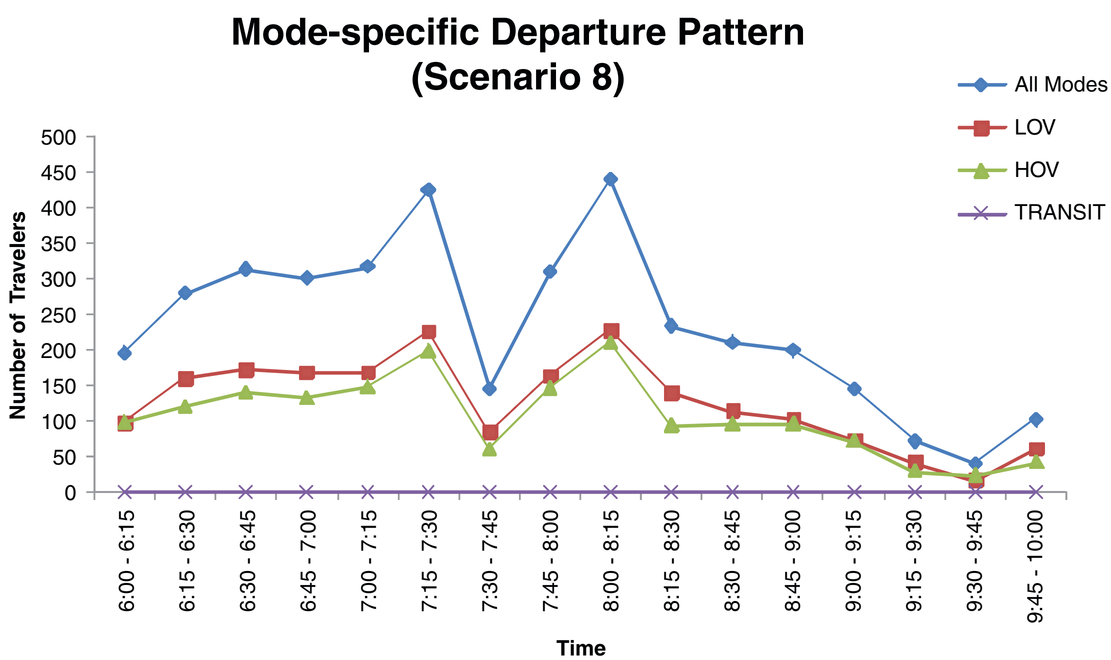

Figure 56. Mode-specific departure pattern for critical OD pairs – Scenario 8.

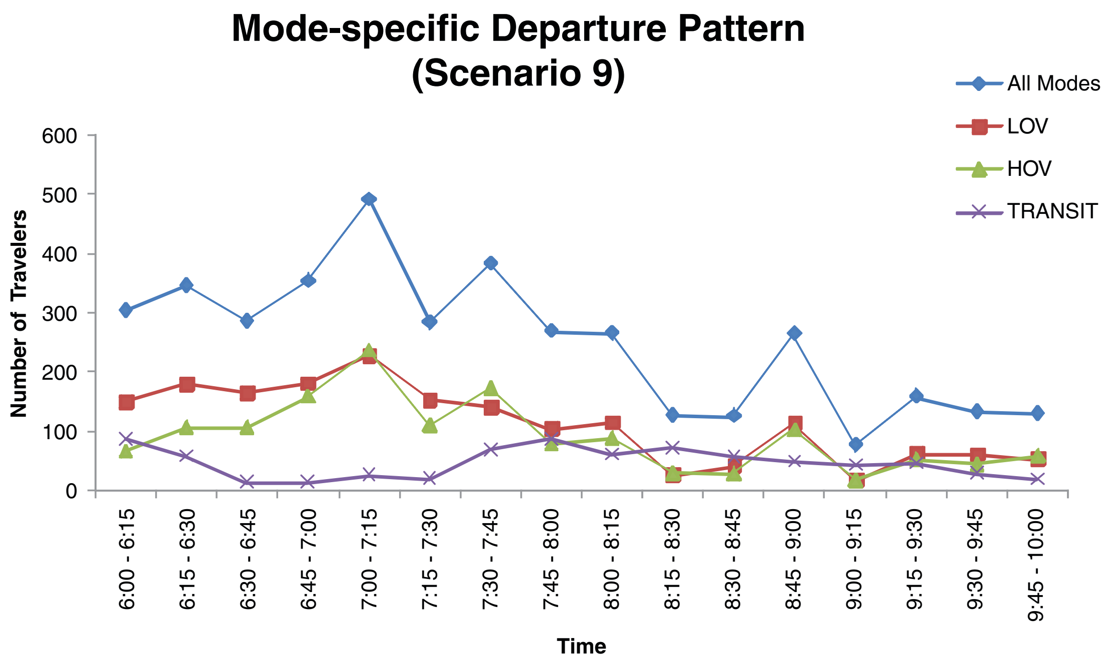

Figure 57. Mode-specific departure pattern for critical OD pairs – Scenario 9.

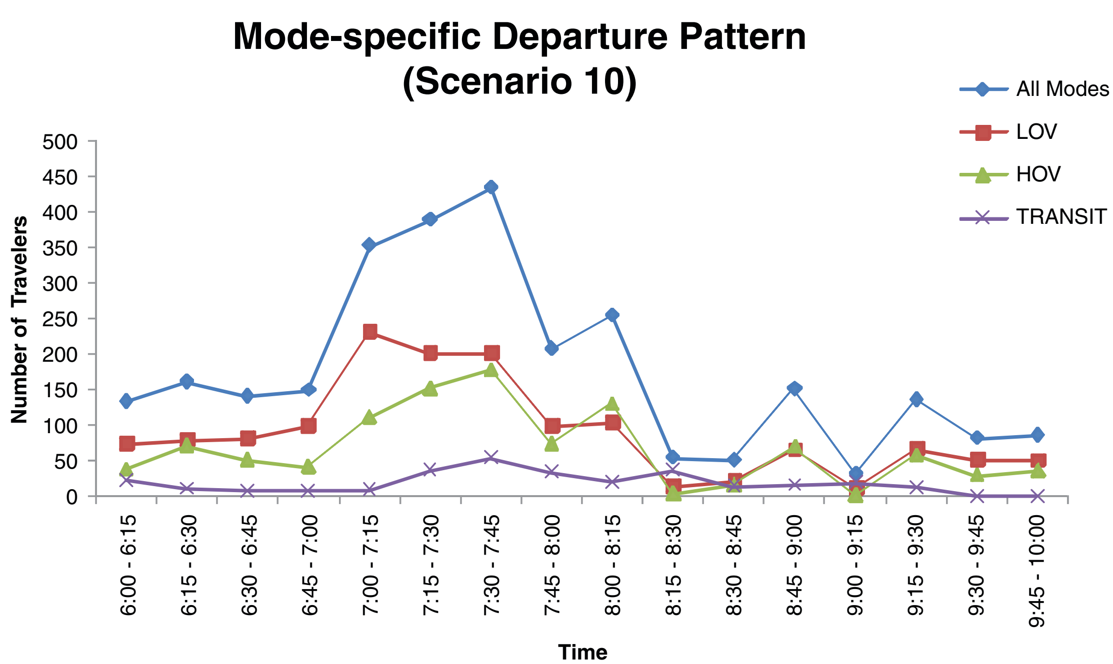

Figure 58. Mode-specific departure pattern for critical OD pairs – Scenario 10.

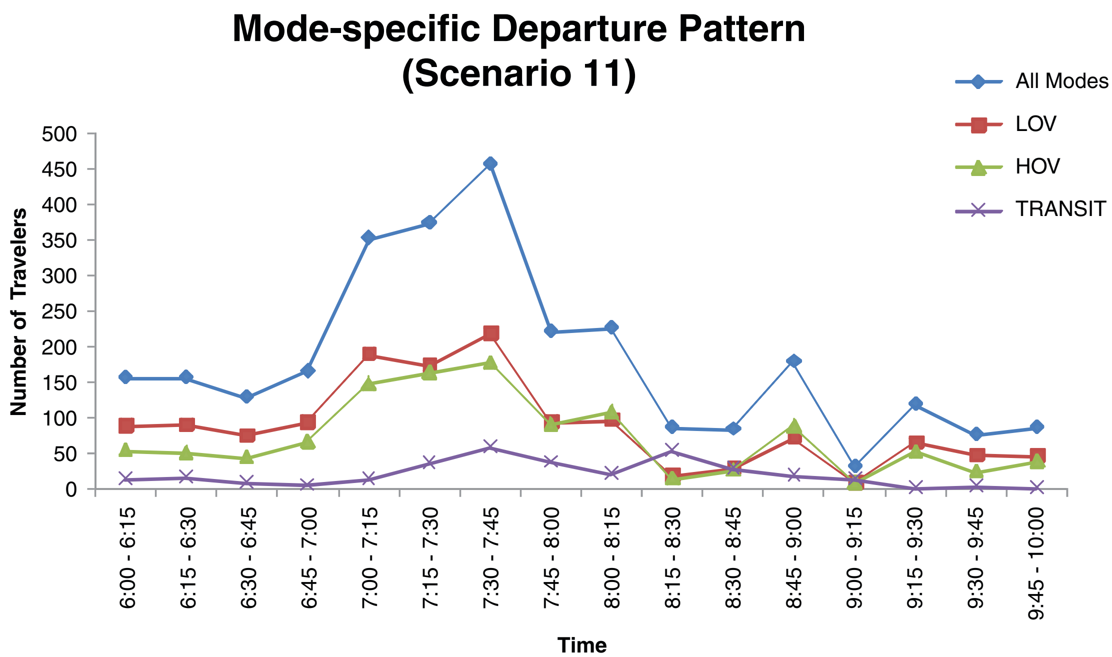

Figure 59. Mode-specific departure pattern for critical OD pairs – Scenario 11.

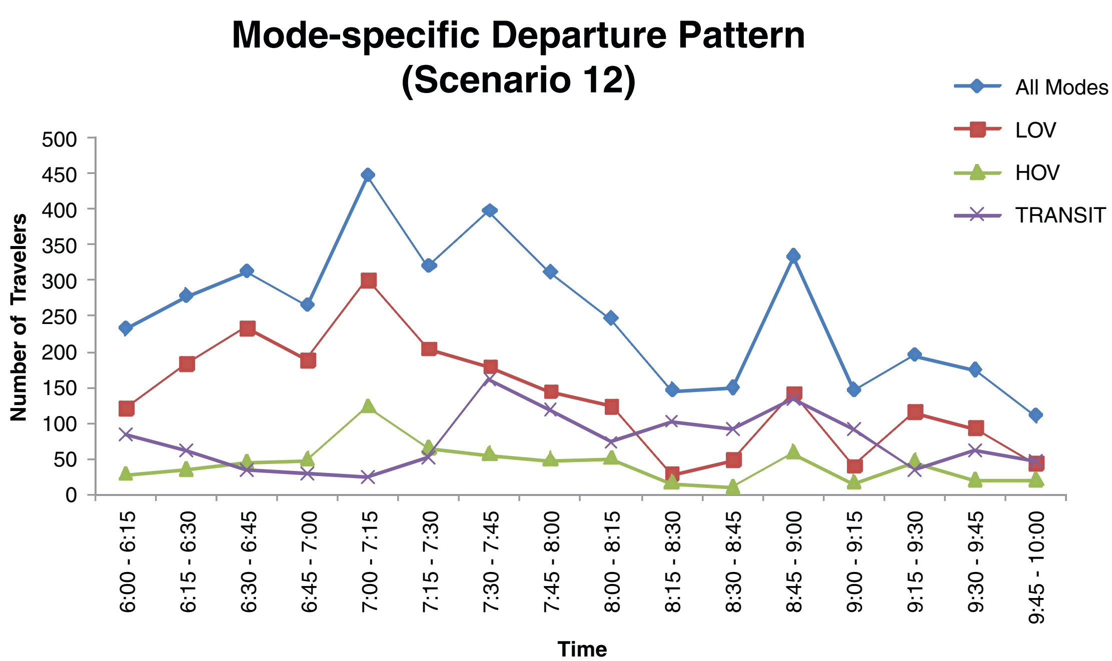

Figure 60. Mode-specific departure pattern for critical OD pairs – Scenario 12.

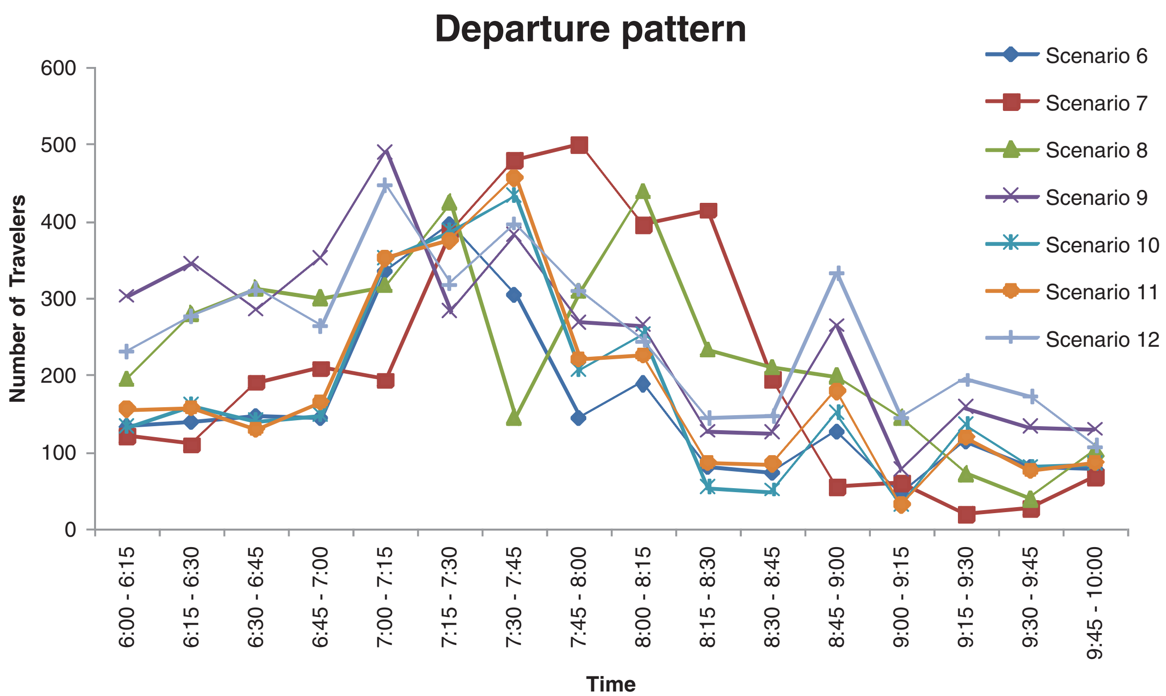

Figure 61. Mode-specific departure pattern for critical OD pairs.

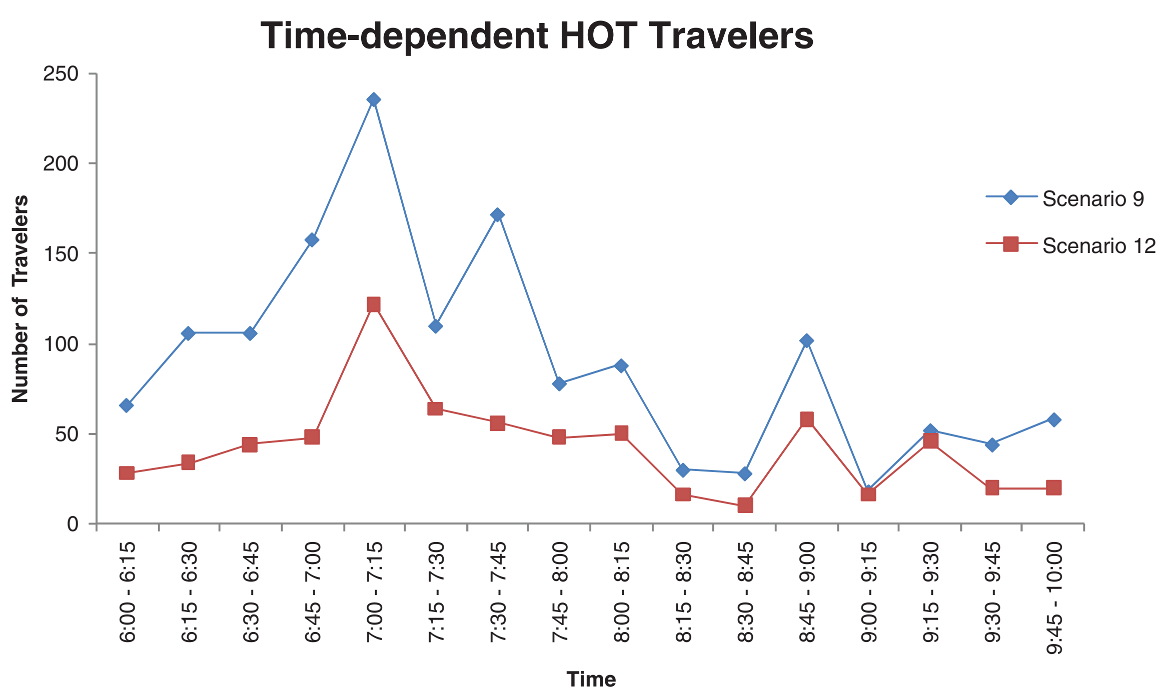

Figure 62. HOT departure pattern for critical OD pairs – Scenarios 9 and 12.

pricing, peak spreading, and BRT operations with integrated congestion management strategies. Scenarios 8, 9, and 12 illustrate that travelers adjust departure times under peak spreading, highway toll, and other ICM strategies, which improve MOEs for network-wide and critical ODs significantly, as shown in Table 27 and Table 29. Moreover, according to Figure 62, the number of travelers in the HOT lanes decreases with an increase in the toll, whereas additional LOV travelers are attracted to the HOT lanes when the toll is lower, consistent with a priori expectations.

6.3.8 Conclusions

This study presents a practical dynamic traveler assignment model to simultaneously capture mode and departure time choice dynamics and to address several unique modeling needs of highway pricing and integrated congestion management benefit analysis and strategy design. Many important deployment issues in applying existing DTA based traffic analysis systems for ICM support have been discussed. One particular focus is on how to represent multimodal networks with park-and-ride options and how to find feasible candidate paths that can capture time-dependent mode transfer costs. To provide the critical demand input in the above traveler assignment model, this study uses estimated network flow patterns and an empirically calibrated stochastic departure time choice model to jointly reconstruct the preferred arrival time demand information. A case study using a large-scale multimodal transportation network data set is presented to illustrate the dynamic intermodal transportation analysis system. Future research needs to systematically incorporate features such as heterogeneous users in response to dynamic tolls, integrating more realistic travel decision models, as well as developing efficient heterogeneous intermodal shortest path algorithms.

6.4 Improvement of the Los Angeles 4-Step Model for Pricing Studies

6.4.1 Objectives of the Study and Short-Term Model Enhancements

This section describes enhancements proposed for the Los Angeles Metropolitan Transportation Agency (LAMTA) regional travel demand model. These enhancements have been designed with the goal of improving the sensitivity of the model to road pricing, particularly HOT lanes.

At the onset of the Congestion Pricing Study, we identified several areas where the LAMTA regional model could be improved for use in the pricing analysis. One primary and ongoing concern at the agency was the poor validation of the 2000 model estimates to observed traffic counts. Other concerns included the lack of speed feedback and consequent reliance on off-model procedures to establish congested speeds, and potentially inappropriate sensitivities of the mode choice model to tolls and the levels of service offered by tolls roads, HOT lanes, and HOV lanes. We also identified the absence of truck and bus volumes from the highway assignments as a potential shortcoming, particularly given the needs of EcoNorthwest's toll optimization program. Finally, we noted an inconsistency between the highway assignment and the mode choice model related to the treatment of HOV trips.

As part of the development of the draft Concept of Operations (ConOps) Plan for the Harbor Freeway and El Monte Busway HOT Lane Implementations, a limited number of very short-term enhancements were introduced during the summer of 2008. Since the ConOps plan required current (2008) model forecasts, the short-term improvements focused primarily on improving the validation of the highway assignment. This validation was undertaken at two levels: a year 2000 regional highway validation, based on the most recent observed traffic volumes; and a 2008 validation, focused on the two ConOps plan corridors.

The following discussion summarizes the main short-term model enhancements:

Person Trip Tables

The LAMTA mode choice model takes as input the person trip tables developed by the Southern California Association of Governments (SCAG). We found that one of the primary reasons for the poor highway validation was related to inconsistencies between LAMTA and SCAG on how their mode choice models are applied. In particular, the Tranplan version of the SCAG model added some serve passenger trips to the home-based school drive alone trips, independently of the mode choice model. The rationale for these added trips is that they were excluded from the trip generation estimation, due to the way in which trip purposes were originally defined. Because these serve passenger trips are not accounted for in the LAMTA model, the end result is a low estimate of vehicle trips. Not surprisingly, the LAMTA highway validation showed that most screenlines were under-estimated. To compensate for the lack of the serve passenger trips, correction factors were applied to the home-based other and non-home-based person trip tables. These factors were developed by comparing the LAMTA and SCAG AM and MD vehicle trip tables, and computing the ratio of SCAG to LAMTA trips on a district basis. The regional statistical areas (RSAs) were used as the districts. District interchanges with less than 10,000 vehicle trips were not factored. A review of the computed factors showed that approximately 97% of all the interchanges were factored by less than 10%. Use of the factored trip tables significantly improved the highway validation. Table 30 compares the highway validation of the SCAG and LAMTA models. Note that the LAMTA estimates include all the short-term model improvements discussed here and not just the factored trip tables.

Volume-Delay Functions (VDF)

The LAMTA model uses the standard BPR function for non-freeway links, and a modified BPR function (*Highway Capacity Manual* 2000) for freeway links (shown in Figure 1). The standard BPR function dates from the time when the prevailing assignment technique was iterative capacity restraint. It was generally found that this technique worked best when the speeds for the first iteration were those that occur at LOS C. Therefore, application of the standard BPR function requires that the link capacities represent LOS C capacity, referred to as practical capacity, so that when volume equals practical capacity, the speed would equal LOS C speed. The LAMTA model applied a factor of 0.75 (UROAD factor) to the coded network capacities when calculating congested speeds, which is understood to be a conversion from the ultimate capacities (LOS E) coded on the network to practical capacities. However, the assignment methodology currently used by LAMTA is an equilibrium assignment, with initial speeds assumed to be free-flow speeds. An examination of the forecast speeds shows that the model tends to underestimate speeds as a function of the estimated highway volume. The model also tends to over-assign the freeways and under-assign arterials.

The short-term solution consisted of addressing the allocation of volumes by facility-type. We found that using the arterial VDF implemented in the Tranplan version of the SCAG model helped to achieve a better split between freeways and arterials. This function is labeled "revised non-freeway" in Figure 63.

The proposed solution for the second phase of the HOT lane study is to implement volume-delay functions consistent with LOS E capacities and free-flow speeds, and discontinue use of the UROAD factor. The HCM 2000 recommends parameters for the BPR function for freeways and arterials as a function of free-flow speed, speed at capacity, and signal density (Exhibits C30-1 and C30-2). These recommendations were adapted to LAMTA facility types and area types as shown in Table 31 and Table 32. It is anticipated that the use of these curves will improve the speed forecasts, a critical need once speed feedback is implemented. It will also help to improve consistency with the travel time estimates produced by the Toll Optimization Model.

Compared to the curves currently used by LAMTA, the HCM 2000 curves are generally "flatter" for V/C ratios lower than 1.0 and steeper for V/C ratios over 1.0 (see Figure 64).

Input Speeds

Since the model currently operates without speed feedback, the split between HOV and mixed flow lanes is largely determined by the assumed input speeds, and particularly the speed differential between the two competing facilities. We examined the average input speeds assumed for the HOV lanes, and decreased the peak period HOV speeds by approximately 5 mph. Other coded input speeds were also revised, particularly select freeway speeds less than 10-15 mph on average for the entire 3-hour peak period. On the ConOps study corridors, input speeds were manually smoothed to avoid changes in speed on sequential links without intermediate entry/exit ramps or lane changes. The

Table 30. Screenline validation.

	Location	Observed Volume	SCAG Volume	% Error	LAMTA Volume	% Error
1	LA - s/o SR-134	1,375,704	1,459,158	6%	1,335,598	-3%
2	LA - LA River	2,414,174	2,531,360	5%	2,339,937	-3%
3	LA - s/o Century Freeway	1,402,915	1,327,068	-5%	1,202,463	-14%
4	OR - Santa Ana River	1,678,439	1,720,908	3%	1,541,472	-8%
5	OR - LA County Line	1,502,817	1,766,953	18%	1,650,567	10%
6	SB/RIV - e/o SR-83	887,627	886,843	0%	851,815	-4%
7	SB - s/o I-10	690,725	746,600	8%	671,321	-3%
8	LA - San Gabriel Valley	1,084,601	1,118,466	3%	1,052,905	-3%
9	SB/RIV - Redlands/Moreno Vly	422,814	417,178	-1%	413,109	-2%
10	VEN - LA County Line	398,798	407,316	2%	387,713	-3%
11	VEN - Camarillo	191,444	224,095	17%	210,858	10%
12	RIV - Palm Springs	130,410	132,433	2%	142,730	9%
13	SB - Victor Valley	122,202	123,194	1%	129,649	6%
14	RIV - n/o SR-74	151,954	205,324	35%	160,229	5%
15	OR - s/o Junction I-5 & I-405	618,840	666,584	8%	703,710	14%

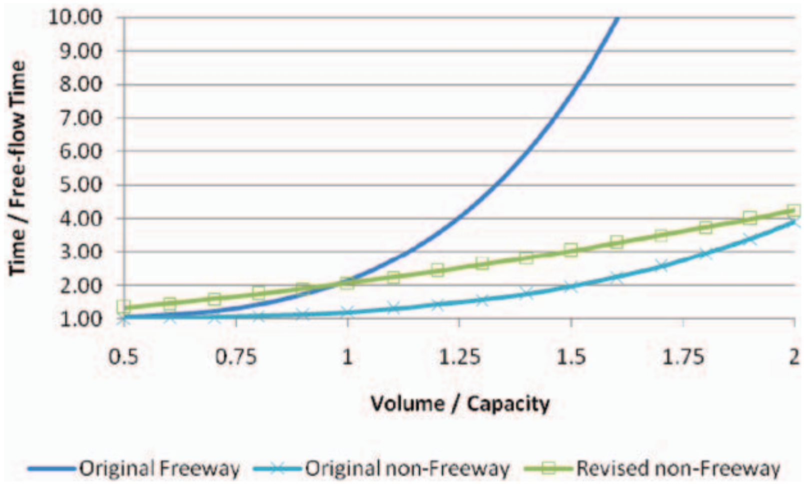

Figure 63. Original and revised VDF curves.

Table 31. HCM 2000 recommended parameters for BPR curve.

Facility Type	Curve ID	Free-Flow Speed	BPR Parameters	
			Coefficient	Exponent
Freeway	F75	75	0.39	6.30
Freeway	F70	70	0.32	7.00
Freeway	F65	65	0.25	9.00
Freeway	F60	60	0.18	8.50
Freeway	F55	55	0.10	10.00
Arterial - low signal density	A50L	50	0.34	4.00
Arterial - med signal density	A50M	50	0.74	5.00
Arterial - low signal density	A40L	40	0.38	5.00
Arterial - med signal density	A40M	40	0.70	5.00
Arterial - med signal density	A35	35	1.00	5.00
Arterial - med signal density	A30	30	1.20	5.00

Table 32. Proposed LAMTA VDF curves and parameters.

Facility Type	Free-Flow Speed					Corresponding VDF				
	Area Type					Area Type				
	CBD	URB	SUB	MNT	RUR	CBD	URB	SUB	MNT	RUR
Freeway	72	72	72	72	72	F70	F70	F70	F70	F70
Major/Expressway	20	30	35	40	50	A30	A35	A40L	A50M	A50L
Primary	20	30	35	40	50	A30	A30	A35	A40M	A50M
Secondary	20	25	30	35	50	A30	A30	A30	A35	A40M
HOV2	72	72	72	72	72	F70	F70	F70	F70	F70
Centroid Connector	15	20	25	35	50	A30	A30	A30	A30	A30
Ramps	40	40	40	40	40	A40L	A40L	A40L	A40L	A40L
HOV3	72	72	72	72	72	F70	F70	F70	F70	F70
Toll	72	72	72	72	72	F70	F70	F70	F70	F70

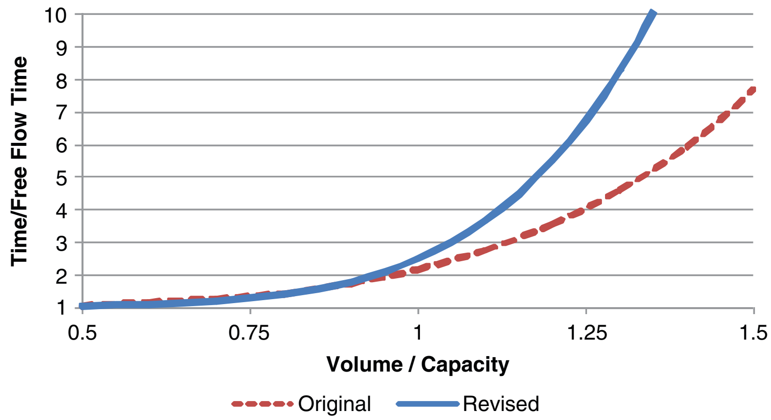

Figure 64. Original and proposed VDF curves for freeways.

speed adjustment process was guided by speed and volume data gathered from PeMS for the two study corridors. These speed adjustments are meant to be temporary; eventually the speed feedback mechanism will determine the appropriate input speeds.

Toll Choice Utility

The availability of a toll mode was determined in part by the length of the trip and the time savings relative to the best non-toll path. It was reformulated this way so that now toll mode availability is solely a function of the presence of a toll path. Furthermore, the utility of a toll mode is now a function of the length of the trip, in addition to time and cost. The intent is to discourage, but not prohibit, very short trips from using the toll roads.

Carpool Choices

The current LAMTA model considers two carpool choices, two-person carpools (SR2), and three or more person carpools (SR3+). The latter choice was formulated into two independent choices, as SR3 and SR4+. This choice set allows studying the option of tolling SR3 carpools while allowing SR4+ carpools to travel for free on the HOT lanes. The mode choice model will be recalibrated to SR4+ targets obtained from the SCAG home interview survey during the second phase of model development tasks.

Vehicle Classes

The mode choice model splits the auto trip tables into HOV-eligible and non-HOV-eligible trips. This classification is based on the availability of a HOV path, the length of the trip, and the time savings on the HOV lane. The original intent was to allow only HOV-eligible trips to use the HOV lanes. In the current version of the model, however, the HOV and non-HOV trip tables are summed prior to assignment. The script was modified so that the HOV classification is carried forward, and only HOV-eligible trips are assigned to the HOV facilities. This results in a total of seven (7) auto vehicle classes, instead of the three (3) previously used. The elemental modes, facility type restrictions, and resulting vehicle classes are shown in Table 33.

Traffic Counts

The screenline traffic count data was carefully reviewed. These count data are collected by SCAG and posted on their highway network. LAMTA posts the equivalent location relative to the LAMTA highway network. A few of the LAMTA equivalent locations were corrected and supplemented the data with a limited number of HOV lane counts. It was observed that SCAG's screenline validation ignored, in some instances, the HOV lanes, so these and a few other missing facilities were added to the screenlines. This ensures a more equitable comparison of SCAG and LAMTA screenline volumes.

The interim model that resulted from the implementation of these short term enhancements was used to forecast traffic for the two ConOps study corridors, Harbor Freeway and El Monte Busway, as well as for Caltrans' EIS. For the remainder of the Congestion Pricing Study, the model will be further enhanced with the full set of improvements identified at the onset of this project. These model enhancements are the subject of the remainder of this section:

- Reformulation of the auto choices and utility functions in the mode choice model,
- Improvements to the highway assignment step,
- Implementation of speed feedback from highway assignment to mode choice, and

Table 33. Vehicle classes and facility usage.

Mode	Occupancy	Toll?	HOV?	Restricted Facility Types	Vehicle Class	#
Drive Alone	One	No	No	Toll, HOV (all)	Free Mixed Flow	1
Drive Alone Toll	One	Yes	No	HOV (all)	Toll Drive Alone	4
SR2 No Toll No HOV	Two	No	No	Toll, HOV (all)	Free Mixed Flow	1
SR2 No Toll HOV	Two	No	Yes	Toll, HOV3+	Free HOV2	2
SR2 Toll No HOV	Two	Yes	No	HOV (all)	Toll Carpool	7
SR2 Toll HOV	Two	Yes	Yes	HOV3+	Toll HOV2	5
SR3+ No Toll No HOV	Three or more	No	No	Toll, HOV (all)	Free Mixed Flow	1
SR3+ No Toll HOV	Three or more	No	Yes	Toll	Free HOV	3
SR3+ Toll No HOV	Three or more	Yes	No	HOV (all)	Toll Carpool	7
SR3+ Toll HOV	Three or more	Yes	Yes		Toll HOV	6

- Incorporation of a time-of-day/peak spreading choice model.

6.4.2 Auto Choices and Utility Functions in Mode Choice

The auto choices in the mode choice model are currently specified as shown in Figure 65. For the sake of clarity, only the choices in the two-person carpool nest are shown; similar choices would exist for each carpool mode. In this model, the options labeled HOV represent trips allowed to use the carpool lanes. Although depicted as a sub-nest of the mode choice model, these options are not actual probabilistic choices. Instead, a set of rules determine whether the trips on any given OD pair are allowed to use the HOV lanes.

It was proposed to reformulate the model so that all of the choices would be probabilistic, with utilities expressed as a function of travel time, travel cost (parking cost, operating cost, and toll cost), and a distance term that discourages short trips from using the toll roads or HOV lanes. The utilities and choice availabilities will no longer be a function of time or distance thresholds, because these thresholds can sometimes result in unintuitive model responses to LOS attributes. The cost coefficients will be stratified by income level, and possibly also by toll versus non-toll costs. The utilities will also include an alternative-specific constant stratified by income level, to capture unobserved attributes.

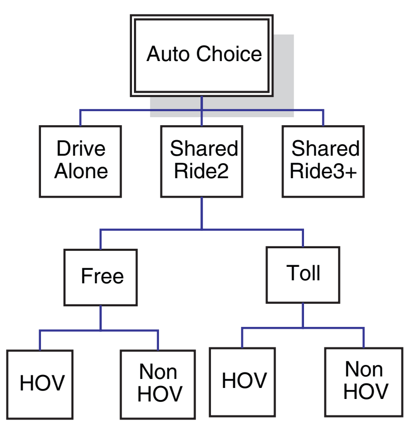

Figure 65. Auto choices in the existing mode choice mode.

One important issue is to determine whether costs are shared among members of a carpool and the degree of sharing. In reality, some carpoolers share costs while others do not. And some costs are more likely to be shared than others. The issue is what cost does a tripmaker perceive when making a mode choice decision, since this affects the characteristics of trips that choose the carpool modes. If it is assumed that operating costs are shared, then all else equal the average trip distance of a carpool will be higher than the average trip distance of drive alone trip. While it was observed that carpools tend to travel longer distances, cost-sharing may over-estimate trip lengths, when combined with the shorter travel times expected when using HOV lanes. It is expected that the SP survey data will provide some guidance on the extent of cost sharing; however it may be limited to the sharing of toll costs. As a first step, we propose to share toll and parking costs among carpool users, but not vehicle operating costs. Therefore the toll and parking costs will be divided by the average vehicle occupancy. This will be revised if needed depending on the SP survey results.

Previous analyses of HOV and express lane usage, conducted in Houston and San Diego, have shown that these facilities tend to carry a smaller proportion of short distance trips than general purpose freeway lanes. It is likely that this is also the case in Los Angeles, where some of the HOV lanes are barrier or buffer-separated from the mixed-flow lanes, with more limited opportunities for access and egress. Also, during peak hours carpools need to cross over four or five lanes of bumper-to-bumper traffic in order to access the HOV lanes; this may be impractical and cumbersome when the freeway portion of the trip spans only a few interchanges. The proposed distance penalty function would apply only to trips less than 2.5 miles in total length.

One remaining outstanding issue is the absence of household size effects in the mode choice model, particularly as they relate to the probability of choosing a carpool mode. Specifically the issue is whether, by assuming no household size effects, the model will overestimate the probability of choosing 3-person and 4-person carpools. The person trip tables are currently not stratified by household size. Therefore, in order to account for household size effects it would be necessary to develop a trip table segmentation sub-model, applied prior to or concurrent with the mode choice model.

6.4.3 Improvements to Highway Assignment

Truck and Bus Volumes

It was proposed to include truck trips and bus vehicle volumes in the highway assignment step. Ignoring these vehicle flows creates inconsistencies between the results of the regional model and the Toll Optimization Model that will be used to study the effects of various toll policies. In corridors where truck and/or bus volumes are significant, ignoring their presence could materially influence optimal tolls and the corresponding projected revenues. Truck trip tables for 2000, 2010, and 2030 were obtained from SCAG's most recent version of the truck model. CSI reviewed and adjusted the validation of trucks to the study facilities. Bus volumes on selected corridors can be summarized from the LAMTA transit network. The truck trip tables will be loaded as additional vehicle classes, while the bus volumes will be preloaded.

Generalized cost

The current LAMTA assignment process is based on travel time impedances only. It was propose to implement generalized cost functions, as shown in the equation below. The objective is to have more consistency between the generalized costs used by the mode choice model, which include time and tolls, and the impedances used during highway assignment.

$$Generalized\ Cost_{lk} = Time_l + \frac{Toll_{lk}}{VOT_k} \qquad \text{(Equation 35)}$$

where l refers to links and k refers to user classes.

6.4.4 Speed Feedback Implementation

In order to study the impact of road pricing on highway traffic volumes, it is necessary to expose the mode choice model to travel times consistent with the results of highway assignment. To accomplish this consistency, it was proposed to feed travel times from highway assignment back to network skimming and mode choice. Furthermore, it was proposed to iterate between assignment and mode choice until the traffic volumes are stable.

To implement speed feedback and model convergence, several issues need to be addressed.

Model Run Times

At a minimum, the entire model sequence will need to be run twice. It is more likely that three or four iterations will be required to achieve stable volumes. Typically tests for stability are limited to the AM Peak and MD periods, because they provide the data for deriving peak and off-peak skims. Even if highway assignments are limited to these two periods while reaching stability, the total model run time will be doubled or even tripled. Therefore strategies for reducing run time need to be considered.

Feedback Implementation

In terms of the mechanics of implementing speed feedback, a program that checks for model convergence (link and/or trip table based) and re-starts the model sequence needs to be developed. These checks and logic cannot be implemented in Tranplan. One possibility would be to develop a program in Fortran. A more attractive option would be to re-implement the highway assignment step in Cube (Voyager or TP+). Cube reads Tranplan matrices and networks. While it cannot write a Tranplan binary network, it can write a fixed-format text file that Tranplan can use to build the network (needed for subsequent skimming). The stability checks can be performed in a Cube script, obviating the need for stand-alone executables. More importantly, the highway assignment step can be distributed among several processors, significantly reducing model run time. The distributed application can be easily adapted to the number of processors available, whether in a single machine or across multiple units.

Feedback Method and Convergence

It is proposed to base the speed feedback on link volume averages, as shown in Figure 66. The averaging will be performed using the method of successive averages (MSA). Other averaging procedures, such as those described by Boyce (2007), will be explored should MSA prove to converge too slowly.

Link flow convergence will be checked using Percent Mean Root Square Error (RMSE), for all links on the network and also for the HOV/HOT links separately. It is understood that stable link flows do not necessarily imply stable trip tables or stable transit ridership. Due to the integer nature of the Tranplan matrices, only limited tests of stability can be performed

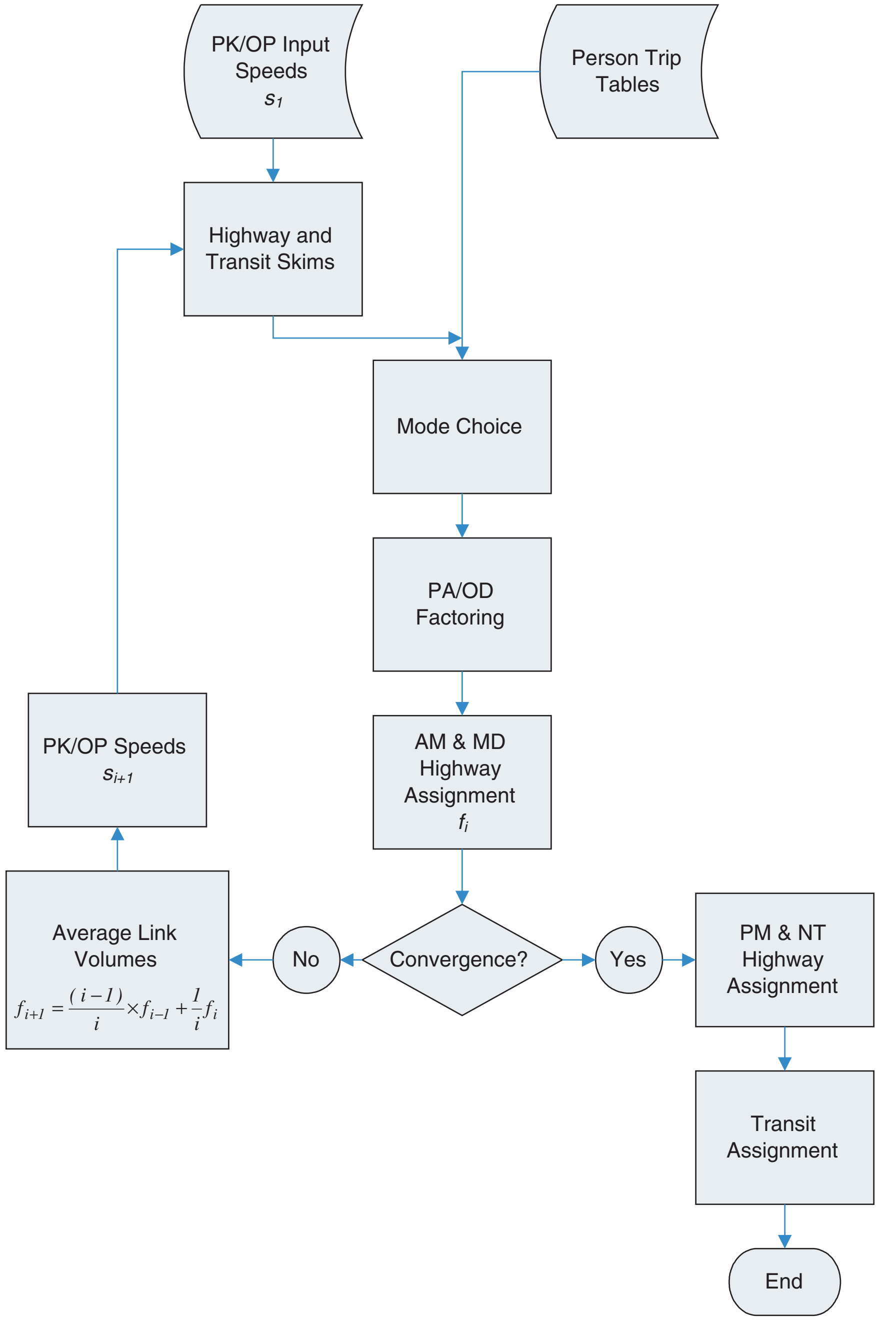

Figure 66. Model system flow with speed feedback.

on the trip tables output by the mode choice program. The convergence of some of the mode trip tables, globally and/or as a function of the number of trips per OD pair, can be tracked. The RMSE limit used to signal convergence will be established by examining the model convergence behavior over several iterations.

6.4.5 Time of Day and Peak Spreading Model

One of the first-order effects of congestion pricing on travel behavior is to shift trips across times of day, primarily from the peak hours to less congested, and therefore less expensive, travel hours. In order to examine the aggregate effects of these time-of-day shifts on vehicle flows, a time-of-day (TOD) model will be implemented within the regional model. The proposed TOD model will replace the existing Factoring model that operates with Production-Attraction (PA) and OD factors. The TOD model structure is shown in Figure 67.

The TOD model will be structured as a multinomial logit model. The TOD choice set must respond to the needs of the HOT lane evaluations, in particular the need to differentiate the peak hour from the shoulders of the peak period. The desired minimum number of time-of-day alternatives is shown in Table 34. It is, however, possible to develop and

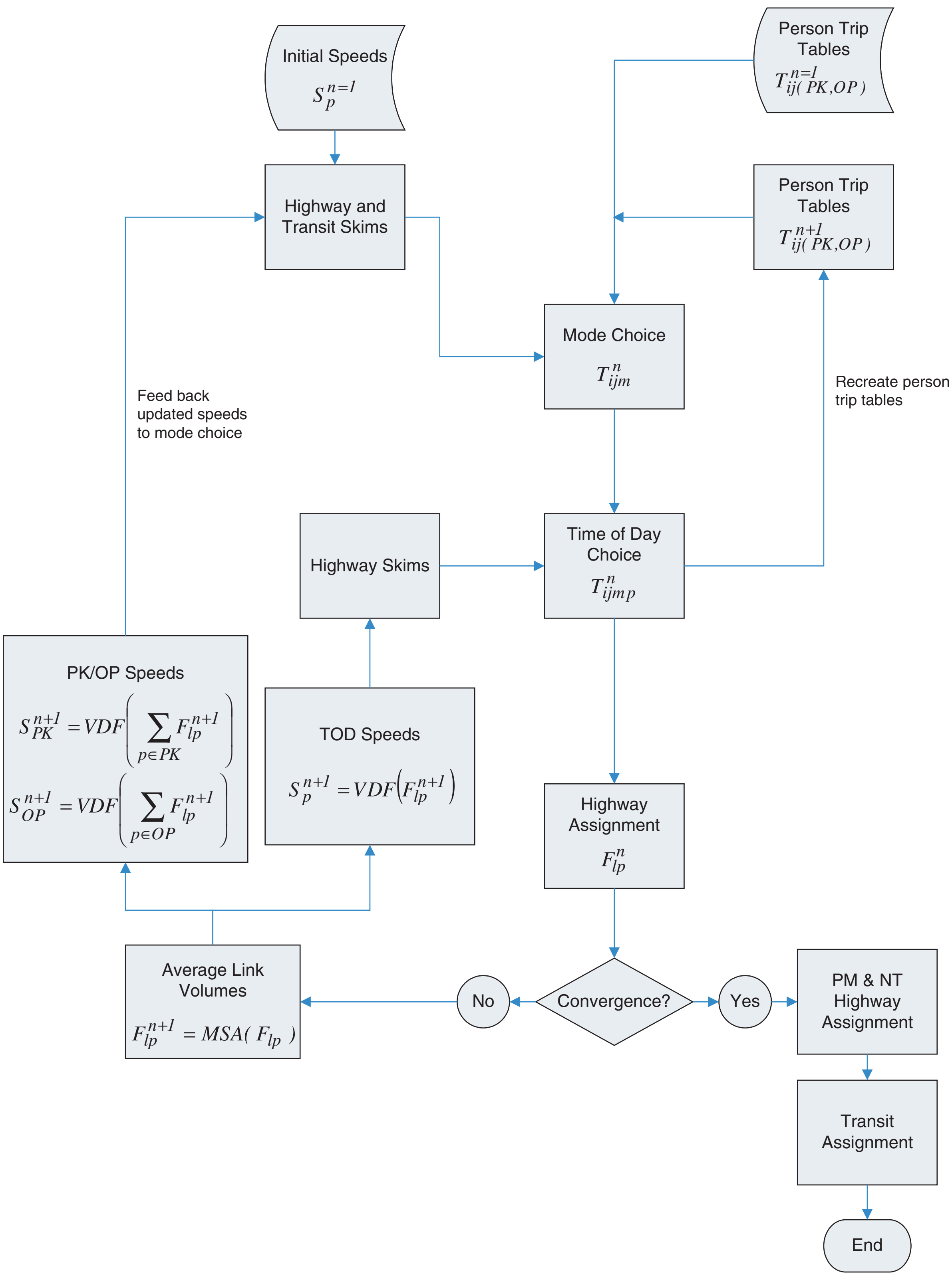

Figure 67. Time-of-day choice model implementation.

Table 34. Minimum set of time-of-day periods.

Choice	Duration (hours)	Relation to Current Model Periods
Pre AM Peak	1	AM Peak Period
AM Peak	1	
Post AM Peak	1	
Midday	6	Midday Period
Pre PM Peak	1.5	PM Peak Period
PM Peak	1	
Post PM Peak	1.5	
Night	11	Night Period

implement a model with a finer time-of-day resolution, for example, one-hour intervals, with little or no additional effort. These TOD choice models have been developed and applied in Columbus, Atlanta, and San Francisco Bay Area ABMs. These ABMs are tour-based, microsimulation models, but the structure of the TOD model can be applied in an aggregate, trip-based framework. In a tour-based framework, the TOD model simultaneously chooses departure time from home, arrival time back at home (end of the tour), and tour duration. In a trip-based framework, the trip tables would be in production/attraction format, so that the trips could be decomposed into outbound (e.g., AM commute) trips and inbound (e.g., PM commute) trips. TOD choice could be applied to these two trips separately, that is, independent of each other. Alternatively, the model could simultaneously predict the outbound (home to activity) trip departure time and the inbound (activity to home) trip departure time.

The utility of any given time period would be expressed relative to a reference period, chosen for convenience to be the start of the day. Continuous shift variables measure the separation between the reference time period and any given time period. Explanatory variables, such as travel time or travel cost, are interacted with these shift variables, and with a duration variable that essentially links the departure and arrival periods. For example, for the case of simultaneous outbound and inbound trip scheduling, the utility function could be specified as follows:

$$U(p,q) = \alpha_p + \alpha_q + \beta^p \times (tt_p + tt_q) \times p + \beta^q \times (tt_p + tt_q) \times q + \beta^{pq} \times (tt_p + tt_q) \times (q - p) \quad \text{(Equation 36)}$$

where

p = departure time period for the outbound trip,
q = departure time period for the inbound trip,
tt_p = outbound trip travel time (when departing from home in period p),
tt_q = inbound trip travel time (when departing from the non-home activity in period q),
α_p, α_q = period-specific constants, to be estimated and calibrated, and
β^p, β^q, β^{pq} = travel time coefficients, to be estimated.

The two shift variables are p and q, and the duration variable is $(q–p)$. In Equation 36 it is assumed that the reference time period is zero for both trips. Explanatory variables may interact with any or all of the shift/duration variables. If outbound trips are scheduled independently of inbound trips, then the utility function would have terms corresponding to only one trip direction, and the duration terms drop out. Models will be developed for each trip purpose (HBW, HBU, HBO and NHB). Possible explanatory variables include travel time, travel cost (tolls), income level, trip mode, trip length, and other origin and/or destination related effects. The models will be estimated with combined RP/SP data, obtained from the SCAG 2000 Home Interview Survey and the LAMTA HOT Lane Stated-Preference Survey.

The model will exhibit peak spreading if either times or costs are varied with departure time. Note that it is not necessary to predict travel times (or costs) for each possible departure time; several departure times may share the same travel time and/or cost. Period-specific highway assignments will be performed for a subset of the time periods shown in Table 34 to obtain the necessary travel times for estimating and applying the TOD model. To reduce the number of highway assignments, we will assume that the PM travel times are the transpose of the AM travel times.

One possible way to implement the TOD model is shown in Figure 67. The initial trip tables, originally obtained from the SCAG regional model, are already segmented into peak and off-peak trips. This initial segmentation is carried through mode choice. After mode choice, the peak and off-peak auto trip tables are added to create total daily auto trips by submode. Then the TOD choice model is applied to the daily auto trip tables. Highway assignments are performed for the three AM time periods and the Midday time period. To feed back travel times to the mode choice model, link volumes for the entire peak period were averaged (as before). To feed back travel times to the TOD model, volumes for each individual time period (three AM periods and a midday period) were averaged. It is proposed to examine the model's convergence behavior at the level of the entire AM time period, as well as for each individual AM hour.

A second possible implementation could be to split the TOD model into two parts; first would be a choice between the four aggregate periods (AM/MD/PM/NT) and second a peak spreading choice, applied within each of the two peak periods. The first level choice would take place after mode choice, while the second peak spreading choice would take place after the model has converged. To iterate at this point between time of day and assignment to achieve consistent speeds may be chosen.

The potential advantage of this second approach is a reduction in the number of highway assignments performed in each model run, and therefore a reduction in model run time. This approach is also more consistent with the way in which the model has been validated to date. It is possible that moving towards hour-length assignments will require adjustments to the volume-delay functions and more extensive model validation; this second approach would avoid this additional effort.

The TOD choice model will not be applied to the transit and non-motorized trip tables. For these trips, using fixed diurnal factors will be continued.

Note that the fraction of the total demand that occurs in the peak period (AM and PM) may change after applying the TOD choice model. Therefore the person trip tables used to apply the mode choice model in the feedback loops are constructed by adding the period-specific trip tables for all modes.

6.4.6 Calibration and Validation

The TOD choice model will be calibrated to targets developed from the SCAG regional home interview survey. The targets will consists of the proportion of trips, by mode and trip purpose and direction (home to work versus work to home, for example) observed during the periods shown in Table 34. It may also be helpful to compare these targets to SCAG's time of day model estimates.

The model will be validated by comparing observed versus estimated traffic counts during the modeled time-of-day periods. A database of period-specific traffic counts has not yet been identified. It may be possible to obtain these data from SCAG, Caltrans or LADOT. Alternatively, data for selected freeways may be obtained from the PeMS database. There are already recent, detailed traffic counts for the two study corridors, I-10 and I-110, for both the mixed flow and HOV lanes, for a regular weekday in 2008.

6.4.7 Conclusions

A trip-based 4-step model in combination with conventional static assignment represents a modeling tool of a limited capability compared to more advanced ABMs and DTA described in Sections 6.1-6.3. There are, however, many ways to improve 4-step models and bring them to a level that would allow for reasonable model sensitivities to different pricing projects and policies in practical terms. The model improvements described here for the LAMTA model in the context of the pricing studies described are generally applicable for most existing 4-step models. The check-list of the most important model fixes and structural improvements in this trip-based framework includes a revision of the model structure and network procedures to incorporate differential tolls and vehicle occupancy categories (including an inclusion of occupancy as the lower-level subchoice in the mode choice structure), improved time-of-day choice (peak-spreading) model sensitivity to congestion pricing, and an extensive model calibration on the highway side to match the observed traffic counts.

CHAPTER 7

Conclusions and Recommendations for Further Research

This research has provided an extensive analysis and synthesis of travel forecasting, best practices, as well as operational research approaches to the modeling highway pricing projects. The conclusions and recommendations are summarized below in four major groups:

- Existing practices and identified gaps,
- Recommended short-term improvements,
- Major long-term improvements and strategic directions, and
- Suggestions for future research.

7.1 Existing Practices and Identified Gaps

The review and analysis of the travel models and network simulation tools applied for T&R studies in practice has revealed a highly diverse picture, with a large proportion of simplified methods commonly applied, along with a growing number of applications of more advanced modeling tools. The following main conclusions can be made regarding the general tendencies observed and the identified gaps where improvements are needed:

- There is a great deal of variation in approaches. In most cases, the model applied for the highway pricing project was essentially a quite modest modification of the existing regional model available for the study. Thus, limitations and deficiencies of the existing regional model were inevitably adopted for the study.
- In most cases, only route itinerary (assignment) and binary route type choice (toll versus non-toll) models were employed for comparison and evaluation of pricing alternatives. This achieves reasonable results under the assumption that pricing would not affect mode choice, time-of-day choice, distribution of the origins and destinations of travel, or travel generation. While this simplification might be in some cases acceptable for intercity highways, it is difficult to defend for most analysis of pricing in metropolitan and urban settings.
- Pricing effects on trip distribution have been incorporated by using mode choice Logsums as the measure of accessibility in destination choice or gravity-type distribution models. The use of mode choice Logsums in gravity models needs to be tested for validity. Unlike in the logit destination choice framework, where appropriate elasticities with respect to cost are expected when reasonable Logsum parameters are used, it is not clear that doubly constrained gravity models behave appropriately to changes in LOS variables such as the introduction of tolls.
- In some cases there is an inconsistency between the travel times and costs used for mode choice models, trip distribution, and assignment, in that the costs and travel times that reflect priced conditions are used in mode choice, and generated in assignment, while the toll costs do not enter the impedance function used for distribution. This is the case when travel times are fed back from a generalized cost assignment into a distribution model that is a function of travel times only.
- In a few cases utility functions in multinomial or nested logit mode choice models are miss-specified. Undesirable specifications include toll utilities that are a function of both the toll alternative travel time and travel time savings with respect to the free alternative. This type of specification may result in counter-intuitive results when the LOS attributes change on either the toll or the free routes. Another potentially problematic specification is the use of thresholds, such as making the toll alternative available only if it meets a pre-defined minimum time savings goal. The nesting coefficients on these models sometimes result in models with unreasonably high elasticity to toll, or time differences when the toll diversion is examined at the root level of the model (where they are comparable with the elasticity of route type binary choice models).

- There is no consensus whether road pricing costs should be shared among vehicle occupants, and if so how. Most models either assume that the full toll cost is either borne by all occupants or that it is equally shared among the occupants. Some models differentiate between cost sharing for HBW trips and cost sharing for other purposes. Sharing road pricing costs among vehicle occupants makes carpools less cost-sensitive, an assumption that may be acceptable for work trips, but is questionable for other purposes, where the majority of carpools are among members of the same household and oftentimes include minors.
- In some regional modeling systems that were specifically modified for congestion pricing projects, peak-spreading models were applied. Trip-based 4-step models are normally based on time-of-day (peak) factors that are not sensitive to relative congestion levels at different periods of the day. AMBs can offer a better framework where peak-spreading effects are captured by time-of-day choice sub-model.
- Peak-spreading or time-of-day models are sensitive to differences in travel times by time of day, but not to differences in toll costs by time of day. This may be simply a result of the few localities where road pricing costs vary by time of day combined with the lack of observed data sufficient to estimate appropriate model parameters.
- Very few models to date have incorporated all trip and tour-level dimensions in a consistent way, and there have not yet been any practical examples of the incorporation of pricing impacts on the day-level, mid-term, and long-term choices, even with the activity-based models that have recently come into use.
- Almost all models, including ABMs, are characterized by a significant discrepancy between the user segmentation by VOT in the demand model compared to network simulation. While at the demand modeling stage, segmentation normally includes several trip purposes, income groups, car occupancy, and time-of-day periods; network simulations are characterized by a limited segmentation. Traffic assignments are implemented by periods of the day and for multiple vehicle classes that typically include vehicle type and occupancy. Trip purposes and income groups, however, are blended together before assignment, creating strong aggregation biases with respect to VOT.
- There are also discrepancies in the cost functions used to build best paths between the network simulations used to build travel time and cost matrices for the demand models and the network simulations used to assign trips to the highway network. Best paths for the demand model may be built on the basis of travel time only, while the assignment is performed on the basis of generalized cost, or vice-versa.
- In almost all modeling efforts where route type choice (toll vs. non-toll) was involved, a problem of inconsistency between the generated trip tables for toll-users and their assignment onto the highway network was reported. This "leakage" of toll users in the network simulation can be significant and constitutes a non-trivial analytical problem that requires special modeling efforts to resolve.
- Most models attempt to equilibrate supply and demand by feeding back travel times and cost from the assignment step to the trip distribution or mode choice steps. In most cases, feedback is executed for a fixed number of iterations, so convergence is not necessarily guaranteed. This may be particularly problematic when forecasting under conditions of high population growth, where congestion effects may be far more pronounced than in the base calibration year.
- Most models break down the network simulation into four broad time periods, typically AM Peak (2 to 4 hours long), Midday, PM Peak (2 to 4 hours long) and Night, and are therefore able to compute LOS differences by time of day only at this level of aggregation. Only one of the regional models reviewed performs the network simulation at a finer time of day disaggregation.

7.2 Possible Short-Term Improvements

The short-term improvements summarized in this section are primarily applicable to trip-based 4-step models. A trip-based 4-step model, in combination with conventional static assignment, represents a modeling tool of a limited capability compared to more advanced ABMs and DTA. Although the major strategic directions for improvement of models are strongly associated with a new generation of advanced ABMs and network simulation tools like DTA, there are many practically useful steps that can be taken to improve 4-step models, as well as simple ABMs, in order to better prepare them for T&R forecasting and ensure reasonable model sensitivities to different pricing projects and policies in practical terms. The following main recommendations can be made:

- A travel model to be applied for highway pricing studies should comply with a minimal set of structural requirements. Foremost among these is reasonable model sensitivities to tolls across all travel dimensions that could be affected by pricing actions to be studied, including: route choice, mode (and car occupancy) choice, trip distribution, and time-of-day choice. Across all these choices, a reasonable level of segmentation and correct VOT estimates (with the necessary aggregations) should be applied.
- The demand model should be segmented by at least four to five travel purposes and three to four income groups, with VOT specific for each combined segment. An additional step that can be effective is to apply differential travel time coefficients by segments, and consequently make VOT values differentiated by network congestion levels. This in

effect represents a simple proxy for measures of travelers' aversion to congestion (other than average travel times alone), including a lack of reliability associated with congested facilities.

- Network procedures that incorporate differential tolls and vehicle categories relevant to the pricing study are necessary. The traffic assignment should incorporate and distinguish relevant vehicle classes (auto, commercial vehicles, trucks, taxis, etc.) with corresponding average VOT per class. The multi-class assignment technique is supported in all major transportation software packages (TransCAD, EMME, and Cube) and can be further applied to differentiate between VOT groups within the same vehicle class. If tolls or vehicle eligibility are differentiated by vehicle occupancy (HOV/HOT lanes) the auto vehicle class should be additionally segmented by the relevant occupancy categories (SOV, HOV2, HOV3, etc.).
- It is highly recommended (although it is not an absolute requirement in the early stages of pricing studies) to incorporate a binary route type choice model (toll versus non-toll facility), either as a lower-level, sub-nest in mode choice or as a pre-assignment procedure. This sub-model allows for capturing a toll bias associated with the perception of a superior level of reliability and safety of the toll facility, as well as provides for better (non-linear) specifications of the tradeoffs between travel time savings and extra costs.
- It is essential for congestion pricing studies to include an improved time-of-day choice (peak-spreading) model sensitive to congestion levels and pricing. Although the trip-base 4-step model structure is not as flexible as ABM structure in addressing time-of-day choice factors, it can incorporate a time-of-day choice model with a fine level of temporal resolution (1 hour or less) that would roughly correspond to the outbound and inbound components of a tour-based time-of-day choice model applied separately for each trip segment.
- There are a growing number of applications where mode and/or occupancy choices are included. In several cases, mode, occupancy, and binary route type choices were combined in one multi-level nested logit choice model structure, where occupancy and route type choice served as lower-level sub-choices. These improvements can be implemented and are equally relevant for both 4-step models and ABMs.
- It is essential to equilibrate the demand model (at least mode choice and route type choice) and the highway assignment to ensure that the results correspond to (or at least approximate) a stable equilibrium solution. It is more difficult to include the trip distribution (and other sub-models like time-of-day choice and/or trip generation) in the global equilibrium, which can require multiple iterations and special averaging algorithms. However, it is essential to eventually ensure a reasonable level of convergence of the entire model system. Recent experience with the New York ABM has shown that effective strategies of equilibration, based on a parallel averaging of trip tables and LOS skims, can achieve a reasonable level of convergence in three to four global iterations, even in one of the largest and most congested regional networks.
- Network simulations should be carefully validated and calibrated to replicate period-specific traffic volumes, as well as period-specific LOS attributes. In this regard, the prevailing practice of model validation by daily traffic counts has to be replaced with more extensive and elaborate validation/calibration by four to five time-of-day periods.
- There are many reserves for improvements that relate to a better understanding and incorporation of rules of financial world. Many of them relate to the way in which a model is used, rather than to its structure per se. These include more thorough procedures for assessing non-modeled days (weekends and holidays) and time-of-day periods (if the model does not cover an entire weekday), as well as explicit consideration of possible ramp-up dynamics during the first several years of the project. The model structure and output should be made to produce the necessary inputs to the Financial Plan. Of special importance is the issue of quantification of risk factors. Risk analysis essentially represents an important strategic direction with many aspects that have yet to be explored by travel forecasters. Some simplified procedures, however, are based on the possible scenarios for main input factors can be applied even with a simple travel model.

7.3 Major Long-Term Improvements and Strategic Directions

The main avenues for improvement of modeling tools applied for pricing studies are seen to be associated with the advanced ABM framework on the demand side and DTA on the network simulation side. ABMs provide clear advantages over trip-based models in the analysis of pricing policies. In particular, such known limitations of trip-based models as a lack of policy sensitivity and insufficient market segmentation can be overcome with these more advanced models. The main advantages of ABM structure for modeling highway pricing scenarios can be categorized according to the following model features:

- Tour-based structure that is essential for accounting for tolls applied by both directions by time-of-day periods, in a consistent and coherent way. This is, however, conditional upon obtaining a level of temporal resolution that matches the details of pricing schedules. Since variable

pricing schemes are frequently the focus of pricing studies, it is essential to have a large set of period-specific simulations, ideally, hourly assignments (or a full-day DTA as a better option as discussed below) in order to address different pricing schedules.
- Microsimulation of individuals that allows for probabilistic variation of individual parameters including VOT, car rationing by license plate, toll discounts associated with different payment types and/or population groups. In addition to that, a fully disaggregate structure of the model output is extremely convenient for reporting, analysis, and evaluation of the pricing scenarios, in particular for screening winners and losers, and for equity analysis across different population groups, etc.
- Entire-day individual activity pattern that allows for a consistent modeling of non-trip pricing options, such as a daily area pricing fee.

There are, however, a number of issues that remain to be addressed by ABMs in practice. First, most ABMs continue to rely on static equilibrium highway assignment algorithms. It is common knowledge that such techniques fail to adequately address congestion due to their lack of ability to reflect queuing. One of the advantages of priced facilities (particularly dynamically priced facilities) is that they offer more reliable travel times than competing congested facilities where the variability of travel time can be quite onerous. From this perspective, the integration of an ABM and DTA in one coherent modeling framework represents one of the most important strategic directions for the field.

The advanced and flexible microsimulation modeling paradigm embedded in ABM and DTA structures opens a constructive way to include many recent theoretical advances in applied operational models. The following main aspects and directions were identified in this research:

- Heterogeneity of road users with respect to their VOT and willingness to pay. This requires a consistent segmentation throughout all of the demand modeling and network simulation procedures to ensure compatibility of implied VOTs. In addition to an explicit segmentation, random coefficient choice models represent a promising tool for capturing heterogeneity.
- Proper incorporation of toll road choice in the general hierarchy of travel choices in the modeling system. Additional travel dimensions (such as whether to pay a toll, car occupancy, and payment type/technology) and associated choice models should be properly integrated with the other sub-models in the model system. The impacts of pricing on long-term choices such as vehicle ownership, workplace location, residential location, and ultimately firm location need to be better understood. Most ABMs are based on cross-sectional data and are unable to fully capture long-term behavior associated with the introduction of pricing policies. Hopefully, as more policies become implemented, more longitudinal data will be available to improve this critical aspect of travel demand models.
- Accounting for reliability of travel time associated with toll roads requires the incorporation of travel time reliability in applied models with quantitative measures that can be modeled on both demand and supply sides.
- More comprehensive modeling of time-of-day choice based on the analysis of all constraints associated with changing individual daily schedules.
- More comprehensive modeling of car occupancy related decisions, including differences in carpool types (planned intra-household, planned inter-household, and casual) and associated VOT impacts.
- More advanced traffic simulation procedures such as DTA and microsimulation, and better ways to integrate them with travel demand models. In this regard, future research needs to systematically incorporate features such as heterogeneous users in response to dynamic tolls, and develop efficient heterogeneous intermodal shortest path algorithms.

Many of these research topics are being addressed in ongoing NCHRP and SHRP 2 projects. Incorporation of the results of these studies in models applied for highway pricing studies in practice represents an important challenge for the transportation modeling profession.

7.4 Suggestions for Future Research in Adjacent and Related Areas

Highway pricing issues are closely intertwined with many general aspects of highway planning and modeling. The following list of topics deserving of further investigation are either directly related to the modeling of pricing or are indirectly related to adjacent research areas that interact strongly with pricing:

- Effects of pricing on environmental quality and energy consumption. These measures are important in assessing the overall pricing benefits.
- Emerging automatic methods for the collection of information on highway volumes, speeds, and reliability. These new sources of information can be effectively used for general model improvement.
- Model development strategies for small MPOs. In general, it is almost impossible to outline a decent and defendable analytical procedure for T&R forecasting without a regional travel model. Simplified sketch-planning tools can be applied at the initial phases of project development

to make a go/no-go decision, as well as to narrow the scope of possible alternatives. As the pricing project progresses to the phases of Environmental Impact and Investment Grade Studies, however, more substantial modeling work must be done. This represents a challenge for small MPOs that do not have sufficient modeling staff and resources to deploy an advanced regional ABM or DTA.

- Household and person travel time and cost budgets. It is known and well established in the micro-economic theory that the willingness to pay for any product (including travel time savings) is a strong function of the overall time and budget constraints. From this perspective, VOT cannot be explained for a particular trip, tour, or even travel day without taking into account the bigger picture of household and person behavior for a longer period of time. This aspect is still missing in almost all travel models, including the most advanced ABMs.
- Time scales for traveler responses to different pricing schemes. An important additional aspect of modeling traveler responses to congestion and pricing relates to different time scales associated with different measures. The range of possible relevant time scales extends from a nearly instantaneous response (like changing a route as the result of real-time travel information or choice of a dynamically priced lane based on the current toll and congestion level on the general-purpose lanes) to the long-term effects (observed only in 20–30 years) like changes in population residential location or business activities.

These particular topics have been identified in many pricing studies as deserving attention and came up frequently in the discussions of the project team with the panel of experts. This can be future research aimed at advancing the theory and practice of modeling road pricing.

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APPENDIX A

Appendix A

A.1. Details of Selected Models Applied for Pricing Studies

A.1.1. Four-Step Trip-Based Models

A.1.1.1. Orange County, California

ORANGE COUNTY TRANSPORTATION AGENCY		
Orange County, California		
Major model feature	**Detailed feature / sub-model**	**Characteristics**
Spatial scale		Regional
Demand model structure		Aggregate trip-based.
Modeled pricing impacts (traveler responses), sub-model structure, form of utility function, incorporation of pricing	Mode Choice & Auto Occupancy	DA Toll, SR2 Toll and SR3+ Toll are elemental alternatives in a nested logit model.
		Utility of a toll mode is a function of its travel time, cost, a constant (unobserved attributes) term, and a 'bonus' term that increases with the difference between the toll and no toll travel time.
	Trip Distribution	The HBW distribution model uses mode choice logsums as the gravity model impedance. The mode choice utility constants used for trip distribution are not equal to the constants used for mode choice.
Willingness to pay / VOT and user segmentation	Vehicle classes	Auto only.
	Vehicle occupancy categories	SOV Toll, SOV No Toll, HOV Toll HOV No Toll, but same VOT for all classes.
	Trip purpose segmentation (low/med/high income) $1989	Home based work ($3.1/$8.4/$19.4)
		Home based other ($1.5/$4.1/$9.7)
		Non home based work ($6.7/hr)
		Non home based other ($6.7/hr)
	Household / person characteristics	Household income (low/med/hi) – VOT for trip distribution vary by income group and trip purpose.
Network simulation tool	Simulation type	Static user equilibrium assignment
	Representation of priced highway facilities	Cost function depends on travel time only.
Demand – Network Equilibrium	Feedback implementation	None.
Surveys and other data sources for model estimation / calibration / validation	Household travel survey	N/A
	Survey of existing toll road users	N/A
	Stated Preference survey	N/A
	Traffic counts	N/A

A.1.1.2. Wasatch Front, Utah

WASATCH FRONT REGIONAL COUNCIL / MOUNTAINLAND ASSOCIATION OF GOVERNMENTS		
Salt Lake, Utah		
Major model feature	**Detailed feature / sub-model**	**Characteristics**
Spatial scale		Regional
Demand model structure		Aggregate trip-based
Modeled pricing impacts (traveler responses), sub-model structure, form of utility function, incorporation of pricing	Mode Choice & Auto Occupancy	DA Toll, SR2 Toll and SR3+ Toll are elemental alternatives in a nested logit model.
		Utility of an auto mode, which includes the toll alternatives, is a function of its travel time, cost, a constant (unobserved attributes) term, and CBD and urbanization indicator variables.
	Trip Distribution	The HBW distribution model uses mode choice logsums in a destination choice framework. For all other purposes, toll costs are expressed in minutes using a VOT factor and added to the travel time. The impedance for the gravity models is the harmonic mean of travel time for the free path and travel time for the toll path.
Willingness to pay / VOT and user segmentation	Vehicle classes VOT is $40/hour for all classes	General purpose lane users
		HOV lane users, short distance
		HOV lane users, long distance
		Toll lane users, short distance
		Toll lane users, long distance
	Vehicle occupancy categories	SOV, HOV2, HOV3+
	Trip purpose segmentation (low income / high income)	Home based work ($1.34/$11.5)
		Home based school ($2.2/$4.2)
		Home based other ($0.8/$5.6)
		Non home based ($2.8/$5.7)
	Household / person characteristics	Household income (low/high)
Network simulation tool	Simulation type	Static user equilibrium assignment
	Representation of priced highway facilities	Cost function depends on travel time, distance and toll costs.
Demand – Network Equilibrium	Feedback implementation	N/A
Surveys and other data sources for model estimation / calibration / validation	Household travel survey	1992
	Traffic counts	N/A

A.1.1.3. Dallas – Fort Worth, Texas

NORTH-CENTRAL TEXAS COUNCIL OF GOVERNMENTS		
Dallas – Fort Worth, Texas		
Major model feature	**Detailed feature / sub-model**	**Characteristics**
Spatial scale		Regional
Demand model structure		Aggregate trip-based.
Modeled pricing impacts (traveler responses), sub-model structure, form of utility function, incorporation of pricing	Mode Choice	The only pricing impact is the inclusion of the toll cost in the utility of the auto alternatives.
Willingness to pay / VOT and user segmentation	Vehicle classes	Drive alone, shared ride HOV lane, shared ride non-HOV lane, trucks. Two values of time: $10/hr for autos and $12/hr for trucks ($1999)
	Trip purpose segmentation	Home based work ($5.91/hr))
		Home based non work ($4.07/hr)
		Non home based ($3.30/hr)
Network simulation tool	Simulation type	Static user equilibrium assignment
	Representation of priced highway facilities	Cost function depends on travel time, operating costs and toll costs.
Demand – Network Equilibrium	Feedback implementation	Fixed number of model iterations.
Surveys and other data sources for model estimation / calibration / validation	Household travel survey	1996 / 4,500 households
	Traffic counts	1999

A.1.1.4. San Francisco Bay Area, California

METROPOLITAN TRANSPORTATION COMMISSION (*)		
San Francisco Bay Area, California		
Major model feature	**Detailed feature / sub-model**	**Characteristics**
Spatial scale		Regional
Demand model structure		Aggregate trip-based.
Modeled pricing impacts (traveler responses), sub-model structure, form of utility function, incorporation of pricing	Mode Choice & Auto Occupancy	DA Toll, SR2 Toll and SR3+ Toll are elemental alternatives in a nested logit model. Trips that use the existing tolled bridges (Golden Gate, Bay, Dumbarton, San Mateo or San Rafael Bridges) are not considered Toll trips.
		Utility of a toll mode is a function of its travel time, cost or log of cost, household income, zonal characteristics, and a constant (unobserved attributes) term. Toll costs are shared among vehicle occupants in the off-peak period.
Willingness to pay / VOT and user segmentation	Vehicle classes	DA Toll, DA No Toll, SR2 Toll, SR2 No Toll, SR3+ Toll, SR3+ No Toll, Trucks.
	Trip purpose segmentation VOT in $1990.	Home based work ($9.65)
		Home based school ($0.36)
		Home based university ($0.67)
		Home based recreation ($0.79)
		Home based shop ($6.58)
		Home based other
		Non home based ($1.08)
		Trucks ($25.0)
		Internal/External ($1.08)
Network simulation tool	Simulation type	Static user equilibrium assignment. Akcelik volume-delay functions.
	Representation of priced highway facilities	Cost function depends on travel time only.
Demand – Network Equilibrium	Feedback implementation	Speed feedback to mode choice.
Surveys and other data sources for model estimation / calibration / validation	Household travel survey	1990 (10,000 households, trip-based survey) 1996 (15,000 households, activity-based survey)

(*) As modified for the I-680 Corridor Value Pricing Study and the FAIR Lanes Study.

A.1.1.5. San Diego, California

SAN DIEGO ASSOCIATION OF GOVERNMENTS (*)		
San Diego, California		
Major model feature	**Detailed feature / sub-model**	**Characteristics**
Spatial scale		Regional
Demand model structure		Aggregate trip-based.
Modeled pricing impacts (traveler responses), sub-model structure, form of utility function, incorporation of pricing	Mode Choice & Auto Occupancy	DA Toll, SR2 Toll and SR3+ Toll are elemental alternatives in a nested logit model. Also considers HOV No Toll as elemental alternatives.
		Utility of a toll mode is a function of its travel time, cost, and a constant (unobserved attributes) term.
	Trip Distribution	The gravity models use generalized cost as the impedance measure, with time valued at $0.35/min ($21/hr) and distance at $0.13/mile for all purposes.
Willingness to pay / VOT and user segmentation	Vehicle classes	SOV, HOV.
	Vehicle occupancy categories	SOV Toll, SOV No Toll, HOV Toll HOV No Toll, but same VOT for all classes.
	Trip purpose segmentation VOT in $1995 (low/med/high income)	Home based work ($1.8/$5.4/$11.2)
		Home based other ($0.9/$2.7/$5.6)
		Non home based ($2.7/hr)
	Household / person characteristics	Household income (low/med/hi)
Network simulation tool	Simulation type	Static user equilibrium assignment
	Representation of priced highway facilities	Cost function depends on travel time, travel costs and distance, with time valued at $21/hour for all vehicle classes.
Demand – Network Equilibrium	Feedback implementation	One feedback iteration.
Surveys and other data sources for model estimation / calibration / validation	Household travel survey	Year 1995 / 2,050 households
	Survey of existing toll road users	Years 1997-1999 / 1,500 commuters
	Traffic counts	Year 2000 / express lane counts

(*) As modified for the I-5 North Coast Managed Lane Value Pricing Study.

A.1.1.6. Minneapolis – Saint Paul, Minnesota

TWIN CITIES METROPOLITAN COUNCIL		
Minneapolis – Saint Paul, Minnesota		
Major model feature	**Detailed feature / sub-model**	**Characteristics**
Spatial scale		Regional
Demand model structure		Aggregate trip-based.
Modeled pricing impacts (traveler responses), sub-model structure, form of utility function, incorporation of pricing	Mode Choice & Auto Occupancy	DA Toll, SR2 Toll no HOV, SR2 Toll HOV, SR3+ Toll no HOV and SR3+ Toll HOV are elemental alternatives in a nested logit model.
		Utility of a toll mode is a function of its travel time, cost, and a constant (unobserved attributes) term.
	Trip Distribution	Mode choice logsums are used as the accessibility term in destination choice models for all purposes.
Willingness to pay / VOT and user segmentation	Vehicle classes	Auto only.
	Vehicle occupancy categories	SOV Toll, SOV No Toll, HOV Toll HOV No Toll, but same VOT for all classes.
	Trip purpose segmentation VOT in $2000	Home based work ($12.27/hr)
		Home based other ($3.67/hr)
		Non home based work ($1.92/hr)
		Non home based other ($2.00/hr)
Network simulation tool	Simulation type	Static user equilibrium assignment
	Representation of priced highway facilities	Cost function depends on travel time only.
Demand – Network Equilibrium	Feedback implementation	Travel times fed back to trip distribution; model converges when VMT difference is less than 5%.
Surveys and other data sources for model estimation / calibration / validation	Household travel survey	Year 2001 / 6,200 households

A.1.1.7. Denver, Colorado

DENVER REGIONAL COUNCIL OF GOVERNMENTS		
Denver, Colorado		
Major model feature	**Detailed feature / sub-model**	**Characteristics**
Spatial scale		Regional
Demand model structure		Aggregate trip-based.
Modeled pricing impacts (traveler responses), sub-model structure, form of utility function, incorporation of pricing	Mode Choice & Auto Occupancy	The only pricing impact is the inclusion of the toll cost in the utility of the auto alternatives. VOT in the mode choice model are adjusted for vehicle occupancy (SOV values multiplied by average vehicle occupancy). VOT for parking costs are twice as high than for toll or operating costs.
Willingness to pay / VOT and user segmentation	Vehicle classes	DA, SR2 and SR3+ (trucks are pre-loaded).
	Time of day	VOT in network simulation varies by time of day: $8/hr peak and $6/hr off-peak.
	Trip purpose segmentation $1996 (low/med/high income) for SOV trips (toll costs)	Home based work ($4 / $8 / $16)
		Home based other ($8.8/hr)
		Non home based ($8.4/hr)
	Household / person characteristics	Household income (low/med/hi) for HBW trips only
Network simulation tool	Simulation type	Static user equilibrium assignment
	Representation of priced highway facilities	Cost function depends on travel time, distance and toll costs. VOT varies by time period.
Demand – Network Equilibrium	Feedback implementation	Convergence is reached when less than 1% of the links show a speed difference of more than 10%. Speeds are fed back to top of model chain.
Surveys and other data sources for model estimation / calibration / validation	Household travel survey	1997 / 4,100 households Not used for model estimation.

Specifically developed for the E-470 toll traffic study.		
Denver, Colorado		
Major model feature	**Detailed feature / sub-model**	**Characteristics**
Spatial scale		Corridor
Demand model structure		
Modeled pricing impacts (traveler responses), sub-model structure, form of utility function, incorporation of pricing	Binary pre-route choice	Logistic diversion model, with toll probabilities expressed as a function of the natural log of travel time savings and square of toll.
	Vehicle occupancy categories	Toll, No toll
	Trip purpose segmentation	Home based work
		Airport trips
		Non home based work
		Non home based other
Network simulation tool	Simulation type	Static user equilibrium assignment
	Representation of priced highway facilities	Cost function depends on travel time only.
Demand – Network Equilibrium	Feedback implementation	None.
Surveys and other data sources for model estimation / calibration / validation	Household travel survey	N/A
	Stated Preference survey	Year 1991

A.1.1.8. Atlanta, Georgia

ATLANTA REGIONAL COMMISSION		
Atlanta, Georgia		
Major model feature	**Detailed feature / sub-model**	**Characteristics**
Spatial scale		Regional
Demand model structure		Aggregate trip-based.
Modeled pricing impacts (traveler responses), sub-model structure, form of utility function, incorporation of pricing	Binary pre-route choice	Logistic diversion model, with probabilities a function of travel time savings and toll cost: Travel time coefficient (min): 0.0875 Cost coefficient ($): 1.121
Willingness to pay / VOT and user segmentation	Vehicle classes $2000	SOV, HOV, Commercial. VOT for passenger car is $15/hour, for Commercial vehicles $35/hour, for purposes of expressing toll cost as time equivalents when building paths. Diversion model parameters are the same for all vehicle classes.
	Trip purpose segmentation	None for the diversion model
Network simulation tool	Simulation type	Static user equilibrium assignment
	Representation of priced highway facilities	Cost function depends on travel time and tolls.
Demand – Network Equilibrium	Feedback implementation	Not implemented for pricing studies
Surveys and other data sources for model estimation / calibration / validation	Household travel survey	2001 / 8,000 households
	Focus group study	2004 / 113 participants

A.1.1.9. Orlando, Florida

FLORIDA TURNPIKE ENTERPRISE		
Orlando, Florida		
Major model feature	**Detailed feature / sub-model**	**Characteristics**
Spatial scale		Regional
Demand model structure		Aggregate trip-based.
Modeled pricing impacts (traveler responses), sub-model structure, form of utility function, incorporation of pricing	Mode Choice & Auto Occupancy	DA Toll, SR2 Toll and SR3+ Toll are elemental alternatives in a nested logit model.
		Utility of a toll mode is a function of its travel time, cost relative to natural log of household income, trip length (HBW only), and a constant (unobserved attributes) term. For HBW trips, vehicle occupancy affects cost-sharing; costs are divided by ln(occupancy + 1). Vehicle occupancy has no effect on cost-sharing for other purposes.
Willingness to pay / VOT and user segmentation	Vehicle classes	SOV Toll, SOV No Toll, HOV2 Toll, HOV2 No toll, HOV3+ Toll, HOV3+ No Toll. All use same VOT in network simulation.
	Vehicle occupancy categories	SOV, HOV2, HOV3+
	Trip purpose segmentation (Range of VOT by income levels) $2000	Home based work peak ($4.5/hr to $9.5/hr)
		Home based work off peak ($4.0 /hr to $13.5/hr)
		Home based other peak ($4.0/hr to $7.50/hr)
		Home based other off peak ($3.0/hr to $8.0/hr)
		Non home based
		Visitors ($5.0/hr)
	Household / person characteristics	Household income (continuous)
	Time of day	VOT vary by time period (peak, off-peak).
Network simulation tool	Simulation type	Static user equilibrium assignment. Akcelik volume-delay functions.
	Representation of priced highway facilities	Cost function depends on travel time and toll cost, with parameters that vary by time period: Time: -0.047 cents/min (peak) / -0.06 cents/min (off peak) Cost: -0.006 cents/cents (peak & midday) / -0.003 cents/cents (night). Equivalent VOT: Peak - $4.7/hr Midday - $6.0/hr Night - $12/hr A queuing model was used to estimate delay at toll plazas.

FLORIDA TURNPIKE ENTERPRISE		
Orlando, Florida		
Major model feature	**Detailed feature / sub-model**	**Characteristics**
Demand – Network Equilibrium	Feedback implementation	Travel times fed back to trip distribution, calculated using method of successive averages. The model executes four feedback iterations.
Surveys and other data sources for model estimation / calibration / validation	Origin / Destination survey	2000
	Stated Preference survey	2000 / 1,044 respondents
	Speed measurements	2000
	Traffic counts	2000

A.1.1.10. Seattle, Washington

PUGET SOUND REGIONAL COUNCIL		
Seattle, Washington		
Major model feature	**Detailed feature / sub-model**	**Characteristics**
Spatial scale		Regional
Demand model structure		Aggregate trip-based.
Modeled pricing impacts (traveler responses), sub-model structure, form of utility function, incorporation of pricing	Mode Choice & Auto Occupancy	The only pricing effect is the inclusion of toll costs in the utility function of the auto alternatives. The mode choice model is multinomial logit.
	Trip Distribution	The HBW distribution model uses a composite impedance variable, partially based on mode choice logsums, in a destination choice framework.
Willingness to pay / VOT and user segmentation	Vehicle classes and time of day (reported VOTs for final assignment only). $2000	Peak: SOV HBW ($10.6/$19.6/$28.6/$38.4), HBO & Carpools ($16.7/hr) Light Trucks ($35.0/hr) Medium Trucks ($35.5/hr) Heavy Trucks ($41.0/hr) Off Peak: SOV HBW ($8.9/$16.4/$23.9/$31.0), HBO & Carpools ($14.0/hr) Light Trucks ($29.3/hr) Medium Trucks ($29.7/hr) Heavy Trucks ($34.3/hr)
	Vehicle occupancy categories	SOV, HOV2, HOV3+
	Trip purpose segmentation $2000	Home based work ($4.0/$7.2/$10.8/$13.8)
		Home based college ($8.4/hr)
		Home based other ($3.8/hr)
		Non home based ($5.1/hr)
	Household / person characteristics	Household income (four groups) for HBW trips.
Network simulation tool	Simulation type	Static user equilibrium assignment. HCM 2000 volume-delay functions.
	Representation of priced highway facilities	Cost function depends on travel time and costs, with parameters that vary by vehicle class.
Demand – Network Equilibrium	Feedback implementation	Travel times fed back to trip distribution. Four feedback iterations performed.
Surveys and other data sources for model estimation / calibration / validation	Household travel survey	1999 Not used for model estimation.
	Traffic counts	Year / vehicle type

Model Developed for the Dulles Greenway traffic study.		
Washington, D.C.		
Major model feature	**Detailed feature / sub-model**	**Characteristics**
Spatial scale		Corridor
Demand model structure		
Modeled pricing impacts (traveler responses), sub-model structure, form of utility function, incorporation of pricing	Binary pre-route choice	Logistic diversion model, with toll probabilities expressed as a function of the natural log of travel time savings, square of toll and a constant term.
	Vehicle occupancy categories	Toll, No toll
	Trip purpose segmentation	Home based work
		Airport trips
		Non work
Network simulation tool	Simulation type	Static user equilibrium assignment
	Representation of priced highway facilities	Cost function depends on travel time only.
Demand – Network Equilibrium	Feedback implementation	None.
Surveys and other data sources for model estimation / calibration / validation	Household travel survey	N/A

A.1.1.11. Austin, Texas

Austin, Texas		
Major model feature	**Detailed feature / sub-model**	**Characteristics**
Spatial scale		Corridor
Demand model structure		
Modeled pricing impacts (traveler responses), sub-model structure, form of utility function, incorporation of pricing	Binary pre-route choice	Logistic diversion model, with toll probabilities expressed as a function of travel time savings, toll cost (relative to natural log of income for HBW), and constants stratified by electronic vs. cash payment.
	Vehicle occupancy categories	Toll, No toll
	Trip purpose segmentation	Home based work
		Home based school
		Home based shop
		Home based other
		Non home based work
		Non home based other
		Trucks
Network simulation tool	Simulation type	Static user equilibrium assignment
	Representation of priced highway facilities	Cost function depends on travel time only.
Demand – Network Equilibrium	Feedback implementation	None.
Surveys and other data sources for model estimation / calibration / validation	Household travel survey	Size / sample, year, structure / questionnaire
	Stated preference survey	N/A

A.1.1.12. Houston, Texas

HOUSTON – GALVESTON AREA COUNCIL		
Houston, Texas		
Major model feature	**Detailed feature / sub-model**	**Characteristics**
Spatial scale		Regional
Demand model structure		Aggregate trip-based.
Modeled pricing impacts (traveler responses), sub-model structure, form of utility function, incorporation of pricing	Mode Choice & Auto Occupancy	DA toll, SR2 toll, SR3 toll and SR4+ toll are elemental alternatives in a nested logit model.
		Utility of a toll mode is a function of its travel time, cost, time savings with respect to the toll free alternative, and a constant (unobserved attributes) term. The toll options are available only if they imply minimum time savings (3 min. for work trips; 2.5 min. for non-work trips).
Willingness to pay / VOT and user segmentation	Vehicle classes	Auto only.
	Vehicle occupancy categories	SOV, HOV2, HOV3+
	Trip purpose segmentation (lowest VOT – highest VOT) $1985	Home based work ($2.7/hr - $5.5/hr)
		Home based other ($1.6/hr - $3.3/hr)
		Non home based ($4.2/hr)
	Household / person characteristics	Household income – five classes.
Network simulation tool	Simulation type	Static user equilibrium assignment, using 24 hr speed averages instead of free-flow speeds and a modified BPR volume-delay function.
	Representation of priced highway facilities	Cost function depends on travel time only.
Demand – Network Equilibrium	Feedback implementation	None.
Surveys and other data sources for model estimation / calibration / validation	Household travel survey	1984 / 1,500 households (estimation) 1994 / 2,400 households (calibration & validation).
	Traffic counts	1995

A.1.2. Activity-Based Tour-Based Models

A.1.2.1. San Francisco, California

SAN FRANCISCO COUNTY TRANSPORTATION AUTHORITY (SFCTA) RPM-9 MODEL		
San Francisco, California		
Major model feature	**Detailed feature / sub-model**	**Characteristics**
Spatial scale		Regional (9 counties)
Demand model structure		Activity-based tour-based microsimulation
Modeled pricing impacts (traveler responses), sub-model structure, form of utility function, incorporation of pricing	Household auto ownership and tour frequency models	Logit models with accessibility indices in the utility functions. Accessibility indices are based on highway and transit travel times. Effect of pricing can be partially captured through impact on travel times; however there is no direct sensitivity to pricing
	Primary tour destination choice	MNL model with mode choice logsum as one of the variables; sensitivity to pricing is ensured through this logsum
	Tour mode choice	Nested logit model segmented by 7 purposes (Work, K-8, High School, College, Other, Work-Based) with 10 modes: 1=SOVFree, 2=1=SOVPay 3=HOV2 Free, 4=HOV2 Pay, 5=HOV 3+ Free, 6=HOV 3+ Pay, 7=Walk, 8=Bike, 9=Walk to transit, 10=Drive to transit. Mode utilities include time and cost variables; binary sub-choice (toll vs. non-toll) is included below auto modes.
	Stop frequency	Chosen within the context of the daily activity pattern model; currently insensitive to pricing
	Stop location choice	Based on the level-of-service of the chosen tour mode, including toll. Sensitive to toll cost if tour mode is auto.
	Trip mode choice	Nested logit segmented by 7 tour purposes, with 14 modes: 1=SOVFree, 2=1=SOVPay 3=HOV2 Free, 4=HOV2 Pay, 5=HOV 3+ Free, 6=HOV 3+ Pay, 7=Walk, 8=Bike, 9=Walk to local, 10=Walk to MUNI Metro, 11=Walk to Premium, 12=Walk to BART, 13=Drive to Premium, 14=Drive to BART. Mode utilities include time and cost variables, and influenced by tour mode choice; binary sub-choice (toll vs. non-toll) is included below auto modes.
	Time-of-day choice	Multinomial logit models with 5 time periods; currently structured before destination choice for all tour purposes except for work; currently insensitive to pricing. Currently re-structuring model to place time-of-day choice between destination choice and mode choice, to enable use of mode choice logsums in time-of-day choice and allow sensitivity to pricing. Also adding half-hourly time-of-day choice model for auto trips (after trip mode choice) to allow sensitivity to pricing in peak period spreading, based on SP data.

SAN FRANCISCO COUNTY TRANSPORTATION AUTHORITY (SFCTA) RPM-9 MODEL		
San Francisco, California		
Major model feature	**Detailed feature / sub-model**	**Characteristics**
Willingness to pay / VOT and user segmentation	Vehicle classes	Vehicle classes in the time-of-day specific assignments and assumed VOT: 1=SOV Free ($15.0/hr) 2=SOV Pay ($15.0/hr) 3=SOV Already Paid ($15.0/hr) 4=HOV2 Free ($30.0/hr) 5=HOV2 Pay ($30.0/hr) 6=HOV2 Already Paid ($30.0/hr) 7=HOV3+ Free ($45.0/hr) 8=HOV3+ Pay ($45.0/hr) 9=HOV3+ Already Paid ($45.0/hr) 10=Externals Free ($15.0/hr) 11=Externals Pay ($15.0/hr) 12=Commercial Vehicles Free ($30.0/hr) 13=Commercial Vehicles Pay ($30.0/hr) Notes: Already Paid refers to area pricing; if a traveler has already paid the area fee, they are free to travel without paying the toll again, and are placed in the 'Already paid' bin. A binary logit model is used to split externals and commercial vehicles into free and pay categories.
	Vehicle occupancy categories	SOV, HOV2, HOV3+ in mode choice; SOV, HOV2, HOV3+ in assignment
	Trip purpose segmentation, VOT in $1989 (currently deterministic for each purpose)	There are two different VOTs available in the SFCTA RPM-9 Models. One is the traditional, fixed value-of-time with segmentation by household income. The other algorithm draws a mandatory and non-mandatory value-of-time for each person day from a log-normal distribution. The draw is based on the ratio of the household income to the number of workers in the household (the per worker household income). The models were calibrated and pricing policies are currently being analyzed using the distributed values of time. Work Segmented VOT: $0-$30k = $3.61/hr $30-$630k = $10.86/hr $60k + = $17.87/hr Distributed VOT: 1/2 of the average hourly wage rate, varying according to a lognormal distribution with mu=0 and sigma = 0.25
		Grade School Segmented VOT: $0-$30k = $2.40/hr

SAN FRANCISCO COUNTY TRANSPORTATION AUTHORITY (SFCTA) RPM-9 MODEL		
San Francisco, California		
Major model feature	**Detailed feature / sub-model**	**Characteristics**
		\$30-\$630k = \$7.23/hr \$60k + = \$12.00/hr Distributed VOT: Either the parents mandatory VOT or \$5/hour, whichever is lower.
		High School Segmented VOT: \$0-\$30k = \$2.40/hr \$30-\$630k = \$7.23/hr \$60k + = \$12.00/hr Distributed VOT: Either the parents mandatory VOT or \$5/hour, whichever is lower.
		University Segmented VOT: \$0-\$30k = \$2.40/hr \$30-\$630k = \$7.23/hr \$60k + = \$12.00/hr Distributed VOT: 1/2 of the average hourly wage rate, varying according to a lognormal distribution with mu=0 and sigma = 0.25
		Other Segmented VOT: \$0-\$30k = \$2.40/hr \$30-\$630k = \$7.23/hr \$60k + = \$12.00/hr Distributed VOT: 2/3 of the mandatory VOT
		Work-Based Segmented VOT: \$0-\$30k = \$2.40/hr \$30-\$630k = \$7.23/hr \$60k + = \$12.00/hr Distributed VOT: 2/3 of the mandatory VOT
	Household / person characteristics	Household income affects VOT in both distributed and segmented calculations. Many other person and household characteristics, particularly in day-pattern and time-of-day choice models.
Network simulation tool	Simulation type	Static user equilibrium multi-class assignment (Cube software)
	Representation of priced highway facilities	Tolls are skimmed during assignment, and fed to demand models in cost matrices. Tolls are considered in path-building and assignment algorithms by conversion to travel time units based on the average VOT for each vehicle class; Area

SAN FRANCISCO COUNTY TRANSPORTATION AUTHORITY (SFCTA) RPM-9 MODEL		
San Francisco, California		
Major model feature	**Detailed feature / sub-model**	**Characteristics**
		pricing is modeled by rules regarding which tours are exposed to costs first, and which tours may be 'free' based on whether toll has been paid in previous choice models.
Demand – Network Equilibrium	Feedback implementation	Feedback is implemented for all models. MSA method is applied for link volumes and trip tables in parallel. Work destination choice shadow pricing uses prices computed in previous iterations, and model is started with skims and shadow prices from a previous model run. Early iterations utilize population sampling to cut down run-time. Full equilibrium requires 3-5 iterations. Model is run 5 times (with full feedback for each run) and results are averaged.
Surveys and other data sources for model estimation / calibration / validation	Household travel survey	Originally estimated using 1990 and 1996 BATS travel surveys, with 10,000 households and 3,700 2-day households each, Model updated/re-calibrated based on 2000 BATS travel survey with 15,000 2-day households.
	Survey of existing toll road users	None available. Aggregate data available on toll bridge crossings.
	Stated Preference survey	SP Survey of commute and non-commute auto trips to downtown San Francisco conducted in summer 2007. Data currently being used to compute updated values-of-time, and mode and time-of-day elasticities with respect to pricing.
	Traffic counts	Extensive set of 1,640 traffic counts from different sources updated on a yearly basis. Transit boardings from various sources, BART station-station daily trip tables, on-board bus speed data, etc.

A.1.2.2. New York, New York

NEW YORK METROPOLITAN TRANSPORTATION COUNCIL		
New York, New York		
Major model feature	**Detailed feature / sub-model**	**Characteristics**
Spatial scale		Regional (28 counties)
Demand model structure		Activity-based tour-based microsimulation
Modeled pricing impacts (traveler responses), sub-model structure, form of utility function, incorporation of pricing	Household auto ownership and tour frequency models	Logit models with accessibility indices in the utility functions. Accessibility indices are based on highway and transit travel times. Effect of pricing can be partially captured through impact on travel times; however there is no direct sensitivity to pricing
	Primary tour destination choice	MNL model with mode choice logsum as one of the variables; sensitivity to pricing is ensured through this Logsum
	Tour mode choice	Nested logit model segmented by 6 purposes with 11 modes: 1=SOV, 2=HOV2, 3=HOV3, 4=HOV4+, 5=Walk to transit, 6=Drive to transit, 7=Walk to commuter rail, 8=Drive to commuter rail, 9=Taxi, 10=School bus, 11=Non-motorized. Mode utilities include time and cost variables; No binary sub-choice (toll vs. non-toll) is currently included.
	Stop frequency & location choice	Based on the distance measures and person, household, and zonal attributes; currently insensitive to pricing
	Trip mode choice	Derived from the tour mode based on the relative stop location; rule-based and currently insensitive to pricing
	Time-of-day choice	Predetermined diurnal distributions by tour departure time and duration by half-hour intervals; segmented by purpose, mode, and geography; currently insensitive to pricing; a stand-alone subroutine for peak-spreading was developed that restructures these distributions based on tolls and travel-time savings
Willingness to pay / VOT and user segmentation	Vehicle classes	Vehicle classes in the time-of-day specific assignments and assumed VOT: 1=SOV ($15.0/hr) 2=HOV2 ($30.0/hr) 3=HOV3+ ($45.0/hr) 4=Externals ($15.0/hr) 5=Trucks ($120.0/hr) 6=Commercials ($120.0/hr) 7=Taxis ($30.0/hr)
	Vehicle occupancy categories	SOV, HOV2, HOV3, HOV4+ in mode choice; SOV, HOV2, HOV3+ in assignment
	Trip purpose segmentation, VOT in $1997 (currently deterministic for each purpose)	Work ($15.8/hr)
		School ($6.50/hr)
		University ($11.7/hr)
		Maintenance ($12.4/hr)
		Discretionary ($10.7/hr)

NEW YORK METROPOLITAN TRANSPORTATION COUNCIL		
New York, New York		
Major model feature	**Detailed feature / sub-model**	**Characteristics**
		At-work ($40.0/hr)
	Household / person characteristics	Household income (low/med/hi) – included in tour frequency and mode choice utilities; however it does not directly affect VOT.
Network simulation tool	Simulation type	Static user equilibrium multi-class assignment (TransCAD software)
	Representation of priced highway facilities	Tolls converted to travel time units based on the average VOT for each vehicle class; additionally area pricing is modeled by adjusting the cost skim matrix.
Demand – Network Equilibrium	Feedback implementation	Feedback is implemented including destination choice, mode choice, stop frequency & location, and assignment. MSA method is applied for link volumes and trip tables in parallel. Full equilibrium requires 8-9 iterations. Practically acceptable equilibrium is achieved after 3 iterations.
Surveys and other data sources for model estimation / calibration / validation	Household travel survey	11,000 households, 1996/7, Household Interview Survey with all trips/activities recorded for all household members for 24 hours.
	Survey of existing toll road users	Not used
	Stated Preference survey	Not used
	Traffic counts	Extensive set of 3,000 traffic counts from different sources updated on a yearly basis. Traffic and transit counts by major screenlines were use for the model update and re-calibration in 2002 and 2005.

A.1.2.3. Montreal, Quebec

<table>
<tr><th colspan="8">MINISTRY OF TRANSPORTATION OF QUEBEC</th></tr>
<tr><th colspan="8">Montreal, Quebec, Canada</th></tr>
<tr><th>Major model feature</th><th>Detailed feature / sub-model</th><th colspan="6">Characteristics</th></tr>
<tr><td>Spatial scale</td><td></td><td colspan="6">Regional</td></tr>
<tr><td>Demand model structure</td><td></td><td colspan="6">Tour-based sample-enumeration model with micro-simulation components</td></tr>
<tr><td rowspan="6">Modeled pricing impacts (traveler responses), sub-model structure, form of utility function, incorporation of pricing</td><td>Household auto ownership and tour frequency models</td><td colspan="6">Expanded records from the extensive household survey (5% of the regional population). Every tour/trip record has and expansion factor (≅ 20) that is calculated for each future year to account for population growth by zone and socio-economic group</td></tr>
<tr><td>Primary tour destination choice</td><td colspan="6">Fixed in the sample according to the observed destination for each record. The expansion factors for future years account for employment growth by zone and occupation type</td></tr>
<tr><td>Tour mode choice</td><td colspan="6">Nested logit model segmented by 3 purposes (work, maintenance, discretionary) with 6 modes: 1=Auto driver, 2=Auto passenger, 3=Walk to transit, 4=Drive to transit, 5=School bus, 6=Non-motorized. Mode utilities include time and cost variables with coefficients segmented by income and gender;</td></tr>
<tr><td>Stop frequency & location choice</td><td colspan="6">Fixed in the sample according to the observed trips in each tour record</td></tr>
<tr><td>Trip mode choice</td><td colspan="6">Included binary toll vs. non-toll sub-choice for auto modes (SOV and HOV); included additional nested level for transit by the main mode (bus, subway, and rail).</td></tr>
<tr><td>Time-of-day choice</td><td colspan="6">Fixed in the sample according to the observed trip departure time in each tour record</td></tr>
<tr><td rowspan="8">Willingness to pay / VOT and user segmentation</td><td>Vehicle classes</td><td colspan="6">Vehicle classes in the time-of-day specific assignments and assumed VOT:
1=Auto / toll ($8.0/h)
2=Auto / non-toll
3=Commercial / toll ($12.0/h)
4=Commercial / non-toll
5=Light trucks / toll ($24.0/h)
6=Light trucks / non-toll
7=Heavy trucks / toll ($36.0/h)
8=Heavy trucks / non-toll</td></tr>
<tr><td>Vehicle occupancy categories</td><td colspan="6">Not considered; auto drivers and passengers are not explicitly linked</td></tr>
<tr><td rowspan="6">Trip purpose segmentation, VOT in CAD$1998 (currently deterministic for each purpose, gender, income group, and time-of-day)</td><td rowspan="2">Gender</td><td rowspan="2">Income</td><td rowspan="2">TOD</td><td colspan="3">Purpose</td></tr>
<tr><td>Work</td><td>Main</td><td>Disc</td></tr>
<tr><td rowspan="4">Male</td><td rowspan="2">Low</td><td>Off</td><td>$7.3</td><td>$4.0</td><td>$3.0</td></tr>
<tr><td>Peak</td><td>$10.3</td><td>$4.0</td><td>$3.0</td></tr>
<tr><td rowspan="2">High</td><td>Off</td><td>$10.2</td><td>$4.0</td><td>$3.0</td></tr>
<tr><td>Peak</td><td>$10.2</td><td>$4.0</td><td>$3.0</td></tr>
</table>

<table>
<tr><th colspan="8">MINISTRY OF TRANSPORTATION OF QUEBEC</th></tr>
<tr><th colspan="8">Montreal, Quebec, Canada</th></tr>
<tr><th>Major model feature</th><th>Detailed feature / sub-model</th><th colspan="6">Characteristics</th></tr>
<tr><td rowspan="5"></td><td rowspan="4"></td><td rowspan="4">Female</td><td rowspan="2">Low</td><td>Off</td><td>$7.3</td><td>$6.4</td><td>$6.0</td></tr>
<tr><td>Peak</td><td>$10.3</td><td>$6.4</td><td>$6.0</td></tr>
<tr><td rowspan="2">High</td><td>Off</td><td>$10.6</td><td>$7.3</td><td>$7.6</td></tr>
<tr><td>Peak</td><td>$10.6</td><td>$7.3</td><td>$7.6</td></tr>
<tr><td>Household / person characteristics</td><td colspan="6">Additional household variables (car ownership, presence of children) – included in mode choice utilities; however they do not directly affect VOT.</td></tr>
<tr><td rowspan="2">Network simulation tool</td><td>Simulation type</td><td colspan="6">Static user equilibrium multi-class assignment (EMME software)</td></tr>
<tr><td>Representation of priced highway facilities</td><td colspan="6">Tolls converted to travel time units based on the average VOT for each vehicle class.</td></tr>
<tr><td>Demand – Network Equilibrium</td><td>Feedback implementation</td><td colspan="6">Feedback is implemented including mode choice, and assignment. MSA method is applied for level-of-service skims. Full equilibrium requires 5-6 iterations. Practically acceptable equilibrium is achieved after 3 iterations.</td></tr>
<tr><td rowspan="4">Surveys and other data sources for model estimation / calibration / validation</td><td>Household travel survey</td><td colspan="6">60,000 households, 1998, Household Phone Interview (Origin-Destination) Survey with all trips/activities recorded for all household members 12 years old and older for 24 hours.</td></tr>
<tr><td>Survey of existing toll road users</td><td colspan="6">Not used</td></tr>
<tr><td>Stated Preference survey</td><td colspan="6">Special SP survey to estimate willingness to pay; 1,000 persons driving in the priced corridors with 11 SP scenarios offered to each person.</td></tr>
<tr><td>Traffic counts</td><td colspan="6">The base year (2000) expansion factors were validated and adjusted to match traffic counts (about 500 locations)</td></tr>
</table>

A.2. Technical Details of Survey Methods for Pricing Studies

The development of models for road pricing analysis requires supporting data collection and travel surveys. In many respects, the types of surveys that are used to evaluate potential or implemented road pricing projects are similar to those used for other transportation planning purposes. There are often some important considerations in the context of a road pricing study that affects both the types and design of special surveys that are required,

In theory, any change in transportation service, including changes in road prices, could affect all travel-related decisions, ranging from residential location and auto ownership to activity participation, destination, mode, and route choices. For facility pricing projects, route choice is an obvious choice dimension for which survey data can be used to refine existing models. Time-of-day choice is important for projects that include time-variable pricing, and surveys for these can be designed to support time-of-day or peak-shifting models. Destination choice can be affected by area pricing schemes, but this element is typically already included in regional travel demand forecasting models.

A unique choice specifically related to road pricing is whether an individual acquires a transponder to allow participation in electronic toll collection (ETC). The transponder acquisition decision is in some ways analogous to a decision whether to acquire a monthly transit pass because, as with transit passes, most tolled facilities give ETC discounts and those discounts can range from 10% to 50%. The transponder acquisition choice is different, however, because it can be mandatory for access to a facility–some facilities such as the California SR 91 Express Lanes require a transponder–and because there can be non-trivial upfront costs associated with acquiring the transponder. As a result, surveys that support modeling transponder acquisition choices can be important components of the data collection program.

A comprehensive household travel survey is generally needed to develop a regional transportation model that can serve as the source for Value of Time (VOT) and other relevant model parameter estimates. However, there is a growing recognition that the household survey data have to be supported by complementary/project-specific **Revealed Preference (RP)** and/or **Stated Preference (SP)** surveys. This is especially crucial for start-up projects in regions with no prior experience with highway pricing where the RP survey cannot provide direct information about and SP surveys are typically designed to address willingness-to-pay factors relevant for road pricing (value of time savings, value of reliability). Survey data collection can also support other model development data needs, including HOV/HOT lane usage and payment media choice.

The sub-sections that follow describe the types of surveys that can be used to support the development of travel forecasting models for road pricing projects. These surveys can be configured as part of a data collection program that is designed to support the evaluation of proposed road pricing projects as they move through stages from preliminary screening to investment grade analysis to post-implementation refinement. The concluding sub-section presents general recommendations for the design of such a survey and data collection program.

A.2.1. Travel Pattern Surveys ("Revealed Preferences")

As for general transportation planning studies, surveys of current travel patterns can be effectively used to support pricing studies. These surveys can be administered as household-based travel/activity diaries or as trip-intercept, origin-destination, and route surveys.

A.2.1.1. Household-Based Travel /Activity Surveys

The standard regional household travel surveys, with its complete and detailed accounting of all travel within a household on surveyed day (or multiple days), can provide useful information about the general patterns of travel within the region in which they are conducted. All major U.S. metropolitan regions have had household travel surveys conducted to support development of their regional travel forecasting models and, in general, road pricing projects would not themselves require new household surveys.

Household travel surveys represent the only holistic framework that allows for an analysis of the entire daily activity pattern of persons and households. This type of survey is necessary for understanding the impact of congestion and pricing on the whole hierarchy of choices, from the short-term trip-level responses to long-term responses that relate to activity pattern (trip frequency) and location of activities. The important principal advantage of a household interview survey is that all related travel dimensions, and generally travel segments of interest, can be analyzed in one coherent framework, while most of the other surveys would focus on a certain trip or fragment of the daily pattern of individuals.

Household travel surveys provide general information about the number of trips (or tours) made, time-of-day distribution of those trips, their geographic distribution and the modes used. They also generally include information about the costs of those trips. However, in most regions, these are dominated by vehicle operating costs which are perceived very differently across individuals and in most cases appear to include little more than gasoline costs, and where parking costs may represent the only significant trip-based costs.

More importantly, household travel surveys are limited in the sense that they might not provide a sufficient number of observations of actual toll road users, as well as do not provide enough (in a statistical sense) trade-offs in terms of travel time, reliability, and price to reliably estimate VOT, and other parameters. Toll costs are not specifically enumerated in all household surveys, in part because many regions do not currently have any toll facilities and, in any case, these surveys do not typically elicit more detailed information about route choices. Since these surveys do not completely capture the details of travel which might be affected by a road pricing project (e.g., route choice and toll costs), it might be appropriate to selectively sample with a refined household travel survey instrument.

Some household travel surveys that have been conducted to support toll facility analyses have included questions designed to collect route choice information. Those survey instruments have included focused questions detailing route segments for trips that are made between origins and destinations served by toll facilities, and so either used those facilities or could have used the facilities. Many, if not most, trips are made between points that are not served by toll facilities, even in regions that have many such facilities.

Because reporting the route choice information can add significant respondent burden, it is useful to screen for selected origins and destinations as the data are captured so that this information is collected only for those trips where it is relevant. This screening requires both real-time geocoding of origins and destinations and information about the locations served by toll facilities. The latter can be provided through skim tables from the regional travel forecasting model.

Figure 68 below shows a portion of the section of a recent household survey that was designed specifically to collect detailed information about toll route choices, as well as the other "usual" trip details [*Resource Systems Group, 2004*]. For each trip segment, respondents were asked whether they used a toll facility. If they indicated that they had used a toll facility, they were asked where they entered and exited the facility. From that information, along with information about ETC use, toll costs can be calculated directly. This additional information can provide a rich base of information to support the modeling of toll route choices.

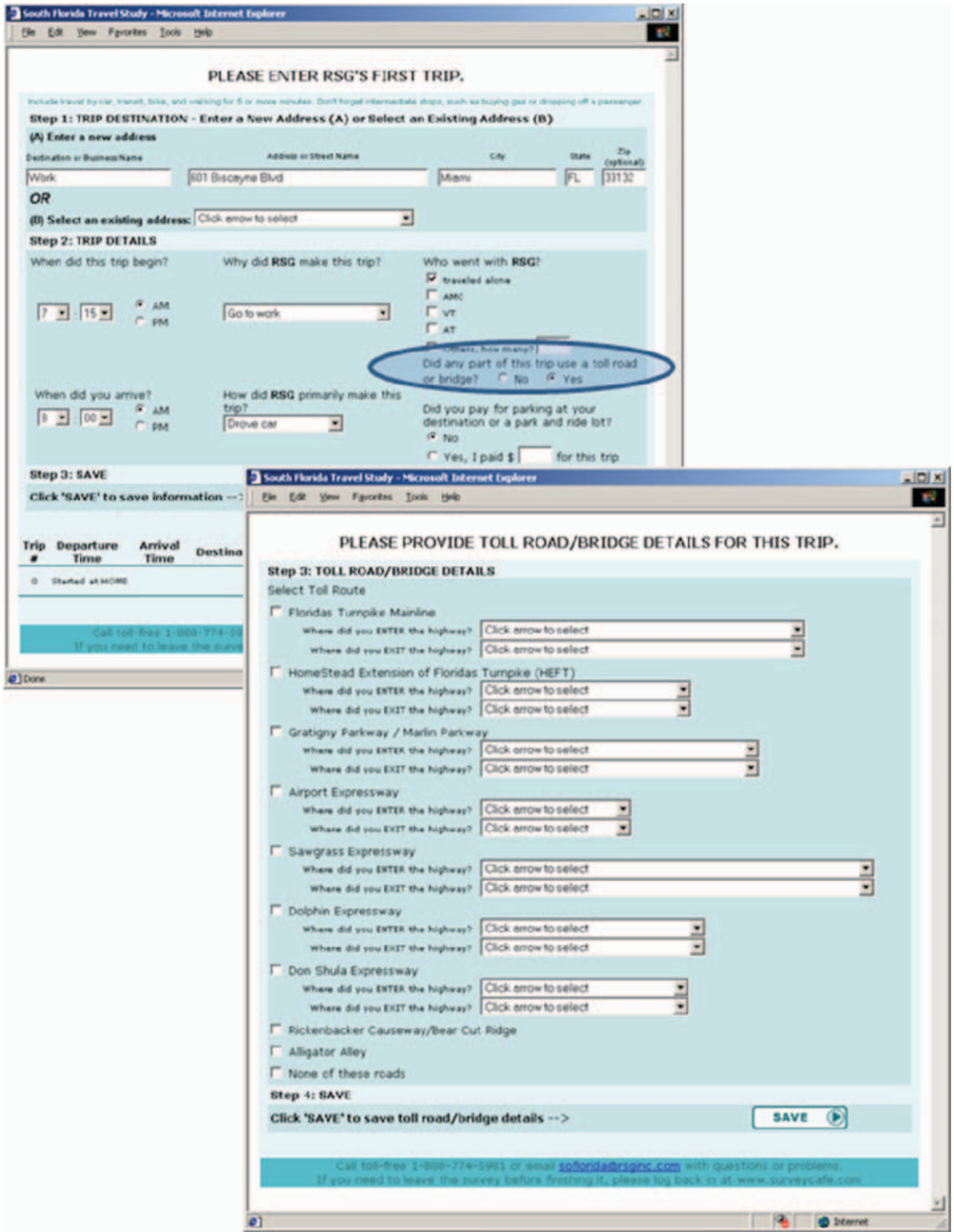


Figure 68: Example South Florida Household Survey Route Choice Screens

A GPS-based supplement is increasingly a feature that is included with household surveys since it can provide detailed route information for all recorded trips. Either vehicle or person-based GPS data collection can be used, but vehicle-based GPS data collection is generally more useful for collecting route information, assuming that tracking routes for transit and pedestrian/bicycle alternatives is not necessary. In theory, the data from these route traces, along with information on ETC use in the vehicles, could be used to support modeling of price response, but to date there do not appear to have been any such applications. If tolled facilities run parallel and very close to non-tolled lanes (e.g. the conversion of an existing HOV lane to a HOT lane), then high resolution GPS location data are needed for a level of accuracy that can identify whether or not a vehicle has used the tolled facilities.

Household travel and activity surveys universally include information about the time that trips were made and these provide some information about current time-of-day choices. However, it is very difficult to infer from those observed choices the degree to which individuals have flexibility to shift their trips/activities to other times-of-day. In addition, in regions that have significant peak period traffic congestion, the observed choices may reflect shifts that individuals have already made away from their preferred times in order to avoid that congestion. While it would be possible to include questions in a household or GPS-follow-up survey to collect information on time-of-day flexibility, those questions must be asked selectively to avoid adding significant respondent burden to an already-burdensome survey process.

Typical household and activity surveys cost in the range of $100 to $150 per household and sample sizes can vary from several hundred to several thousand depending on the survey's purpose.

A.2.1.2. Origin-Destination Surveys

Surveys that collect information about the origins, destinations and other details have been widely used to determine the characteristics of trips that are observed at selected locations [*Hagen, 2006*]. These types of surveys are particularly useful for characterizing the trips that currently travel in particular corridors that are, or might be, served by a toll facility and the trips that cross into or out from a cordon that might be subjected to area pricing. This type of focused information is especially useful in estimating the numbers and types of trips that might be affected by facility or area pricing. Although regional travel forecasting models can also be used to synthetically provide this information, those models are typically not refined sufficiently to estimate these details as precisely as can be done with an origin-destination survey.

Significantly higher precision in the origin-destination table can be provided using a matrix estimation procedure, assuming that sufficient count data are available to support that procedure. A combination of origin-destination survey data, synthetic modeling and matrix estimation can be used to provide the additional precision required for road pricing studies.

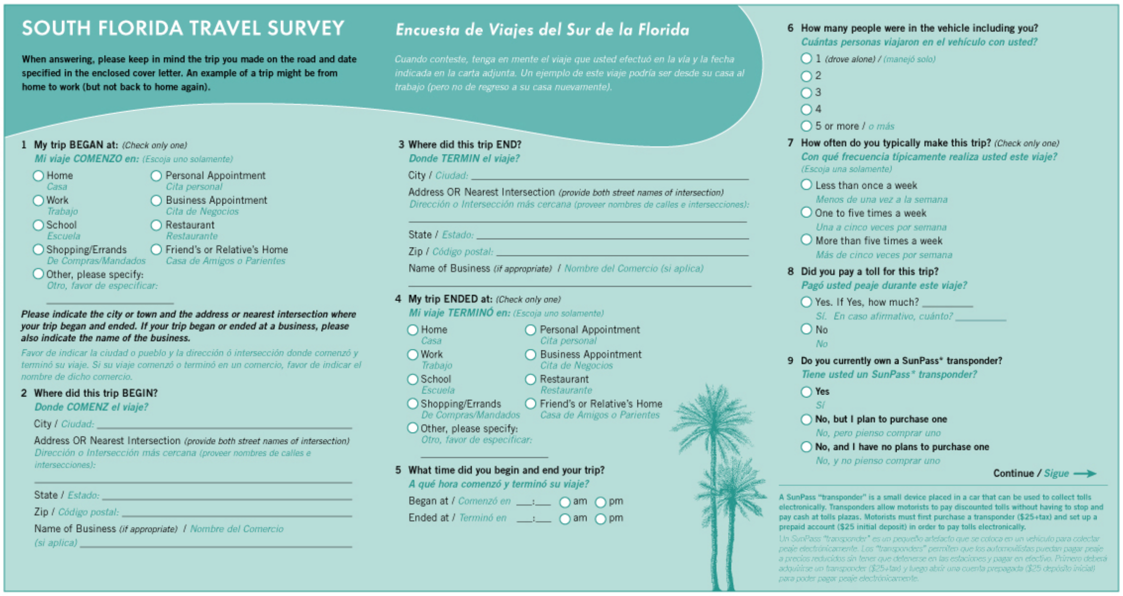
Sampling trips for origin-destination surveys is a special challenge. Roadside interviews typically have high response rates and, generally, result in high quality data for the facilities on which the interviews are conducted. However, these surveys are logistically difficult and at least one state – Florida – does not allow them because of safety and operational concerns. One alternative is to record license plates of a sample of vehicles on a facility, match those plates with addresses using vehicle registration data and use mailout/mailback questionnaires. Response rates for these license plate surveys, however are typically much lower and the small uncontrolled sample problematic in analysis.

An alternative approach for origin-destination surveys is to intercept vehicles at locations where they are already stopped and hand drivers mailout/mailback questionnaires. This alternative has been widely used on toll facilities; questionnaires are distributed at toll plazas where vehicles are stopped to pay tolls. However, most modern toll facilities operate with a combination of conventional plaza booths where vehicles stop to pay cash tolls and lanes that allow vehicles with electronic toll collection (ETC) devices to pass through without stopping. While origin-destination survey forms can be distributed to cash customers at these plazas, safety and operational issues generally preclude distributing forms to ETC customers.

It would be possible to record license plates of ETC customers, match addresses and mail survey forms to those addresses, but there is generally a more efficient and reliable way to sample ETC customers using ETC data. The agencies responsible for electronic toll collection maintain databases that record vehicle transactions at all of the locations where tolls are collected. Each of these transactions is linked to ETC registration data that includes a mailing address and other contact information. While privacy restrictions generally prevent the agencies from providing these data to third parties, they can generally use the data themselves to contact a sample of customers who use a facility at selected times.

For example, the 11-state E-ZPass Consortium in the Northeast has supported numerous travel surveys by sampling E-ZPass transactions at selected facilities on selected days and then mailing survey questionnaires to those customers. Ideally, the transactions are sampled for the same time periods and locations as for cash surveys so that the two samples can be weighted back to a common base. Data for weighting can be provided by the cash/ETC transaction counts at each location, but it is also useful to collect other primary data such as occupancy counts and vehicles' states of registration from direct observations to adjust for possible differences in response rates (Jacobs and Spitz, 2006). In addition, for toll facilities with multiple interchanges, the ETC-based origin-destination survey data can be re-weighted so that they accurately represent the on-off patterns reflected in ETC transaction data.

Figure 69 and Figure 70 show examples of origin-destination survey forms. **Figure 69** is a form that was used as part of license plate matching origin-destination survey conducted on major toll-free routes in South Florida for Florida's Turnpike Enterprise. Since the survey stations were on toll-free routes, a simple toll route choice question is included to identify trips that used toll facilities. Both English and Spanish languages are incorporated in the form and an accompanying web-based questionnaire was offered as an alternative for those who preferred to complete the survey on the web.



SOUTH FLORIDA TRAVEL SURVEY

When answering, please keep in mind the trip you made on the road and date specified in the enclosed cover letter. An example of a trip might be from home to work (but not back to home again).

Encuesta de Viajes del Sur de la Florida

Cuando conteste, tenga en mente el viaje que usted efectuó en la vía y la fecha indicada en la carta adjunta. Un ejemplo de este viaje podría ser desde su casa al trabajo (pero no de regreso a su casa nuevamente).

PLEASE TAPE CLOSED BEFORE MAILING / FAVOR DE SELLAR CON CINTA ADHESIVA ANTES DE ENVIAR

1 My trip BEGAN at: *(Check only one)*
Mi viaje COMENZO en: (Escoja uno solamente)
- Home / *Casa*
- Personal Appointment / *Cita personal*
- Work / *Trabajo*
- Business Appointment / *Cita de Negocios*
- School / *Escuela*
- Restaurant / *Restaurante*
- Shopping/Errands / *De Compras/Mandados*
- Friend's or Relative's Home / *Casa de Amigos o Parientes*
- Other, please specify: / *Otro, favor de especificar:* ______

Please indicate the city or town and the address or nearest intersection where your trip began and ended. If your trip began or ended at a business, please also indicate the name of the business.

Favor de indicar la ciudad o pueblo y la dirección ó intersección donde comenzó y terminó su viaje. Si su viaje comenzó o terminó en un comercio, favor de indicar el nombre de dicho comercio.

2 Where did this trip BEGIN?
Donde COMENZ el viaje?
City / *Ciudad:* ______
Address OR Nearest Intersection *(provide both street names of intersection)*
Dirección o Intersección más cercana (proveer nombres de calles e intersecciones): ______
State / *Estado:* ______
Zip / *Código postal:* ______
Name of Business *(if appropriate)* / *Nombre del Comercio (si aplica)* ______

3 Where did this trip END?
Donde TERMIN el viaje?
City / *Ciudad:* ______
Address OR Nearest Intersection *(provide both street names of intersection)*
Dirección o Intersección más cercana (proveer nombres de calles e intersecciones): ______
State / *Estado:* ______
Zip / *Código postal:* ______
Name of Business *(if appropriate)* / *Nombre del Comercio (si aplica)* ______

4 My trip ENDED at: *(Check only one)*
Mi viaje TERMINÓ en: (Escoja uno solamente)
- Home / *Casa*
- Personal Appointment / *Cita personal*
- Work / *Trabajo*
- Business Appointment / *Cita de Negocios*
- School / *Escuela*
- Restaurant / *Restaurante*
- Shopping/Errands / *De Compras/Mandados*
- Friend's or Relative's Home / *Casa de Amigos o Parientes*
- Other, please specify: / *Otro, favor de especificar:* ______

5 What time did you begin and end your trip?
A qué hora comenzó y terminó su viaje?
Began at / *Comenzó en* ___:___ am pm
Ended at / *Terminó en* ___:___ am pm

6 How many people were in the vehicle including you?
Cuántas personas viajaron en el vehículo con usted?
- 1 *(drove alone)* / *(manejó solo)*
- 2
- 3
- 4
- 5 or more / *o más*

7 How often do you typically make this trip? *(Check only one)*
Con qué frecuencia típicamente realiza usted este viaje? (Escoja una solamente)
- Less than once a week / *Menos de una vez a la semana*
- One to five times a week / *Una a cinco veces por semana*
- More than five times a week / *Más de cinco veces por semana*

8 Did you pay a toll for this trip?
Pagó usted peaje durante este viaje?
- Yes. If Yes, how much? ______ / *Sí. En caso afirmativo, cuánto?* ______
- No / *No*

9 Do you currently own a SunPass* transponder?
Tiene usted un SunPass transponder?*
- Yes / *Sí*
- No, but I plan to purchase one / *No, pero pienso comprar uno*
- No, and I have no plans to purchase one / *No, y no pienso comprar uno*

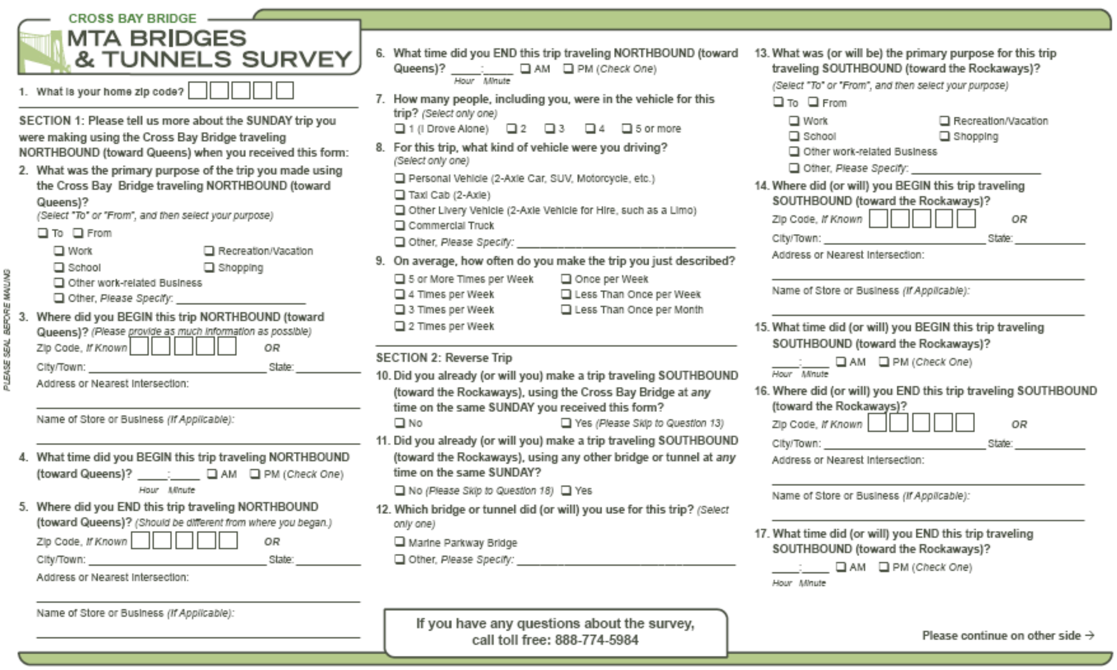
Continue / *Sigue* →

A SunPass "transponder" is a small device placed in a car that can be used to collect tolls electronically. Transponders allow motorists to pay discounted tolls without having to stop and pay cash at tolls plazas. Motorists must first purchase a transponder ($25+tax) and set up a prepaid account ($25 initial deposit) in order to pay tolls electronically.

Un SunPass "transponder" es un pequeño artefacto que se coloca en un vehículo para colectar peaje electrónicamente. Los "transponders" permiten que los automovilistas puedan pagar peaje a precios reducidos sin tener que detenerse en las estaciones y pagar en efectivo. Primero deberá adquirirse un transponder ($25+tax) y luego abrir una cuenta prepagada ($25 depósito inicial) para poder pagar peaje electrónicamente.

Figure 69: Example Origin-Destination Survey Form

Figure 70 shows one of almost 100 forms that were developed as part of a very large-scale origin-destination survey of the New York metropolitan region's major bridges and tunnels [*Jacobs and Spitz, 2006*]. That survey effort included distributing mailback forms to cash customers at all of the toll plazas and mailout/mailback sampling of ETC customers. The ETC sample was generated from ETC records of those customers who used the facilities at the same time as the cash form distributions. The survey form collected information both about the sampled trip/direction and about the return or previous trip. Traffic counts and concurrent auto occupancy and vehicle state of registration measurements were used to develop expansion weights applied to the sample records for analysis.



CROSS BAY BRIDGE
MTA BRIDGES & TUNNELS SURVEY

1. What is your home zip code? ☐☐☐☐☐

SECTION 1: Please tell us more about the SUNDAY trip you were making using the Cross Bay Bridge traveling NORTHBOUND (toward Queens) when you received this form:

2. What was the primary purpose of the trip you made using the Cross Bay Bridge traveling NORTHBOUND (toward Queens)? *(Select "To" or "From", and then select your purpose)*
❑ To ❑ From
❑ Work ❑ Recreation/Vacation
❑ School ❑ Shopping
❑ Other work-related Business
❑ Other, *Please Specify:* ____

3. Where did you BEGIN this trip NORTHBOUND (toward Queens)? *(Please provide as much information as possible)*
Zip Code, *If Known* ☐☐☐☐☐ *OR*
City/Town: ____ State: ____
Address or Nearest Intersection: ____
Name of Store or Business *(If Applicable)*: ____

4. What time did you BEGIN this trip traveling NORTHBOUND (toward Queens)? ___:___ *Hour Minute* ❑ AM ❑ PM *(Check One)*

5. Where did you END this trip traveling NORTHBOUND (toward Queens)? *(Should be different from where you began.)*
Zip Code, *If Known* ☐☐☐☐☐ *OR*
City/Town: ____ State: ____
Address or Nearest Intersection: ____
Name of Store or Business *(If Applicable)*: ____

PLEASE SEAL BEFORE MAILING

6. What time did you END this trip traveling NORTHBOUND (toward Queens)? ___:___ *Hour Minute* ❑ AM ❑ PM *(Check One)*

7. How many people, including you, were in the vehicle for this trip? *(Select only one)*
❑ 1 (I Drove Alone) ❑ 2 ❑ 3 ❑ 4 ❑ 5 or more

8. For this trip, what kind of vehicle were you driving? *(Select only one)*
❑ Personal Vehicle (2-Axle Car, SUV, Motorcycle, etc.)
❑ Taxi Cab (2-Axle)
❑ Other Livery Vehicle (2-Axle Vehicle for Hire, such as a Limo)
❑ Commercial Truck
❑ Other, *Please Specify:* ____

9. On average, how often do you make the trip you just described?
❑ 5 or More Times per Week ❑ Once per Week
❑ 4 Times per Week ❑ Less Than Once per Week
❑ 3 Times per Week ❑ Less Than Once per Month
❑ 2 Times per Week

SECTION 2: Reverse Trip

10. Did you already (or will you) make a trip traveling SOUTHBOUND (toward the Rockaways), using the Cross Bay Bridge at *any* time on the same SUNDAY you received this form?
❑ No ❑ Yes *(Please Skip to Question 13)*

11. Did you already (or will you) make a trip traveling SOUTHBOUND (toward the Rockaways), using any other bridge or tunnel at *any* time on the same SUNDAY?
❑ No *(Please Skip to Question 18)* ❑ Yes

12. Which bridge or tunnel did (or will) you use for this trip? *(Select only one)*
❑ Marine Parkway Bridge
❑ Other, *Please Specify:* ____

If you have any questions about the survey, call toll free: 888-774-5984

13. What was (or will be) the primary purpose for this trip traveling SOUTHBOUND (toward the Rockaways)? *(Select "To" or "From", and then select your purpose)*
❑ To ❑ From
❑ Work ❑ Recreation/Vacation
❑ School ❑ Shopping
❑ Other work-related Business
❑ Other, *Please Specify:* ____

14. Where did (or will) you BEGIN this trip traveling SOUTHBOUND (toward the Rockaways)?
Zip Code, *If Known* ☐☐☐☐☐ *OR*
City/Town: ____ State: ____
Address or Nearest Intersection: ____
Name of Store or Business *(If Applicable)*: ____

15. What time did (or will) you BEGIN this trip traveling SOUTHBOUND (toward the Rockaways)? ___:___ *Hour Minute* ❑ AM ❑ PM *(Check One)*

16. Where did (or will) you END this trip traveling SOUTHBOUND (toward the Rockaways)?
Zip Code, *If Known* ☐☐☐☐☐ *OR*
City/Town: ____ State: ____
Address or Nearest Intersection: ____
Name of Store or Business *(If Applicable)*: ____

17. What time did (or will) you END this trip traveling SOUTHBOUND (toward the Rockaways)? ___:___ *Hour Minute* ❑ AM ❑ PM *(Check One)*

Please continue on other side →

Figure 70: Example Toll Facility Intercept/ETC Origin Destination Survey Form

Costs for origin-destination surveys vary considerably depending on the administration method and the complexity of the application and sample sizes similarly depend directly on the ways that the data are intended to be used.

A.2.2. Stated Preference Surveys

For more than 20 years, Stated Preference (SP) surveys have been used to estimate values of travel time and other parameters related to the effects of tolls and road pricing (see, for example, [*Adler and Schaevitz, 1989*]). SP surveys include a set of hypothetical scenarios in which conditions (e.g., travel times, tolls) are varied and respondents are asked to indicate what they would most likely choose under those specified conditions. The conditions are varied according to an experimental design that optimizes the information about the respondents' preferences from each of the scenarios which they evaluate..

SP surveys are especially useful in applications where an alternative such as a toll facility does not currently exist, but is being planned for the future. In those types of applications, revealed preference surveys are not useful for estimating price effects because road prices, which are the variables of interest, do not vary (all zero) across trips within the region. While other cost elements, such as operating costs, do vary across trips, those variations are highly correlated with trip lengths and travel times and thus generally do not provide reliable indications of the effects of price on travel choices.

In regions that do have existing toll facilities, revealed preference data from household and origin-destination surveys can be used to estimate price effects, but there are also complementary uses for stated preference surveys in these regions. The uses include:

- Estimating the effects of prices that are **outside the range of existing prices** or pricing structures, such as time-varying tolls or that do not currently exist in the region,
- Estimating the effects of **travel time reliability** and other variables that are difficult to measure and/or associate with revealed preference observations,
- Determining the effects of **new features of facilities** such as open road tolling, express lanes or "fair lanes",
- Determining the effects of pricing on choices for **alternatives that do not exist** or that are not easily captured within revealed preference surveys. Examples would include effects of open road tolling on transponder acquisition or of variable pricing on time-of-day choices.

In addition, SP surveys can be used to sharpen the information on price effects that is otherwise provided by revealed preference surveys, where the lack of variation in tolls may be problematic. There are often compelling reasons for doing this.

- *The confidence interval of the marginal rate of substitution between time and cost (value of time) as estimated using revealed preference data alone is often quite wide.* This is a result of the measurement errors associated with inferring travel times for chosen and alternative routes, and of the inherent statistical error associated with estimating the value for a ratio of two random variables, particularly when the two random variables are correlated with each other, as travel cost and travel time tend to be.
- *Stated preference data can be used to estimate the distribution of preferences across the population.* Many differences in preferences, such as different travel time sensitivity across trip purposes and varying degrees of cost sensitivity across income groups, can be explained using systematic effects that in turn can be modeled directly. There are other random effects that cannot be measured or directly represented in a preference function, however, but which can be quantified using methods such as mixed-logit or hierarchical Bayes modeling. These methods can estimate the distribution of cost sensitivity and of values of time across the population and this distributional estimate and can in turn be used to help estimate population responses to different pricing levels.

For all of these reasons, SP surveys have been used to assist in the evaluation of most of the major road pricing projects, both within the U.S. and internationally. These surveys can take on many different forms.

A.2.2.1. Choice Dimensions and Scenario Design

The stated preference surveys that have been conducted to support road pricing projects have most often focused on the choice between tolled and toll-free routes. For conventional toll facility studies, these surveys would typically present two alternatives; a toll-free route with a given travel time and an alternative tolled route with a lower travel time and a toll at some level.

Many road pricing projects, however, involve more complex effects beyond simply influencing route choice. Some projects, such as HOT-lanes, affect occupancy and mode and so the stated preference scenarios would include other modes and occupancy levels as available choice alternatives. For projects that have time-varying prices, different travel periods should be included among the stated preference alternatives. For area pricing projects, the scenarios could allow alternative destinations. In some special cases, effects on trip frequency may also be included in the stated preference experiments. For example, a recent study, illustrated in **Figure 71**, evaluated a proposed new bridge toll on a facility for which the only toll-free alternative was a significantly longer route. In this case, it was possible that discretionary trips could be reduced, so stated preference experiments were constructed to assess the reduction that might result from different toll levels [*Falzarano & Szeto, 2003*].

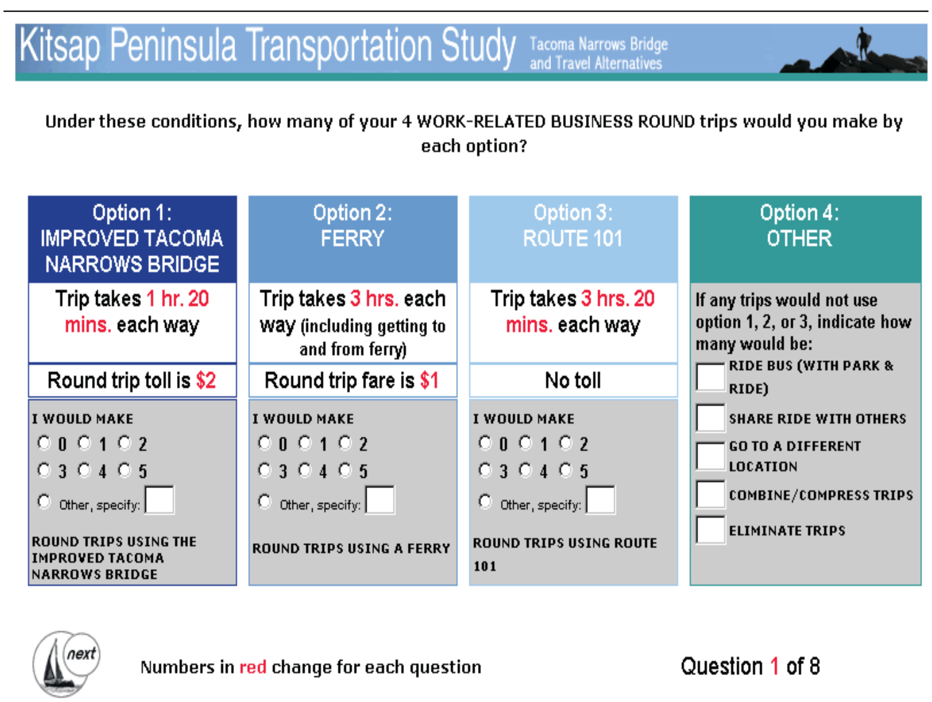


Figure 71: Example SP Scenario to Measure Possible Trip Frequency Changes

Finally, as noted earlier, transponder acquisition choice can be a significant issue in the forecasting of demand for priced facilities since the availability of a transponder can affect both access to a cashless facility and the price charged for using a facility. In addition, both anecdotal and quantitative evidence suggests that individuals who use transponders are simply less price sensitive than those who pay out-of-pocket because the price is less apparent to the latter. Transponder acquisition can be modeled using data from stated preference experiments in which the decision whether to acquire a transponder is included as a choice alternative. These experiments should be designed in a way that reflects the fact that this choice is linked to the likely use of the toll facility, and to the level of discount applied on ETC transactions.

Figure 72 shows an example transponder acquisition SP scenario that was included in a survey research program by Resource System Group that preceded construction of the California SR-91 Express Lanes.

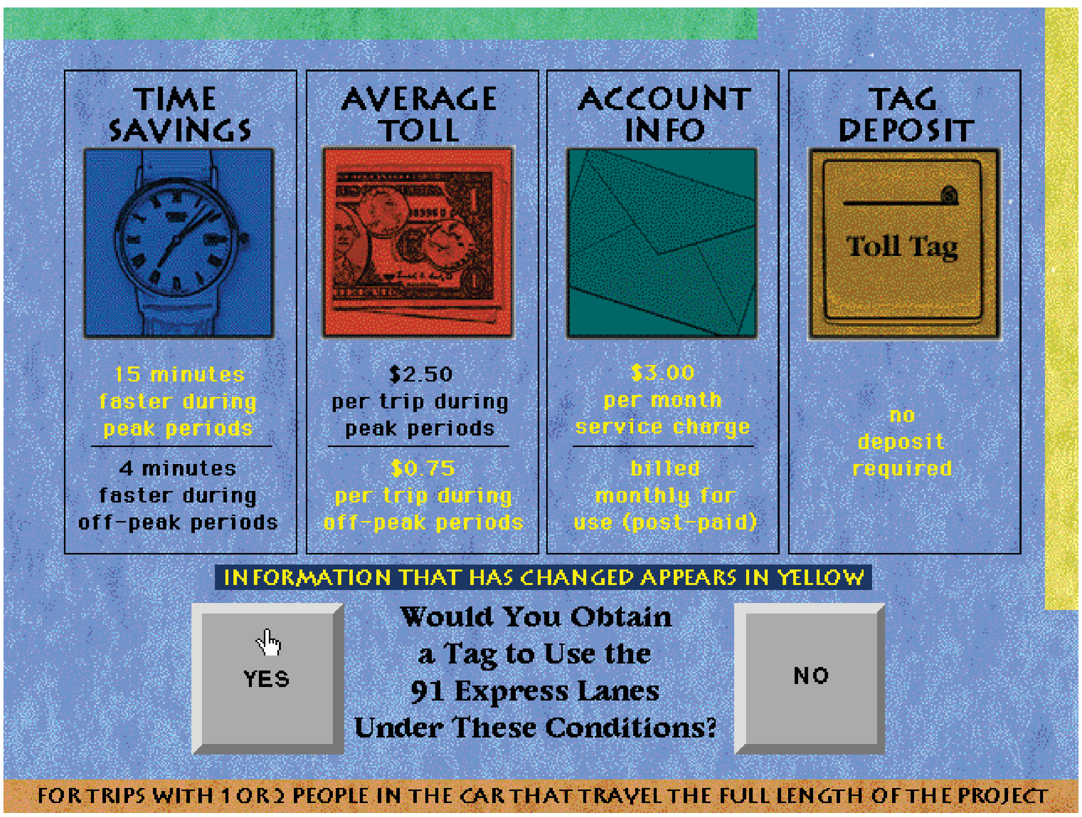


Figure 72: Example Transponder Acquisition Choice Experiment

Figure 73 shows a more typical stated preference scenario for a general road pricing study [*Adler, et al, 2007*]. In this scenario, respondents are presented with tolled and toll-free options, time-of-day and mode alternatives.

Figure 73: Example SP Scenario with Typical Pricing Choice Options

A.2.2.2. Trip Attributes Relevant for Pricing Studies

Travel times and toll prices are the primary attributes in most stated preference experiments done for road pricing. The trade-offs between travel time savings and extra cost associated with tolls, are expressed in terms of Value of Time (VOT). In the presence of road pricing However, there are other attributes that may also be significant in travelers' choices. Some of the other attributes or features that have been tested in stated preference experiments for road pricing projects include:

- Travel time components – time in free flow conditions and time in congested traffic,
- Travel time reliability,

- Occupancy-based toll levels,
- Fair lanes policy,
- Commercial vehicle restrictions,
- ETC discounts,
- Travel time variability,
- Driving distance along the route, and
- Non-toll "running" costs.

This is by no means an inclusive list as individual projects may have unique features for which stated preference surveys can provide information. Examples of this from past studies include testing the willingness of travelers to use toll facilities having a long tunnel section vs. at grade sections, and having a smooth asphalt surface vs. jointed concrete.

It is important to recognize that not all of these variables or features are necessarily salient for all travelers. For example, a recent study found that vehicle operating and maintenance costs are not even considered by over ¼ of the travelers surveyed, and those who did consider them, applied significant discounts to their effects relative to tolls [*Hensher, 2007*]. In addition, some attributes such as travel time variability may be important primarily as conditioning variables that affect the actual travel conditions faced at the point in time at which a decision is made. So, for example, travel time variability may be less relevant to spur-of-the-moment route choice decisions because travelers can and do make route choices dynamically, based on actual conditions at a given point in time which often include a fairly accurate estimate of current travel times based on real-time traffic reports or prior direct observations. Variability and reliability issues may be most important for frequent corridor uses in their decision of whether or not to purchase a transponder.

A.2.2.3. Choice Context

In all stated preference experiments, respondents are asked to respond to choices in some defined context. In some past studies, this has been couched in a very general context, such as assuming travel in general or for some given trip purpose for which respondents are asked to simply choose between different travel time and cost alternatives. The limitation of this approach is that travel circumstances for a given individual and even for a given trip purpose for that individual may vary significantly from day-to-day. Without additional guidance, respondents may respond assuming a memorable, but atypical context or may assume only a typical condition and thus not reflect the variations around that typical experience.

Other stated preference experiments are framed around a particular trip, which could be one that was in process at the time the traveler was asked to participate in the survey, or it could be a selected, recently completed trip. In either case, respondents are asked to describe that trip, thus creating a "base case" revealed preference observation, and then to assume that the same travel context would apply for each of the stated preference experiments. Assuming that the trips are sampled in a way that covers all of the likely contexts, this approach ensures that both the typical and less typical travel conditions are accounted for. Having the respondent fully describe the trip also helps ensure that respondents consider all of the important conditions that might influence or constrain their choices.

There are at least two important challenges, however, in framing stated preference experiments around a particular trip context. One of the most difficult challenges is to ensure that the scenarios described in the experiments are all realistic alternatives for each respondent's trip. If, for example, some of the new travel times presented in the experiments are unrealistically short, respondents will discount those alternatives in ways that are not easily predictable, and which in any case will not provide reliable data. Using computer-based instruments or pre-processing respondents' trip information can be helpful in generating realistic stated preference experiments. Given the wide variety of trips that are made, and the need to vary attributes sufficiently, however, it can be very difficult to ensure that realistic scenarios are created for every case, so it is always important to review the resulting survey data to check for possible outliers.

The second challenge in framing stated preference experiments around a particular trip is in understanding how the response for a single trip might translate into longer-term behavior. In focus groups conducted to understand travelers' response to express lanes and variable pricing, several participants have indicated that they would budget their travel so that they did not spend more than a certain amount per month. If traffic conditions were such that tolls were consistently very high most days, they would be more selective about what threshold they would use to choose between tolled and toll-free lanes. On the other hand, if tolls were only occasionally very high, they would use a somewhat lower threshold. Some stated preference surveys have included questions designed to understand these travel budgeting issues, and to look at the frequency of using priced facilities over a number of trips (see Figure 4).

Another common approach for SP surveys supporting the modeling of road pricing is to ask respondents if they have made a recent trip in the relevant corridor, and, if so, to ask for details on the most recent trip and use the information to customize the SP choice context. The use of the "most recent" trip rather than the most "typical" one is meant to avoid bias and replicate a random sample, just as we ask household survey respondents to complete a diary for a specific assigned day and not necessarily a typical day for them. A design issue that commonly arises is the limit on how distant in the past the most recent trip can be in order to qualify for the survey. We do not want to be so restrictive that it is difficult to find respondents, but on the other hand do not want to include trips that are so far back in the past that people have forgotten some of the important details. A typical strategy is to set the limit at 1 or 2 weeks prior to the interview, while a retrospective limit of longer than 1 month is rarely used in practice.

A.2.2.4. Instrument Design

Stated preference surveys have been conducted using several different types of instruments. One important challenge is that the stated preference experiments generally each involve trade-offs among several variables that vary across two or more travel alternatives. It can be difficult for respondents to keep all of this information in their minds unless it is presented visually and, for this reason, telephone-only instruments are rarely used. However, hybrid instruments can be used where trip context information is collected over the phone and the stated preference experiments are provided separately by mail or over the web. In addition, simplified experiments can be designed that are more amenable to phone-based administration. **Figure 74** shows the general form of questions that were used to estimate values of time for a Georgia DOT I-75 value pricing study using a phone interview approach (NuStats, 2006).

Now assume you're making a future trip on I-75 just like the one that you just told me about. It's a trip on the same day, at the same time of day, for the same purpose, and you're under the same time pressures. You are traveling on the segment of I-75 between I-285 and I-575 and have the option of using the new carpool lane if you want to.

Order A: If you were to use the general traffic lanes on this segment of I-75, your trip would take TT+[#] and be free. If you used the new carpool lane as a single driver you would pay [$] and your trip would take TT, saving [#] minutes. You could also choose to carpool with at least [N] passengers and use the lane for free. Now under these conditions, would you choose to:

Use the carpool lane, pay [$] and save [#] minutes	1
Use the general lane for free	2
Carpool with [N] or more passengers to use the carpool lane for free	3
DK	98

Order B: If you were to use the carpool lane on this segment of I-75 as a single driver, you would pay [$] and your trip would take TT. If you were to use the general traffic lanes, your trip would take TT+[#], [#] minutes longer than in the toll lane, but it would be free. You could also choose to carpool at least [N] passengers to use the carpool lane for free. Now under these conditions, would you choose to:

Use the general lane for free	2
Use the carpool lane, pay [$] and save [#] minutes	1
Carpool with [N] or more passengers to use the carpool lane for free	3
DK	98

Notes: Values of [$], [#] and [N] were customized according to previous answers about the specific trip, and varied according to an experimental design. Each respondent was given either Order A or Order B at random to control for possible order-related bias.

Figure 74: Example of Stated Preference Design for Phone Interview

SP experiments can be designed as printed forms, but there may be several versions required to cover all likely contexts and to cover the required experimental design. More commonly, stated preference experiments for road pricing projects use computer-based instruments that can be more flexibly adapted to varying contexts and to more complex experimental designs. Significant detail can be used from the trip context description to tailor the experiments so that they are realistic for each trip. Furthermore, trip origins and destinations can be geocoded in real-time and those data can be used, also in real-time, to determine travel time and cost ranges based on transportation network model data. Both computer-assisted personal interviews (CAPI) and computer-assisted self interviews (CASI) have been used and web-based administration is increasingly common. See **Figure 75** for examples.

Figure 75: Example CASI/CAPI-Based SP Questions

Another common strategy when face-to-face interviews are infeasible or inefficient is to use a multi-stage CATI and mailout approach. Responses from a previous CATI or mailback survey are used to create a customized, respondent-specific printed SP questionnaire. The questionnaire is then mailed to the respondent, who can then be asked to provide their answers over the telephone, via the internet, or by mail. This strategy is often used to carry out a follow-up survey to a regional household travel survey.

A.2.2.5. Sampling

Sampling for stated preference surveys can also be conducted in any of several ways. For facility-based studies, some type of intercept sampling is often the only viable alternative. This can be because the population using the facility or corridor is widely dispersed geographically and may, for example, include significant numbers of trips made by individuals who live well outside the region in which the facility is located. Intercept sampling can be conducted using the methods described earlier for origin-destination surveys but it can also be accomplished using intercepts at activity centers in the corridor of interest. For area pricing or cordon pricing, it may be most efficient to intercept people within the potential priced area. For studying corridor-specific projects, it is often effective to use Random Digit Dialing (RDD) or address-based sampling within the residential areas that would be served by the project. For broader regional studies, the options are wider and include more standard phone, mail or web/email recruiting. Stated preference surveys have also been administered along with conventional household travel/activity surveys, usually as an add-on to some fraction of those surveys.

In general, the sampling plan for a stated preference survey should result in a representative sample of trips within the area of interest. It is important to sample a sufficient range of travelers and trip types to support the statistical estimation of coefficients of a choice model. By collecting data from the full range of traveler and trip types, it is possible to identify the ways in which different characteristics affect choice behavior. These differences can then be reflected in the structure and coefficients of the resulting choice model. The survey sample that supports mode choice model estimation does not need to be perfectly population proportional as long as: 1) any of the behavioral differences are properly represented in the model and 2) the model is applied for forecasting using appropriate population proportions and/or sample weights.

There are no universally-accepted guidelines for the sample size required for stated preference surveys. Sample sizes of 400-1,000 are common for stated preference-based road pricing surveys, but larger or smaller sample sizes may be appropriate, depending on several factors:

- The number of scenarios presented to each respondent: ranges are typically from four to 16 scenarios (more scenarios generally means that the respondent sample size can be smaller, although this is not a one-to-one tradeoff—generally the more responses from each individual, the less additional statistical information that each new response provides),
- The number of behaviorally-distinct traveler segments: models may be segmented by trip purpose, time period, vehicle occupancy and other dimensions (more segments generally means that the respondent sample size should be larger),
- The type and required precision of the estimates: estimating values of time which involves computing the ratio of two coefficients (which themselves are random variables) requires a fairly large sample size to yield a tight confidence interval so "investment grade" studies that rely on high precision in this estimate will require

large samples. Conversely, general planning or feasibility studies may require smaller samples.

As with the sample size, the costs of stated preference surveys can vary significant depending on several factors, such as the study's complexity, survey sample size and method of administration. Costs ranging from $30,000 to over $300,000 have been reported, with typical U.S. "investment grade" stated preference studies costing somewhere in the middle of that range.

A.2.3. Special Issues & Survey Types

A.2.3.1. Surveys of Commercial Vehicles

The approaches and methods described in previous sections generally apply equally to both passenger and commercial vehicle surveys. However, there are at least two special issues to be considered in designing and administering stated preference surveys of commercial vehicles. First, the driver of the vehicle may or may not be the person who makes the trip decisions that could be affected by road pricing changes. Independent owner-operators generally make these decisions themselves but other fleet and common carrier drivers most often operate under guidelines established by others. As result, the survey administration plan for stated preference surveys of commercial vehicles should identify ways of ensuring that the survey is completed by the actual decision-makers.

The second issue for commercial vehicle stated preference surveys is that values of time are typically much higher (and the tolls are correspondingly higher) than for passenger vehicles. The implied values of time for the stated preference scenarios should be checked to ensure that they encompass an appropriate range for each vehicle type. In addition, there may be a wide variation in values of time across the commercial sector, varying with characteristics such as the type and value of goods carried, the distance traveled, whether the vehicle travels full or empty, and the time of day or night. Capturing these sources of variation in a representative way requires care in sampling strategies.

A.2.3.2. Behavioral Experiments and Follow-up Surveys

Stated preference surveys ask respondents to put themselves into hypothetical situations (scenarios) and indicate what they would likely do in those situations. A logical extension of that approach is to create real pricing experiments for a sample of individuals. Two current studies in the U.S. illustrate this approach.

The Puget Sound Regional Council is conducting an FHWA-sponsored pilot study in which "Travel Choices Meters" were installed in 500 vehicles. The drivers were given $600 to spend (or not spend) over a year under conditions in which the meters deducted from this account in accordance with a simulated variable road pricing program. **Figure 76** shows the toll map and schedule provided to respondents, and the in-vehicle unit that was used to show respondents what they were being charged at any moment, as well as the cumulative amount they had been charged for the trip and in total. Drivers' responses to the pricing were recorded using GPS devices installed in the vehicles, providing GPS traces on 750,000 trips. Preliminary analysis has indicated that such a pricing system could reduce VMT by about 10%. For more information, see www.**psrc**.org/projects/**trafficchoices**/. A similar effort is being undertaken by the University of Iowa in which 1,200 cars will be outfitted with a GPS device and mileage-based charges will be levied against an initial budget, although the emphasis in this latter study is more on testing in-vehicle technology than it is on studying behavioral responses to pricing.

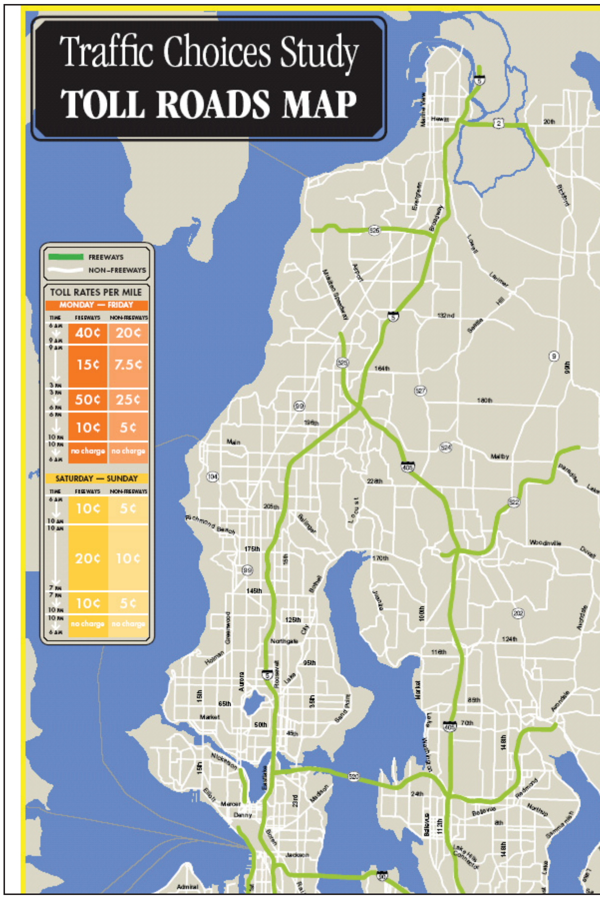


Figure 76: Traffic Choices Study Toll Map/Schedule and In-Vehicle Price Meter Provided to Respondents

Follow-up surveys conducted after a road pricing project is implemented can be especially useful for both documenting the effects of the road pricing project and for determining how the project might be refined to better accomplish its objectives. Significant follow-up survey efforts have accompanied several major road pricing projects. Examples include work related to the SR-91 Express Lanes project [*Sullivan, 2000*] and the Lee County LeeWay variable bridge pricing project [*Burris, et al, 2004*]. A unique panel survey in Minneapolis [*Zmud et al, 2007*] included a series of SP questions and other types of questions with the same respondents both before and after the opening of the I-394 MnPASS HOT lane facility.

A.2.3.3. Attitudinal / Public Opinion Surveys

The surveys described in the previous sections are designed to provide information that can be used to estimate the effects of road pricing changes or new toll road facilities. Surveys and other research methods can also be used to inform decision makers about public attitudes and opinions regarding pricing policies or programs. Several of the FHWA Value Pricing Pilot projects and many of the private toll road ventures have included significant qualitative research components. This qualitative research has consisted of both traditional focus groups and individual depth interviews (IDIs) for selected key stake-holders.

Qualitative research provides an opportunity to learn how these projects are perceived, what types of concerns they raise with different segments of the general public, both user and non-users, and how those concerns can be addressed. For example, the early qualitative research on variable pricing suggested that many individuals have a hard time understanding why a policy of increasing peak period prices can improve travel times: they assume that most peak periods travels are people making work trips that cannot be made at other times. They are also concerned about how any additional money that is collected is used; they strongly prefer that it be used to improve travel conditions in the corridor in which the tolls are collected.

Quantitative research can be used to determine public opinions about a proposed project or program before it is implemented and/or determine effects after implementation. While opinion polling is a well-established method for a wide range of applications, there is one important caveat regarding these methods for road pricing projects and programs. Qualitative research has indicated that individuals in general have a difficult time understanding details of how modern road pricing approaches work or would work, even in areas with existing conventional tolling and especially in regions that have no existing tolled facilities. For example, in a recent focus group for a proposed express lane project (new ETC-only lanes in the median of an existing interstate highway) participants were asked if they had heard about any proposed projects and what they thought about them. Most said that they had heard about the project it and opposed it. On further prompting, the opposition was determined to stem from their perception that the lanes would have conventional toll plazas, which they knew "wouldn't work" (the perception came from or was supported by a local newspaper article that had simply described the new lanes as "toll lanes").

The point of this anecdote is that individuals can have a hard time imagining the implications of a new road pricing approach and, unless those implications are appropriately conveyed in the survey questionnaire, their stated opinions will not be fully informed. In that regard, qualitative research can be very valuable in informing the design of a quantitative survey instrument.

There have been several public opinion/attitude surveys conducted in association with road pricing projects. The most comprehensive effort was a three-wave panel survey designed to be conducted before and after implementation of the I-394 MnPASS project in the Minnesota Twin Cities region [*Douma, et al, 2006*]. The survey measured baseline pre-project attitudes and later waves were designed to measure changes in those attitudes after the project was operational. Other surveys have been conducted primarily to inform decision makers of the level of project support.

As with the other methods, the costs of this type of research can vary considerably. Qualitative research projects involving focus groups commonly include 6-12 groups at approximately $5,000 per group. Public opinion and attitudinal surveys typically have sample sizes of 800-1,200 completes at $30-$60/complete.

A.2.3.4. Related Data Collection Methods

Traveler surveys comprise only part of the data collection effort that is required to support reliable modeling of the shifts in travel patterns that might result from road pricing changes. Good traffic count coverage is important for providing model validation data. For road pricing studies, it is also useful to compile traffic counts by time-of-day, season, vehicle type, and, for toll facilities with mixed cash/ETC, transaction type. For toll road facilities, toll plaza, ramp, and ETC data can be used together with matrix estimation procedures to develop accurate on-ramp to off-ramp (facility origin-destination) estimates.

Travel speeds and variations in those speeds determine the travel times that drivers face when they decide between competing routes. The speeds used in travel forecasting models are often not calibrated closely enough for pricing analysis to accurately represent the travel time differences between competing routes, particularly as they vary with traffic volumes and travel conditions. Travel surveys can be designed so that they collect reported travel times but those are also not necessarily accurate representations of actual speeds. Special travel time surveys can be conducted using GPS devices, but the most comprehensive data on travel speeds and variations in those speeds is likely to come from other sources such as ETC operations data (for tolled facilities with multiple plazas), traffic operations centers or the commercial traffic monitoring services that now collect data in most major U.S. urban areas.

A.2.3.5. Combining RP and SP Data

It is critical to use both RP and SP data in order to get an accurate model of traveler responses to pricing. While SP data is typically necessary to estimate distributions across the population and provide detailed market segmentation information, it also has potential shortcomings. Research from the limited number of managed lane systems already in place has indicated that willingness to pay estimates estimated from RP data tend to be roughly twice as high as those derived from SP data, in the same context. Reasons hypothesized for this are that travelers have inaccurate perceptions of the time that they actually save on the systems, as well as evidence of possible "protest" responses against pricing options that may outlined in the SP exercises. Carefully pooled analysis of both types of data will be necessary to take advantage of the strengths and avoid the shortcomings of each.

From the formal statistical point of view, combined model estimation that is based on both RP and SP data, benefits synergistically from the different nature of RP and SP data. The data are not just blended together, but are used in the best possible statistical manner in which the SP-related parameters are properly scaled by the observed data from RP. This allows for elimination (or mitigation) of many systematic biases inherent to pure SP surveys.

One strong data set in this regard is the data from the MnPASS system in Minneapolis. As yet the trip data from the panel surveys have not been combined with objective data on HOT lane travel times and prices and general lane travel times in order to derive RP models. Another important data set for pooled analysis is the data from the Traffic Choices pricing experiment in the Seattle region mentioned above. That experiment combines some of the best elements of SP research—an experimental design of prices that vary by time and space—with critical elements of RP data—objective GPS measurement of travel speeds, times and prices, along with responses that involve actual payment of money.

A.2.4. Choice Attributes to Support Advanced Models

A.2.4.1. Measuring Distributions of Willingness to Pay Tolls

It is vital to collect data that will allow us to measure the distribution of the value of time across the relevant traveling population. For example, a recent Stated Preference study of users of the new MnPASS HOT lane facility [*Zmud, et al., 2007*], used a survey method to explicitly estimate each respondent's individual willingness to pay and associated Value of Time (VOT), and found much more variation across the sample than could be captured through observable segmentation variables alone. The observed distribution resembled the log-normal distribution seen in **Figure 77** and compared to a symmetric normal distribution.

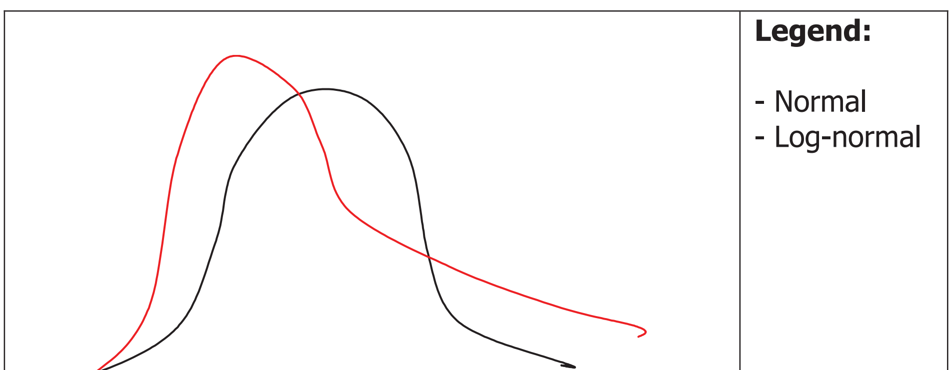


Figure 77: Possible Value-of-Time Distributions

[*Ben-Akiva, et al, 1993*] pioneered an econometric approach to directly estimate the parameters of such log-normal VOT distributions from typical SP and RP data sets. This research was done as part of a study for Cofiroute of proposed tolls on the French national motorways, and the resulting distributed models were applied using a customized multi-user-class static assignment routine. Now, 15 years later, there is a variety of approaches and software products available for estimating and applying such models estimated using a mixed logit approach and applied using stochastic microsimulation. In particular, distributed VOT was incorporated in the San-Francisco County Transportation Authority (SFCTA) model (see **Figure 78**) that is currently being applied in the comprehensive congestion pricing study in the Bay Area.

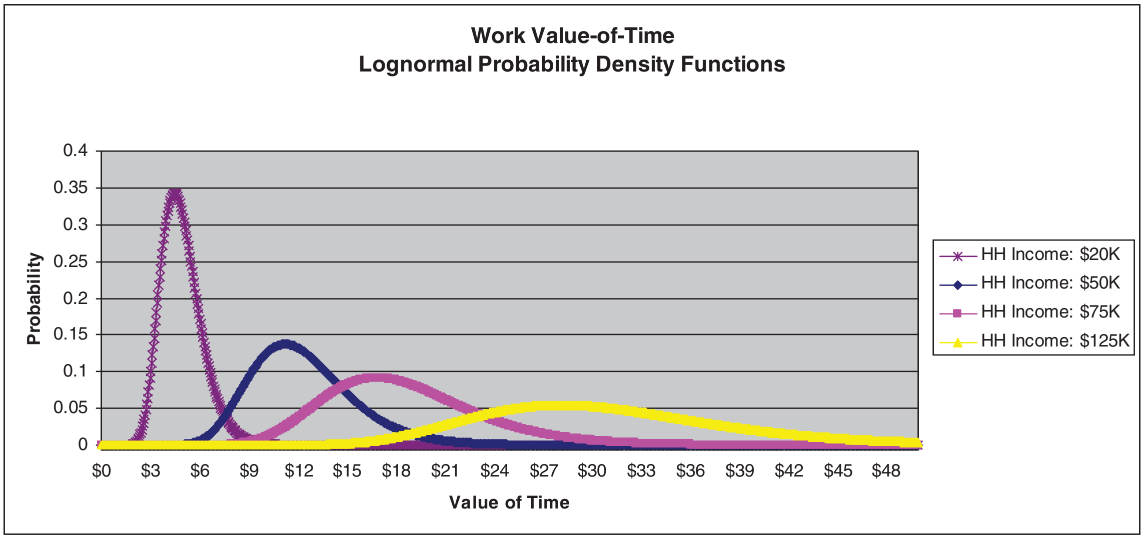


Figure 78: Distributed VOT in the SFCTA model

A.2.4.2. Measuring the Value of Reliability

Willingness to pay for reductions in the day-to-day variability of travel time is referred to as Value of Reliability (VOR). [*Small, et al, 2005*] presented an interesting and operational approach for actual estimation of the Value of Reliability (VOR) in a consistent way with VOT by splitting their impacts on traveler choice. The adopted quantitative measure of variability was the upper tail of the distribution of travel times, such as the difference between the 80th and 50th percentile travel times (see **Figure 79**).

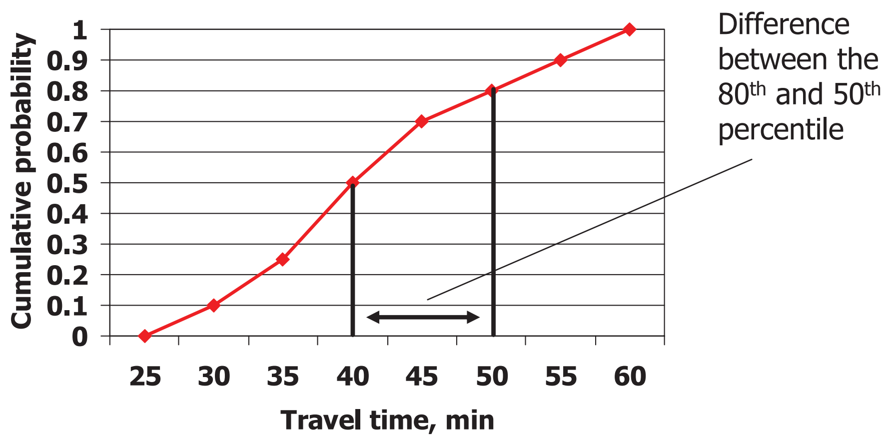


Figure 79: Travel Time Reliability Measure

The authors argue that this measure is better than symmetric standard deviation, since in most situations being "late" is more crucial than being "earlier", and many regular travelers will tend to leave build a "safety margin" into their departure times that will leave them an acceptably small chance of arriving late (i.e. planning for the 90th percentile travel time would mean arriving late 10 percent of the time). Reliability as defined above proved to be valued by travelers as highly as the median travel time. A number of recent toll-related SP experiments have used the 90th or 80th percentile travel time directly as an attribute. An example is a survey done in San Francisco to study possible area pricing policies (RSG, 2007), as shown in **Figure 80**.

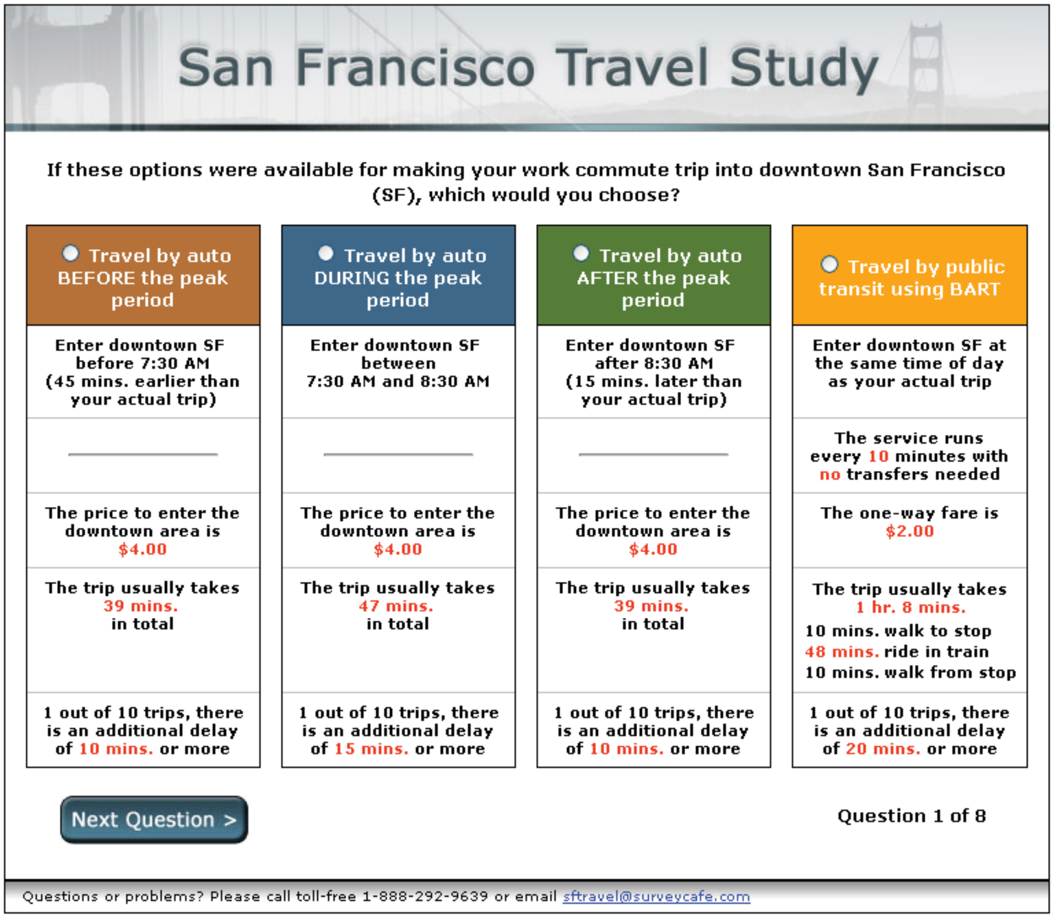


Figure 80: Experiment Including Reliability as the 90th Percentile Travel Time

Making this approach operational within the framework of travel forecasting models requires explicit modeling of travel time distributions, as well as making assumptions about how travelers acquire information about the uncertain situation they are about to experience. Dynamic traffic assignment and microsimulation tools are crucial for the application of models that include travel time variability, since static assignment can only predict average travel times.

In general, the following types of reliability measures in **Table 35** can be used in the model estimation and application. Note that supporting speed/travel time surveys are typically needed for the supply side of estimation. It is also important that there are several simplified ways to account for reliability by means of operational proxies, for example, perceived highway time differentiated by congestion levels. While the direct measures of reliability can be incorporated only in a framework of an Activity-Based microsimulation model, operational proxies can be incorporated in aggregate 4-step models.

Table 35: Reliability Measures

Measure of reliability	Demand side	Supply side	
		Estimation	Application
Derived reliability measures based on the observed or generated travel time distribution statistics	Impact of percentile-based or other measure estimated along with average travel time and cost	Repeated observations for the same trip and individual (RP, SP)	Dynamic / learning framework or multiple network simulations
Direct reliability measured based on explicit formulations like "probability of certain delay"	Impact of probability of delay estimated along with average travel time and cost	Direct question (SP or enhanced RP)	Dynamic / learning framework or multiple network simulations
Direct reliability proxies measured by the variation of travel times	Impact of percentile-based or probability of delay estimated along with average travel time and cost	Observed (RP), modeled (RP), or assumed (SP) variation of travel time.	Modeled travel time variation as function of facility type, volume, etc (auxiliary regressions).
Indirect observed or modeled reliability proxies like V/C (RP) or Perceived highway time differentiation by congestion levels	V/C-based measures or perceived travel time (speed/delay/LOS-specific) estimated along with average travel time and cost	Network skims for V/C and/or perceived time components	Network skims for V/C and/or perceived time components

A.2.4.3. Measuring the Choice of Departure Time as Affected by Pricing

One response to pricing that is directly related to travel time reliability and has been very difficult to capture with either RP or SP methods is the shift in departure times in response to differences in prices and congestion across the day. Even in the most advanced activity-based models of activity scheduling, it has not been possible to measure the effect of travel times on departure time choice very accurately. A key reason for this is the fact that travel times are endogenous — the more people that choose to travel in a given period, the longer the travel times tend to be. A similar analytical problem may occur with dynamic pricing on managed lanes, where the price is also dependent on the demand (and vice versa). The Seattle Traffic Choices data, as well as RP data from existing priced facilities that use fixed pricing schedules by time of day and week (e.g., the various Orange County toll roads), could prove to be very valuable in this context.

An important issue in modeling the effect of time of day pricing on travel demand is the fact that prices that influence one part of a travel tour may also indirectly influence the other trips in the tour as well. For example, when a commuter considers adjusting the time of travel to work in response to pricing, he or she may also consider that they need to spend a certain amount of time at work, and thus adjust the departure time for the trip returning home as well. [*Hess, et al, 2007*] report on the results of a series of CAPI

SP experiments carried out in the Netherlands and the UK, in which the SP choice screens explicitly captured this “knock on” effect by presenting the times and cost for both the trip to work and the trip back home.

A.2.5. Typology of Available Surveys for Pricing Analysis and Modeling

In the framework of a different research project – SHRP 2 (second Strategic Highway Research Program) 2 C04 (“Improving Our Understanding of How Highway Congestion and Pricing Affect Travel Demand”) – currently being implemented by the same team in parallel, we have identify available datasets collected in different regions that are useful to support pricing analysis and modeling. The following represent the major types of surveys that are used to support the analysis and modeling of transportation pricing and congestion, where the categories represent a combination of survey general methods and the purposes for which the surveys are done:

- **Type 1:** General Comprehensive Household Interview Surveys - Revealed Preference (RP)
- **Type 2:** Stated Preference (SP) Follow-on and Linked to Household Interview Surveys
- **Type 3:** Managed Lane Studies - Combined Revealed Preference and Stated Preference (RP/SP)
- **Type 4:** Regional Pricing Options and Area-Based Pricing - Combined Revealed Preference and Stated Preference (RP/SP)
- **Type 5:** New Facilities with Tolling - Combined Revealed Preference and Stated Preference (RP/SP)
- **Type 6:** Time of Day Tolling - Combined Revealed Preference and Stated Preference (RP/SP)
- **Type 7:** Existing Facilities: Adding Tolls - Combined Revealed Preference and Stated Preference (RP/SP)

Even in each of these categories, there are variations in their structure, scope, and design. In view of the objectives of the study, there are advantages and disadvantages to be carefully evaluated. No one single survey type can provide a full basis for a comprehensive analysis of all impacts of congestion and pricing on travel behavior. Altogether, however, we anticipate that the set of existing, as well as planned concurrent surveys, can provide good coverage of the main travel dimensions of interest, and good empirical foundation for this research project

Household Interview Surveys represent the only holistic framework that allows for an analysis of the entire daily activity pattern of persons and households. There are several valuable Household Interview Surveys implemented in such over-congested regions as New York, 1996/7 and San Francisco 2000. They provide general observed patterns of behavior under congestion conditions. By comparison to other regions like Mid-Ohio or Atlanta for which comprehensive household interview surveys are also available, the impact of congestion and pricing on activity patterns and lifestyle can be estimated.

Household Interview Surveys with a subsequent SP follow up survey represent probably the most promising approach for data collection for the current study. This type of data collection was implemented in Seattle [*Cambridge Systematics, et al 2007*] and Montreal, is ongoing in Chicago and will be available in early 2008), and is planned for the new major data collection effort in NY (2008-2009). In this case the SP participants are recruited from the households that have already been surveyed. The SP design is built on the relevant reported trip that was implemented, for one or more of the priced facilities (either existing or planned). Thus, in the model estimation, not only are the characteristics of this particular trip available, but also the whole context of the person daily pattern is known The last characteristics, means that additional important situational variables are available, like the number and timing of the other trips and activities undertaken by the person on the same day.

A wide range of more specific surveys focused on toll road users and relevant trips is available. Most of these focused surveys had a **Combined Revealed Preference/Stated Preference form.** The RP/SP combination ensures behavioral realism of the trip selected for the subsequent analysis as well as all associated household, person, and travel characteristics. The SP side, however opens a way to explore a wide range of responses to non-existing alternatives that can include priced and free highway facilities, improved transit, shifting the trip to a different time-of-day period, etc. Different methods of combined RP/SP estimation have been applied for models developed for SR-91, I-15, MnPass, and A-25 (in Montreal, QC).

Some of the existing surveys have the form of a multi-day repeated observations and/or multi-wave panel like SR-91 and I-15 data sets processed and used by Small and Brownstone [*Brownstone & Small, 2005; Small, Winston & Yan, 2005*]. Repeated observations for the same trip of the same person can provide the basis for a direct measurement of reliability.

Managed Lane Studies are extremely useful for understanding the trade-offs between travel time savings, reliability, and price since in this case managed lanes and free lanes always constitute two explicit and available route options with monitored level-of-service characteristics. The behavioral framework delimiting possible responses includes route and pre-route choice, and may also include time-of-day choice, occupancy choice (if relevant) as well as some other choices.

A different emphasis and range of responses is pertinent to **Regional Pricing Options and Area-Based Pricing Studies**. In these studies, pricing is primarily considered as a measure of congestion relief by moving travelers from auto modes to transit (and not necessarily providing a free highway alternative like in most Area-Pricing schemes). These studies are especially beneficial for understanding and modeling the impact of congestion and pricing on mode choice. In this cases, travel time, reliability, and price trade-offs made by the travelers are inter-modal. A proper modeling of mode choice in the presence of congestion requires the development of reliability estimates not only for highway modes, but also for different transit modes. Model development and application studies for area pricing in New York and San Francisco are now underway, both of which have clearly shown the importance of an inter-modal view on reliability and the differentiation of transit modes by reliability and other level-of-service characteristics [*Resource System Group, 2007*].

Some specific features are associated with studies of **New Facilities with Tolling**. Several such facilities have recently been proposed and/or built in the state of Texas, and some in the state of Florida as well. In general, Greenfield toll facilities are considered as the most complicated for modeling and predicting of traveler responses. The available RP/SP studies (and especially if both "before and after" statistics are available) are beneficial for a better understanding of the sources of patronage of the toll facility. In a certain sense, the entire demand for a new facility can be considered as "induced", although trips may be diverted from other routes over a fairly wide geographical area. It is of particular importance, to understand and capture differential elasticities for route, mode, and time-of-day switches underlying the demand for new facility.

Another important aspect of the dynamics of congestion and pricing is associated with **Time of Day Tolling** studies. These studies are normally associated with congestion pricing schemes and specifically address/target time-of-day choice (in combination with mode choice in urban areas). Pricing schemes with differential-by-time-of-day tolls, as well as real-time variable tolls, provide an ideal basis for understanding and modeling time-of-day related responses to congestion and pricing.

A special case is provided by studies of **Adding Tolls to Existing Facilities**. There can be different facility types and regional frameworks that create different set of possible behavioral responses. There are however, several unique aspect associated with this type of surveys. They allow for capturing psychological effects like resistance to newly-introduced tolls, ramp-up period associated with certain learning and adaptation of the regional travelers to the new travel conditions created by the tolls, etc.

Table 36 contains an inventory of survey datasets that have been collected over the past several years and which have supported or could support analysis of road pricing projects. The datasets have been divided into seven types, ranging from general purpose household interview surveys to those that have been purpose-designed to support specific road pricing applications. While this list is long, it is by no means exhaustive of all of the relevant work in these categories and is intended primarily to be illustrative of the types of efforts that have been undertaken to support these applications. One of the essential tasks of the SHRP project that has to be strongly coordinated with the course of the current NCHRP project is to select several available datasets for pilot studies and estimation of advanced models for pricing. Our intention is to select datasets from the same regions / studies where the NCHRP pilot studies are going to be implemented.

Table 36: Existing Survey Datasets for Road Pricing Analysis and Modeling

Type 1: General Comprehensive Household Interview Surveys - Revealed Preference (RP)

Survey type	Region	Year	Sample / Characteristics	Team Members Familiar	Research/modeling framework	Land use data	Time and cost data	Reliability measures	Pricing Measures and Other considerations
Household Interview –RP	NY metropolitan	1996/7	11,000 HH, 1 day	Vovsha, Donnelly	NYMTC regional AB model development	Zonal level	Network skims	Network loading proxies	Tolls on bridges, tunnels, some toll roads
Household Interview- RP	Denver metropolitan	1996/7	4,500 HH, 1day	Vovsha, Bradley	DRCOG regional AB model development	Zonal and point level	Network skims	Network loading proxies	Very limited tolling at time of survey.
Household Interview- RP	Mid-Ohio (Columbus)	1999	5,500 HH, 1day	Vovsha, Donnelly	MORPC regional AB model development	Zonal level	Network skims	Network loading proxies	None
Household Interview- RP	Sacramento metropolitan	1999	3,500 HH, 1day	Bradley, Bowman	SACOG regional AB model development	Zonal and parcel level	Network skims	Network loading proxies	None
Household Interview- RP	SF Bay Area	2000	15,000 HH, 2 days	Bradley, Freedman	SFCTA and MTC regional AB model development	Zonal level	Network skims	Network loading proxies	Tolls on bridges
Household Interview- RP	Atlanta, GA metropolitan	2001	8,100 HH , 1 day	Vovsha, Bradley, Bowman	ARC regional AB model development	Zonal and grid cell level	Network skims	Network loading proxies	None
Household Interview- RP	Chicago metropolitan	2007	15,000 HH, 1/2 days	Vovsha, Bradley	CMAP regional (AB) model development	Zonal level	Network skims	Network loading proxies	Tolls on some interstates. Contains some supplementary
Household Interview-RP	Seattle metropolitan	2006	5,000 HH, 2 days	Bradley, Picado	PSRC regional (AB) model development	Zonal and grid cell level	Network skims attached	Network loading proxies	Tolls on a couple roads/bridges. Contains some supplementary
Household Interview RP (Origin-Destination)	Montreal metropolitan	1998	48,000 HH, 1 day	Vovsha, Donnelly	MTQ tour-based model for A-25 and A-30 T&R study	Zonal level	Network skims attached	Network loading proxies	None
Household Interview RP (Origin-Destination)	Ottawa metropolitan	2001	21,000 HH, 1 day	Vovsha, Donnelly	TRANS regional model	Zonal level	Network skims attached	Network loading proxies	None
Quasi-experimental RP GPS data capture / Puget Sound Traffic Choices experiment	Seattle metropolitan	2006	500 HH, all vehicles instrumented. 1 month prior to & 4 months after tolling.	Picado	Traffic Choices experimental study of distance-based pricing	Zonal and grid cell level	Derived from GPS data & skims	Proxies or derived from GPS data	Prices that vary by geography, road type, time of day, with GPS capture of routes and payment.

Type 2: Stated Preference (SP) Follow-on and Linked to Household Interview Surveys

Survey type	Region	Year	Sample / Characteristics	Team Members Familiar	Research/modeling framework	Land use data	Time and cost data	Reliability measures	Pricing Measures and Other considerations
SP follow-on to Household Interview	Seattle metropolitan	2006	500 diary trips as basis / 4 SP choices per person	Bradley	PSRC study focused in potential tolling corridors.	Zonal and grid cell level	SP levels pivoted from skim data	SP levels of explicit chance of long delay	Experiment offered choice of tolled and non-tolled options in both peak and off-peak – measured dep. time switching.
SP follow-on to Household Interview	Chicago metropolitan	2007	500 diary trips as basis / 4 SP choices per person	Vovsha, Bradley	CMAP study focused in general responses to tolls and pricing	Zonal level	SP levels pivoted from skim data	SP levels of explicit chance of long delay	Experiment offered choice of tolled and non-tolled options in both peak and off-peak – measured dep. time switching.

Type 3: Managed Lane Studies - Combined Revealed Preference and Stated Preference (RP/SP)

Survey type	Region	Year	Sample / Characteristics	Team Members Familiar	Research/modeling framework	Land use data	Time and cost data	Reliability measures	Pricing Measures and Other considerations
RP/SP panel survey for MnPASS corridor travelers	Minneapolis metropolitan	2005/ 2006	2000 relevant trips, 300 3 wave panel members/ 5 SP choices per person	Bradley	Attitude and behavior study for the MnPASS HOT lane project – before and after	Zonal level	SP levels using design, RP levels derived fr. operational data, counts	Not in SP RP tr. time distributions based on operational data, counts	Panel provides before and after RP and SP for small sample. SP provides individual-level VOT estimates. Simple 1-stage telephone interviews used. RP time/cost data not yet in place.
RP/SP survey for SR 91 Express Lanes	Orange County	Various; TBD	TBD	Small	OCTA behavioral study for the SR 91 Express Lane usage	Zonal level	SP levels using design, RP levels derived fr. operational data, counts	In SP(?) RP tr. time distributions based on operational data, counts	Results show higher VOT estimates for RP choices than for SP. (Did this include before and after component?)
RP/SP survey for I-15 HOT Lane	San Diego County	Various; TBD	TBD	Brownstone	SANDAG(?) behavioral study for the I-15 HOT Lane system usage	Zonal level	SP levels using design, RP levels derived fr. operational data, counts	In SP(?) RP tr. time distributions based on operational data, counts	Results show higher VOT estimates for RP choices than for SP. (Did this include before and after component?)
RP/SP survey for Houston HOT lane?	Houston region	Proposed 2007/08	TBD	Freedman Kockelman	HGAC behaviroal study of existing toll users	Zonal level	TBD	TBD	TBD
SP survey for potential I-75 managed lanes	Atlanta metropolitan	2006/ 2007	Appr. 4000 relevant trips/ 5 SP choices per person	Bradley	Georgia DOT and SRTA, various potential sites along I-75	Zonal level	SP levels using design. No RP models.	Not considered in SP	SP provides individual-level VOT estimates. Simple 1-stage telephone interviews used.
RP/SP survey for possible LT/I495 Managed Lane w/ time of day pricing	New York region, Licoln Tunnel corridor	2007	1200 trips/9 SP choices/person	Adler	Lincoln Tunnel HOT Lane Study	Zonal level	SP levels using design, RP levels derived fr. operational data	Not in SP RP tr. time distributions based on operational data, counts	Currently tolls on Hudson River crossings. Also significant existing express bus service thropugh Tunnel.
RP/SP survey for proposed new express lanes w/ time of day pricing	SR-91, Orange County, CA	1992	800 trips/9 SP choices/person	Adler	To support investment-grade traffic and revenue study for private consortium	Zonal	SP levels pivoted from skim data	Not in SP RP tr. time distributions based on operational data, counts	No existing tolls. Study estimated higher VOT than expected but SP estimates turned out to be within 5% of independently-estimated
RP/SP survey for proposed new express lanes w/ time of day pricing	Orlando, FL	2000	1000 trips/9 SP choices/person	Adler Picado	To support feasibility study for Florida's Turnpike/DOT	Zonal	SP levels pivoted from skim data	Not in SP RP tr. time distributions based on operational data, counts	Region has significant existing toll road alternatives; RP data augmented with OD survey.
RP/SP survey for proposed new express lanes w/ time of day pricing	Miami, FL	2002	1200 trips/9 SP choices/person Includes transponder acquisition choi	Adler	FHWA Value Pricing Pilot project for Florida's Turnpike	Zonal	SP levels pivoted from skim data	Not in SP RP tr. time distributions based on operational data, counts	Region has significant existing toll road alternatives; RP data augmented with OD survey and 400 HH surveys with route choice.
RP/SP survey for managed lane options	Houston Katy Freeway (I-10)	2001	900 trips/9 SP choices/person	Adler	Used to support analysis of managed lane options	Zonal	SP levels pivoted from skim data	Not in SP RP tr. time distributions based on operational data, counts	Existing HOV lanes

Type 4: Regional Pricing Options and Area-Based Pricing - Combined Revealed Preference and Stated Preference (RP/SP)

Survey type	Region	Year	Sample / Characteristics	Team Members Familiar	Research/modeling framework	Land use data	Time and cost data	Reliability measures	Pricing Measures and Other considerations
SP survey for potential area pricing in San Fran.	San Francisco / Bay Area	2007	600 relevant trips/ 5 SP choices per person	Adler Bradley, Freedman	SFCTA survey of potential response to area pricing.	Zonal level (finer grain for SF)	SP levels pivoted from skim data	SP levels of explicit chance of long delay	Experiment offered choice of tolled and non-tolled options in both peak and off-peak – measured dep. time switching.
SP survey for time of day pricing in the Netherlands	Randstad metropolitan	2002	?	Bradley	Study for Dutch Ministry of Transport to incorporate time of day switching in National Traffic Model.	Zonal level	SP levels pivoted from skim data	SP levels of explicit uncertainty of departure time.	Experiment offered choice of tolled and non-tolled options in both peak and off-peak – measured dep. time switching. Effect on mode choice integrated in experiment. Used a fully tour-based
SP survey for time of day pricing in the UK	West Midlands region	2004	?	Bradley	Study for UK Ministry of Transport, transferring Dutch study to UK context.	Zonal level	SP levels pivoted from skim data	SP levels of explicit uncertainty of departure time.	Experiment offered choice of tolled and non-tolled options in both peak and off-peak – measured dep. time switching.
RP/SP survey to evaluate road pricing options	Minneapolis/St. Paul, MN	1995	800 trips/9 SP choices/person	Adler	FHWA Value Pricing Pilot project for MNDOT	Zonal	SP levels pivoted from skim data	Not in SP RP tr. time distributions based on operational data, counts	No existing tolls

Type 5: New Facilities with Tolling - Combined Revealed Preference and Stated Preference (RP/SP)

Survey type	Region	Year	Sample / Characteristics	Team Members Familiar	Research/modeling framework	Land use data	Time and cost data	Reliability measures	Pricing Measures and Other considerations
SP survey for new facilities	Montreal metropolitan	2002	1,000 diary tours as basis/ 11 SP choices per person	Vovsha, Donnelly	MTQ tour-based model for A-25 and A-30 T&R study	Zonal level	SP levels pivoted from skim data	SP levels of explicit chance of long delay	?
RP/SP survey for proposed new toll road	Maryland Intercounty Connector	2005	2400 trips/9 SP choices/person	Adler	Used to support traffic and revenue study for new road	Zonal	SP levels pivoted from skim data	Not in SP RP tr. time distributions based on operational data, counts	Used data to compute individual values of time
RP/SP survey for managed lane options	Dallas LBJ Freeway	2004	1200 trips/9 SP choices/person	Adler	Used to support TxDOT analysis of managed lane options	Zonal	SP levels pivoted from skim data	Not in SP RP tr. time distributions based on operational data, counts	
RP/SP survey for new toll roads	Austin, TX	1999	2400 trips/9 SP choices/person; 200 truck trips	Adler	Used to support traffic and revenue studies	Zonal	SP levels pivoted from skim data	Not in SP RP tr. time distributions based on operational data, counts	Concurrent OD survey conducted
RP/SP survey for new toll facility	Alaskan Way Viaduct, Seattle, WA	2005	1800 trips/9 SP choices/person	Adler Picado	Used to support Washington DOT's toll feasibility study	Zonal	SP levels pivoted from skim data	Not in SP RP tr. time distributions based on operational data, counts	Data used to estimate individual values of time
RP/SP survey for new toll roads and variable tolling	Florida statewide	2006 / 2007	3600 trips/9 SP choices/person	Adler Picado	Used to support feasibility studies	Zonal	SP levels pivoted from skim data	Not in SP RP tr. time distributions based on operational data, counts	Conducted throughout state both in locations that have limited and extensive toll road options; includes both local and intercity trips
RP/SP survey for proposed new toll road w/ time of day pricing	Toronto, Ontario	1993	800 trips/9 SP choices/person 400 Trucks	Adler	To support investment-grade traffic and revenue study for Ontario Transport	Zonal	SP levels pivoted from skim data	Not in SP RP tr. time distributions based on operational data, counts	Included transponder acquisition since project was designed as all-ETC
RP/SP survey for proposed new toll road	Tampa, FL	2004	1100 trips/9 SP choices/person Includes transponder acquisition choice	Adler Picado	To support feasibility study for Florida's Turnpike/DOT	Zonal	SP levels pivoted from skim data	Not in SP RP tr. time distributions based on operational data, counts	Region has existing toll road alternatives; RP data augmented with OD survey and 400 HH surveys with route choice.

Type 6: Time of Day Tolling - Combined Revealed Preference and Stated Preference (RP/SP)

Survey type	Region	Year	Sample / Characteristics	Team Members Familiar	Research/modeling framework	Land use data	Time and cost data	Reliability measures	Pricing Measures and Other considerations
RP/SP survey for time of day pricing	New York Tappan Zee Bridge	1998	2000 trips/9 SP choices per person plus 300 trucks	Adler	FHWA Value Pricing Pilot project for NYSTA	Zonal	SP levels pivoted from skim data	Not in SP RP tr. time distributions based on operational data, counts	Existing bridge tolls on this and alternate routes Mixed mode intercept/web/CATI with mailout/mailback
RP/SP survey to evaluate time of day pricing options	Pennsylvania Turnpike corridor	2002	1200 trips/9 SP choices/person	Adler	FHWA Value Pricing Pilot project for Pennsylvania Turnpike	Zonal	SP levels pivoted from skim data	Not in SP RP tr. time distributions based on operational data, counts	Existing toll facility
RP/SP survey to evaluate bridge pricing options	Seattle SR-520	2003	900 trips/9 SP choices/person	Adler	Feasibility study for Washington DOT	Zonal	SP levels pivoted from skim data	Not in SP RP tr. time distributions based on operational data, counts	No current tolls
RP/SP survey to evaluate time of day pricing options	Illinois Tollway	2004	2200 trips/9 SP choices/person; separate truck survey	Adler	FHWA Value Pricing Pilot project for IL State Highway Authority	Zonal	SP levels pivoted from skim data	Not in SP RP tr. time distributions based on operational data, counts	Used data to compute individual values of time

Type 7: Existing Facilities: Adding Tolls - Combined Revealed Preference and Stated Preference (RP/SP)

Survey type	Region	Year	Sample / Characteristics	Team Members Familiar	Research/modeling framework	Land use data	Time and cost data	Reliability measures	Pricing Measures and Other considerations
RP/SP survey to evaluate response to open road tolling	Florida statewide	2002	100 respondents: qualitative/quantitative survey with 16 SP choices/person	Adler	Feasibility study for Florida's Turnpike	N/A	N/A	N/A	Developed models of transponder acquisition and potential toll diversion from possible ORT implementation
Origin-Destiantion (RP only)	Houston	1999	13,000 trips	Freedman	Hardy Toll Road, the Sam Houston Tollway, and the	N/A	N/A	N/A	Existing tolls paid only
RP/SP survey to evaluate effects of new bridge toll	Tacoma Narrows Bridge	2000	1200 respondents/9 SP choices/person	Adler	Used to support traffic and revenue study for new bridge	Zonal	SP levels pivoted from skim data	Not in SP RP tr. time distributions based on operational data, counts	Developed model to estimate possible trip reductions and mode substitution (ferry) from tolling

A.3. Travel Time Reliability Measures

A.3.1. Highway Utility Components

Highway travel utility is a basic expression combining various LOS attributes as perceived by the highway user. It is directly used in the highway trip route choice, for example between the Managed Lanes and General-Purpose Lanes on the same facility. It also constitutes an essential component in mode and time-of-day (TOD) choice utilities. The form of highway utility function is also important for modeling other (upper-level) travel choices since it serves as the basis for calculating accessibility measures. Consequently, it is essential to explore the highway travel utility and its components first, having in mind a simplified framework of route choice in the highway network, since the complexity builds up as additional choice dimensions are considered.

In most travel demand models, including those developed for practical and research purposes, highway utility takes the following simple form:

Equation 37: $U = a \times T + b \times C$;

where:

T	=	travel time,
C	=	travel cost,
$a < 0$	=	coefficient for travel time,
$b < 0$	=	coefficient for travel cost,
a/b	=	Value of Time (VOT).

Coefficients for travel time and cost normally take negative values, reflecting the fact that travel, in itself is an onerous function necessary only for visiting the activity location. Thus, the travel utility is frequently referred to as "disutility" of travel. There are some research works where the negative character of travel utility was questioned in some contexts. In particular, a positive travel utility was associated with long recreational trips on weekends [*Stefan et al., 2007*]. Also, an interesting effect was observed for commuting trips where commuters seem to prefer (or expect) to traveling for some minimum time (e.g., 20-30 minutes) and are not interested in reducing it below this threshold [*Redmond and Mokhtarian, 2001*].

The representation of highway travel utility as a linear function of two variables with constant coefficients is an extremely simplified one. A great deal of the SHRP 2 C04 project effort is devoted to elaboration of this basic form in the following ways:

- Investigation of the highway user **perception of travel time by congestion levels**. This means that a simple generic coefficient for travel time could be replaced with the coefficients differentiated by congestion levels.
- Inclusion and estimation of additional utility components of which **travel time reliability** has been identified as the most important component. Reliability is seen as an additional and non-duplicating term along with the average travel time and cost.

- Testing more complicated functional forms that are **non-linear in time and cost**, as well as accounting for randomly distributed coefficients or VOT (in addition to any explicit segmentation accounting for the observed user heterogeneity). With these enhancements, VOT is not assumed as a constant, but as a varying parameter depending on the absolute values of time and cost as well as reliability.

As a working model we adopt the following general expression for the highway travel utility that will be explored component-by-component in the current research:

Equation 38: $U=\sum_{k=1}^{5}\left[a_k\times\varphi_k(T_k)\right]+\sum_{m=1}^{3}\left[b_m\times\phi_m(C_m)\right]+\sum_{n=1}^{3}c_nR_n$,

where:
$k=1$ - uncongested highway travel time component,
$k=2$ - congested highway travel time component (extra delay),
$k=3$ - parking search time,
$k=4$ - walk access/egress time (e.g. from the parking lot to trip destination,
$k=5$ extra time associated with carpooling (picking-up/dropping/off passengers),
T_k = (average) travel time by component,
$m=1$ - highway toll value,
$m=2$ - parking cost,
$m=3$ - vehicle maintenance and operating cost,
C_m = travel cost value by component,
$n=1$ - disutility of time variation (1st measure of reliability),
$n=2$ - schedule delay cost (2nd measure of reliability),
$n=3$ - utility of (lost) activity participation (3rd measure of reliability),
R_n - reliability measures by component.
a_k, b_m, c_n -=- coefficients to be estimated,
$\varphi_k(\ldots), \phi_m(\ldots)$ -=- functions for non-linear transformation of time and cost variables.

This formulation makes it more difficult to calculate VOT although it is still possible in the same way that a Value of Reliability (VOR) can be calculated for the 1st type of reliability measure (assuming that this reliability measure is in min). VOR essentially represents travelers' willingness to pay for reduction in travel time variability in the same way as VOT represents their willingness to pay for (average) travel time savings. More specifically, the VOT (in the context of willingness to pay tolls for saving time in congestion conditions) can be calculated by the following general formula:

Equation 39: $VOT(T_2,C_1)=\frac{\partial U/\partial T_2}{\partial U/\partial C_1}=\frac{a_2\varphi_2'(T_2)}{b_1\phi_1'(C_1)}$.

A similar calculation can be implemented for VOR. With non-linear transformation functions, VOT and VOR are no longer constant values. They now depend on the absolute values of time and cost variables at which the derivatives of the transformation functions are taken.

The innovative components that relate to perceived highway time, travel time reliability, and non-linear transformations are discussed in the subsequent sections. It should be noted that some components, specifically perceived travel time and three reliability measures, might be correlated statistically (and also conceptually duplicative at least to some extent). Thus, it is highly improbable that the entire formula (Equation 38) would ever be applied. It rather serves as a conceptual framework in which particular structures can be derived and tested statistically against each other.

A.3.2. Perceived Highway Time

Perceived transit time has been long recognized and used in travel models. For example, in most mode choice models and transit assignment algorithms, out-of-vehicle transit time components like wait and walk are weighted compared to in-vehicle travel time. It is not unusual to apply weights in the range of 2.0 - 4.0 reflecting that the travelers' perception of out-vehicle time is different and it is perceived as more onerous compared to in-vehicle time.

Contrary to the transit modeling practice, practically all travel models include a generic highway time term, i.e., the same coefficient is applied for each minute of highway time regardless of the travel conditions. However, there is some compelling statistical evidence that highway users perceive travel time differently by congestion levels. For example, driving in free-flow conditions might be very different from driving in heavily congested (stop-and-go) conditions. It is intuitive and behaviorally appealing that highway users driving in congested conditions might perceive the longer travel time as an additional delay or penalty on the top of free-flow (or some expected reasonable) time. In the segmentation of travel time coefficients by congestion levels, the time spent in congestion conditions is expected to have a larger disutility. A larger disutility associated with congestion would have at least two behavioral interpretations:

- Negative psychological perception that is similar to the weight for walking to or waiting for transit service,
- Simplified operational proxy for reliability that should be explored in combination with the explicit reliability measures.

There are several research works reporting statistical evidence of quite high perceptional weights that highway users put on travel time in congested conditions [*NCHRP Report 431, 1999; Axhausen et al., 2006; Levinson et al., 2004; MRC & PB, 2008; Wardman et al., 2008*]. Also, there have been multiple indications in recent analyses of travel surveys that a perception of the time saved by respondents in the Revealed Preference (RP) survey, is about double the actual measured time saved [*Small et al., 2005; Sullivan, 2000*]. In the RP framework, this might well be a manifestation that travelers operate with perceived travel times, where time spent traveling through congested segments is psychologically doubled.

Two examples of estimated perceptions of travel time are discussed below in order to illustrate the magnitude of the weights as well as possible approaches to differentiate travel time by congestion levels. It should be noted that in both cases the approaches are very simple on the supply side. The network simulation can be implemented, and required LOS skims can be generated by static assignment, though DTA could offer additional improvements. This technique can be easily applied with both ABMs and 4-step models.

First example was documented in [*NCHRP Report 431, 1999*]. The travel time was broken into two parts:

- Time in uncongested conditions (LOS A-D),

- Time in congested conditions (LOS E-F that is close to the "stop-and-go" condition).

The choice framework included route choice only presented in the SP survey context. Travel time and cost variables were not estimated but stated in the SP questionnaires. Highway utility expression included total time, cost, and percentage of congested time. Using the previously introduced notation, the adopted utility specification can be written in the following way:

Equation 40: $U = a \times (T_1 + T_2) + b \times C + c \times \frac{T_2}{T_1 + T_2}$.

This is different from the suggested formula (Equation 38), but can be transformed into an equivalent formula with certain assumptions (fixed total travel time). The estimation results confirmed a very high significance of the additional term of percentage of congested time. The authors translated it into a recommended mark-up value of 2.5 to VOT savings under congested conditions compared to uncongested conditions. More detailed estimation results are summarized in **Table 37**. By virtue of the specified utility function, the cost of shifting 1 min from uncongested to congested time is dependent on the total travel time. For an average time of 30 min, the VOT equivalent of the additional perceived burden associated with congestion itself is about $15/hour, which is roughly equal to the average commuting VOT applied in most models.

Table 37: Cost of Shifting 1 Minute from Uncongested to Congested Time

Total travel time, min	Cost of shifting 1 min from uncongested to congested time, $	Equivalent in VOT $/hour
10	0.77	46.2
15	0.51	30.6
20	0.30	18.0
30	0.26	15.6
45	0.17	10.2
60	0.13	7.8

The second example is taken from the recently completed travel demand model for the Ottawa-Gatineau, Canada, region [*MRC & PB, 2008*]. The model framework, choice context, and utility formulation were different from those used in the [*NCHRP Report 431, 1999*] study. However, the bottom-line results look similar in many respects. In this study, a mode choice model was estimated for 5 travel purposes and 2 time-of-day periods (AM and PM) based on the RP data from the large household travel survey (5% of the population that corresponds to 23,870 households in the sample). Travel time and cost variables were provided from static assignment equilibrium skims from the modeled network.

The highway utility included travel cost with one generic coefficient and travel time broken into the following two components (note that this breakdown of travel time is different from the one adopted for [*NCHRP Report 431, 1999*]):

- Free-flow (minimal) time,
- Extra delay, calculated as congested time minus free-flow time for the entire origin-destination path.

The highway utility function had the following form:

Equation 41: $U = a_1 \times T_1 + a_2 \times T_2 + b \times C + \sum_s (d_s \times h_s)$,

where:

s = additional mode-specific constants and household/zonal variables,

h_s = values of additional variables,

d_s = estimated coefficients.

The estimation results are shown in **Table 38,** as translated into VOT terms. They confirm that for several segments, specifically AM and PM work trips, as well as PM discretionary trips, each minute of congestion delay is perceived as about twice as onerous as the free-flow (minimal) time component. For other segments, however, statistical tests did not show a significant difference between free-flow and congestion time components, thus two coefficients were pooled together.

Table 38: VOT Estimates for Free-Flow Time and Congestion Delay

Trip purpose	VOT, $/hour			
	AM		PM	
	Free-flow time	Congestion delay	Free-flow time	Congestion delay
Work	22.2	42.7	19.4	40.0
University	10.0	10.0	11.0	11.0
School	5.1	5.1	5.1	5.1
Maintenance	10.7	10.7	12.1	12.1
Discretionary	9.0	9.0	11.4	29.3

The third example is taken from the research work of *Mark Wardman et al, 2008* where they provided new evidence on the variation in the valuation of motorists' travel time savings across a finer gradation of time types, than has been hitherto attempted (6 different levels of congestion), by means of analyzing SP data collected from different tolled road context in the UK and US. The summary of the time relativities is presented in **Table 39**. The study confirms that a reasonable value for the perceived time weight in congested conditions lies in the range 1.3 to 2.0.

Table 39: Highway Time Weight by Congestion Levels

Travel time conditions	UK	US
Free Flow	1.00	1.00
Busy	1.05	1.03
Light Congestion	1.11	1.06
Heavy Congestion	1.31	1.20
Stop Start	1.20	1.38
Gridlock	1.89	1.79

A.3.3. Reliability Approach 1: Time Variability Measures

Time variability can be measured by any compact measure associated with travel time distribution (for example any combination of the mean, dispersion, and higher moments). Taking into account such considerations as behavioral realism and simplicity of the model estimation (specifically, formulation of SP alternatives), as well as application, three main forms have been proposed and tested so far (see *ITS, 2008* for a good discussion):

- **Standard Deviation**, that is a symmetric measure assuming that being early or late is equally undesirable (probably not a realistic assumption for many trips and underlying activities).
- Difference between 80th, 90th, or 95th and 50th percentile travel times that is frequently referred to as **buffer time**. This is an asymmetric and more behaviorally appealing measure since it specifically targets late arrivals and is less sensitive to early arrivals.
- Simplified asymmetric measures in terms of **probability of certain delays**; delay thresholds such as 15 or 30 min are frequently used in the SP framework.

An illustrative example of the Standard Deviation approach is provided in [*NCHRP Report 431, 1999*] in the context of binary route choice. The following form of utility function was adopted:

Equation 42: $U = a \times T + b \times C + c \times SD(T)$,

where:
$SD(T)$ = standard deviation of travel time.

Standard deviation of travel time was calculated based on the set of 5 travel times presented in the SP questionnaire for each highway route alternative. The estimation results showed that highway users assign a very high value on each minute of standard deviation that is comparable with or even higher than the VOT associated with average travel time itself (i.e., $c \geq a$). Also a certain logical variation across trip purposes and income groups was captured as summarized in **Table 40** (for one of the several reported model specifications).

Table 40: Value of Reliability measured as Standard deviation of Time

Trip purpose and income group	Value of Reliability	
	$ per min SD	$ per hour SD
Work trips, higher income	0.258	15.5
Work trips, lower income	0.215	12.9
Non-work trips, higher income	0.210	12.6
Non-work trips, lower income	0.167	10.0

A good example of the second time variability measure was presented in [*Small, et al., 2005*]. The adopted quantitative measure of variability was the upper tail of the distribution of travel times, such as the difference between the 80th and 50th percentile travel times (see **Figure 81**). The authors argue that this measure is better than a symmetric standard deviation, since in most situations, being "late" is more crucial than being "early", and many regular travelers will tend to build a "safety margin" into their departure times that will leave them an acceptably small chance of arriving late (i.e., planning for the 80th percentile travel time would mean arriving late for only 20% of the trips).

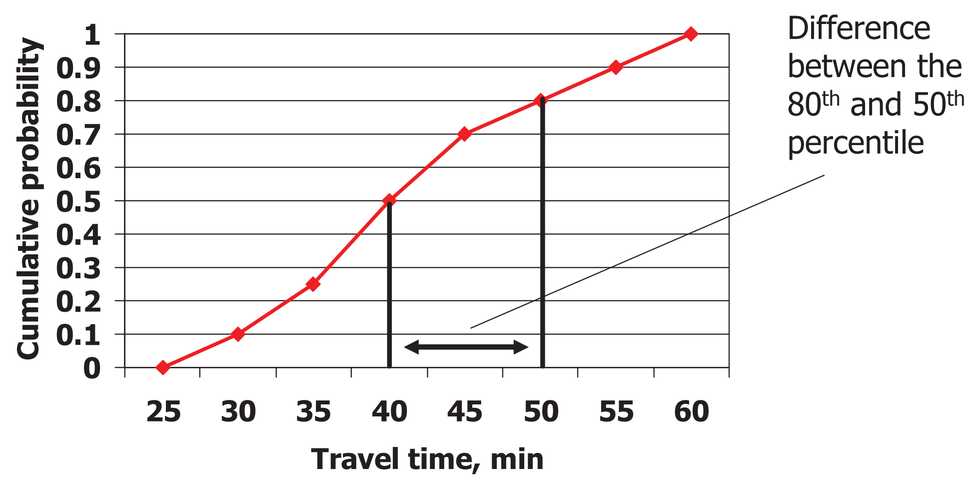


Figure 81: Travel Time Variability Measure

The choice context included binary route choice between the Managed (tolled) Lanes and General Purpose (free) lanes on the section of SR-91 in Orange County, CA. The survey included actual users of the facility and the model was estimated on the mix of RP and SP data. The variation of travel times and tolls was significantly enriched by combining RP data from actual choices with SP data from hypothetical situations that were aligned with the pricing experiment. Distribution of travel times was calculated based on the independently observed data. The measures were obtained from field measurements on SR-91 taken at many times of day, on 11 different days. It was assumed that this distribution was known to the travelers based on their past experience. The utility function was specified by the following formula:

Equation 43: $U = a \times T + b \times C + c \times R(T)$,

where:

$R(T)$ = difference between the 80th and 50th percentile.

Reliability, as defined above, proved to be valued by travelers as highly as the median travel time (VOT was roughly equal to VOR, i.e., $a \approx c$). This particular model form, with the condition of equal VOT and VOR, has a very interesting and intuitive interpretation (that itself could be used for a model formulation in a slightly simplified form where it is assumed from the outset that $a = c$). Indeed, if we assume that willingness to pay for saving 1 min of average travel time (the 50th percentile) is equal to willingness to pay for 1 min of reduction of the difference between the 80th and 50th percentile, then we can combine both terms in the highway utility function since they have the same coefficient. This means that the underlying decision-making variable is the travel time value at the 80th percentile. This variable essentially combines both average travel time and time variation measure.

An example in **Table 41** illustrates this possible approach. In the example, we assume that the highway user has to choose between two roads for commuting that are characterized by different time distributions. Road 1 is longer but more reliable – the travel time varies from 41 min to 50 min. Road 2 is shorter but travel time is less predictable and varies from 29 min to 52 min. We assume that the highway user is familiar with both roads and makes his/her choice based on a rational consideration of the known distributions. In practical terms, this can be interpreted as a recollection of at least 10 trips on each road in the past, sorted by travel times from the best to worst.

Table 41: Illustration of Reliability Impact

Percentile	Travel time, min		Preference
	Road 1	Road 2	
10	41	29	
20	42	30	
30	43	35	
40	44	39	
50	45	40	Road 2 by conventional approach
60	46	41	
70	47	45	
80	48	50	Road 1 by suggested approach
90	49	51	
100	50	52	

Although Road 2 has a better (lower) average travel time and would be preferred in most conventional modeling procedures, Road 1 has a better 80th percentile measure. In reality, the user would probably prefer Road 1 as the more reliable service. This choice framework with a single measure can be used as a simplified version of the approach. Rather than estimating two separate terms (average travel time and additional time associated with 80th-50th percentile, a single measure of 80th (or any other percentile large than 50th if yields a better statistical fit) could be used. For example, in a similar context, a 90th percentile measure was used in [*Brownstone & Small, 2005*]. This framework is based on a plausible assumption that travelers under congestion conditions, characterized by travel time uncertainty, behave as rational risk-minimizers. They do not base their decisions on the average values. However, they do not adopt the extreme mini-max approach (minimize risk and choose according to the worst possible case) either. The decision point probably lies somewhere between the 80th and 90th percentiles.

It is important to note that making this approach operational within the framework of regional travel models requires explicit deriving these measures from simulation of travel time distributions, as well as adopting assumptions regarding the ways in which travelers acquire information about the uncertain situation they are about to experience. DTA and traffic microsimulation tools are crucial for the application of models that include explicit travel time variability, since static assignment can only predict average travel times.

Other approaches for measuring variability of travel time can also be considered. They are similar to the approach described above in conceptual terms, but use a different technique in both the estimation and the application stages. For example, in the travel model developed by for the [*Toll T&R Study in Montreal, 2002*], probability of delays longer than 15 and 30 min was introduced in the SP questionnaires for trucks. The subsequent estimation of the choice model revealed a very high significance of this variable comparable with the total trip time (in line with the VOR estimation of *Small, et al., 2005*). Application of this model required special probability-of-delay skims that were calculated based on the observed statistics of delays as a function of the modeled Volume-over-Capacity (V/C) ratio. Although this technique requires a multi-day survey of travel times and speeds, it can be applied in combination with the static assignment method. Many regions with continuous traffic monitoring equipment now have such data available for important highway segments. A problem yet to be resolved, however, is that when calculating the travel time reliability measure over the entire origin-destination path, the highway links cannot be considered independent.

Reliability is closely intertwined with VOT. In RP models, if variability is not measured explicitly and included as a variable, this omission will tend to inflate the estimated value of average time savings. In reality, variability in travel time tends to be correlated with the mean travel time, and people are paying for changes in both variables, so omitting one will tend to attribute the total effect to the other. Consequently, an important use SP data sets that include reliability, is to use them in combination with RP data sets for which good objective estimates of travel time variability can be derived.

It should be mentioned that the direct using of travel time variability in the behavioral modeling framework is not the most appealing approach, compared to the other two (discussed below). The principal conceptual drawback of this approach is that it does not explicitly consider the nature of underlying activities and mechanisms that create the disutility. Needless to say, the largest part of disutility associated with unreliable travel time is being late (or too early) at the activity location, and consequently, losing some part of the planned activity participation. The practical advantage of the time variability approach, however, is in its relative simplicity and exclusive reliance on the data supplied by the transportation networks.

A.3.4. Reliability Approach 2: Schedule Delay Cost

This approach has been widely accepted by the research community since its inception [*Small, 1982*]. According to this approach, the impact of travel time (un)reliability is measured by explicit cost associated with the delayed or early arrival at the activity location. This approach considers a single trip at a time and assumes that the preferred arrival time that corresponds to zero schedule cost is known. The essence of the approach is that the trip cost (i.e., disutility) can be calculated as a combination of the following three components:

α = value of travel time and cost,

β = cost of arriving earlier than the preferred schedule,

γ = cost of arriving later than the preferred schedule.

By definition, only one of the schedule costs can have a non-zero value in each particular case depending on the actual arrival time versus the preferred one. There can be many analytical forms for the schedule cost as a function of the actual time difference (delay or early arrival). It is logical to assume that both functions should be monotonically increasing with respect to the time difference. It is also expected, in most cases, that the schedule delay function should be steeper than the early arrival function for most activities (being late is more onerous than being earlier). The details, however, depend on the activity type, person characteristics, and situational context.

The most frequently used forms include simple linear function (i.e., constant schedule delay cost per minute), non-linear convex function (assuming that large delays are associated with growing cost per minute), and various piece-wise functions accounting for fixed cost associated with any delay along with a variable cost per minute – see **Figure 82**.

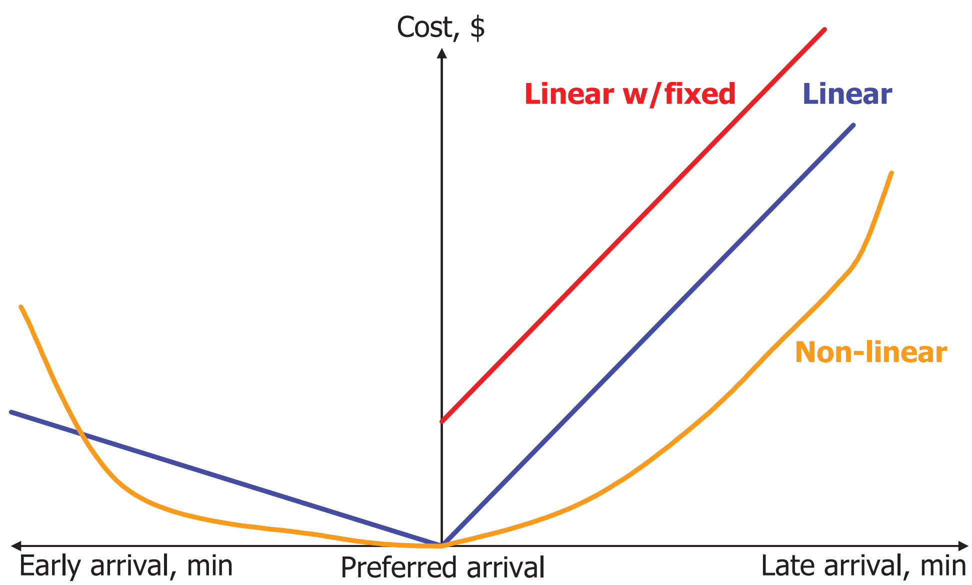


Figure 82: Schedule Delay Cost

An example of a schedule delay model estimated in a highway route choice context with a specially designed SP survey is given in [*NCHRP Report 431, 1999*]. The utility function was specified in the following way:

Equation 44: $U = a \times T + b \times C + c \times SD(T) + \beta(\Delta t) + \gamma(\Delta t)$,

where:

Δt = difference between actual and preferred arrival time,

$\beta(\Delta t)$ = early arrival cost specified as a non-linear convex function,

$\gamma(\Delta t)$ = late arrival cost specified as a linear function with a fixed penalty.

The estimation results with respect to the schedule delay cost are summarized in **Table 42** (for one of the tested model specifications). Interestingly, as reported by the authors, in the presence of explicit schedule delay cost, the travel time variability measure (standard deviation) lost its significance. The authors concluded that in models with a fully specified set of schedule costs, it is unnecessary to include the additional cost of unreliability of travel time.

Table 42: Estimation of Schedule Delay Cost

Component	Marginal values, $
Early arrival (non-linear):	
- by 5 min	0.028/min
- by 10 min	0.078/min
- by 15 min	0.128/min
Late arrival dummy:	
- work trips	2.87
- non work trips	1.80
Late arrival (linear)	0.310/min
Extra late arrival dummy	0.98

Schedule delay cost should be distinguished from TOD choice and the associated disutility of shifting the planned (preferred) trip departure/arrival time, although in practical estimation analysis, the data might mix these two factors. To clearly distinguish between the planned schedule and schedule delay, the person should explicitly report actual and preferred arrival time for each trip. Schedule delay cost assumes that the person has planned a certain schedule, but in the implementation process on the given day the delay occurs to disturb this plan. TOD choice relates to the stage of schedule planning. The outcome of this process is the preferred arrival time.

Comparing schedule delay to time variability as two different measures of time reliability, it should be noted that the schedule delay approach provides a better behavioral insight than travel time variability. It explicitly states the reasons and attempts to quantify the factors of the disutility associated with unreliable travel time, specifically perceived penalties associated with not being at the activity location in time. The schedule delay approach, however, has its own theoretical limitations as identified by the following:

- The approach is applied separately for each trip made by a person during the day and it is assumed that the schedule delay cost for each subsequent trip is independent of the previous trip. Technically this approach is based on a fixed departure time and a preferred arrival time for each trip. In general, this is not a realistic assumption, since the activity duration requirements would create a dependence of the departure time for the next trip on the arrival time for the previous trip.
- This approach does not consider activity participation explicitly, though it makes a step towards such a consideration compared to the travel time variability approach.
- If applied for the evaluation of user benefits from travel time savings, this approach must incorporate TOD choice, i.e., travelers' reconsideration of departure time in response to the

changed congestion. Otherwise, travel time savings can result in early arrival penalties overweighting the value of saved travel time.

On the practical side, in order to be implementable, the schedule delay approach imposes several requirements that are not easy to meet, especially with the conventional RP surveys:

- For each trip, in addition to the actual arrival time, the preferred arrival time should be identified. While the preferred arrival time is generally known to the traveler (or perceived subconsciously), it is generally not observed by the modeler in RP type of data. To explore this phenomenon and estimate models that address it, the SP framework proved to be very effective, since the preferred arrival time and schedule delays can be stated in the design of alternatives. In some research, simplified assumptions about the preferred arrival time were adopted. For example, in [*Tseng & Verhoef, 2008*], the preferred arrival time was calculated as a weighted average between the actual departure time and would-be arrival time under free-flow traffic conditions.
- Application of this model for forecasting would again require input in the form of preferred arrival times. This can be accomplished either by means of external specification of the usual schedules on the activity-supply side (that would probably be possible for work and fixed non-work activities), or by means of a planned schedule model on the demand side. The latter would generate individual schedule plans (departure times) based on the optimal activity durations conditional upon the average travel times. The subsequent simulation (plan implementation) model would incorporate schedule delay cost based on the simulated travel times.

A.3.5. Reliability Approach 3: Lost Utility of Activity Participation

The third approach is based on a concept of time-dependent utility profile by activity type [*Supernak, 1992; Kitamura & Supernak, 1997*]. Recently this approach was adopted in several research works on DTA formulation integrated with activity scheduling analysis [*Kim at al., 2006; Lam & Yin, 2001*]. The essence of this approach is that each individual has a certain temporal utility profile for each activity that is characterized by function *U(t)*. The utility profile can either be estimated as a parametric or a non-parametric function of time and time can be modeled in either continuous or discrete form. The utility profile represents an instant utility of participation in the activity at the given point of time (or during the discrete time unit that starts at the given point of time). The total utility of participation in the activity can be calculated by integrating the utility profile from the arrival time (τ) to departure time (π):

Equation 45: $U(\tau,\pi)=\int_{\tau}^{\pi}U(t)dt$.

Simple utility profiles are independent of the activity duration. In this case, it is assumed that the marginal utility of each activity at each point of time is independent of the time already spent on this activity. This might be too simplifying an assumption, at least for certain activity types like household maintenance needs where the activity loses its value after the errands have been completed. More complicated utility profiles can be specified as two-dimensional functions *U(t,d)* where d denotes the activity duration until moment *t*. In this case, the total utility of activity participation can be written as

Equation 46: $U(\tau,\pi)=\int_{\tau}^{\pi}U(t,t-\tau)\,dt.$

Hypothetical, but typical temporal utility profiles specified in a discrete space with an hourly resolution are shown in **Figure 83**. The work activity profile is adjusted to reflect the fixed schedule requirements (higher utility to be present at 8.00 AM and 5:00 PM points). The shopping activity profile is much more uniform, with an additionally assumed convenience to undertake this activity after usual work hours.

Figure 83: Example of Utility Profiles

The concept of utility profiles is instrumental in understanding how individuals construct their daily activity schedules. According to this concept, each individual maximizes a total daily utility of activity participation. If we consider a predetermined sequence of activity episodes, it can be said that individuals switch from activity to activity when the time profile of the second activity exceeds the time profile of the previous activity. Travel episodes are placed between activity episodes in such a way that the whole individual daily schedule represents a continuous sequence of time intervals as shown in Figure 84.

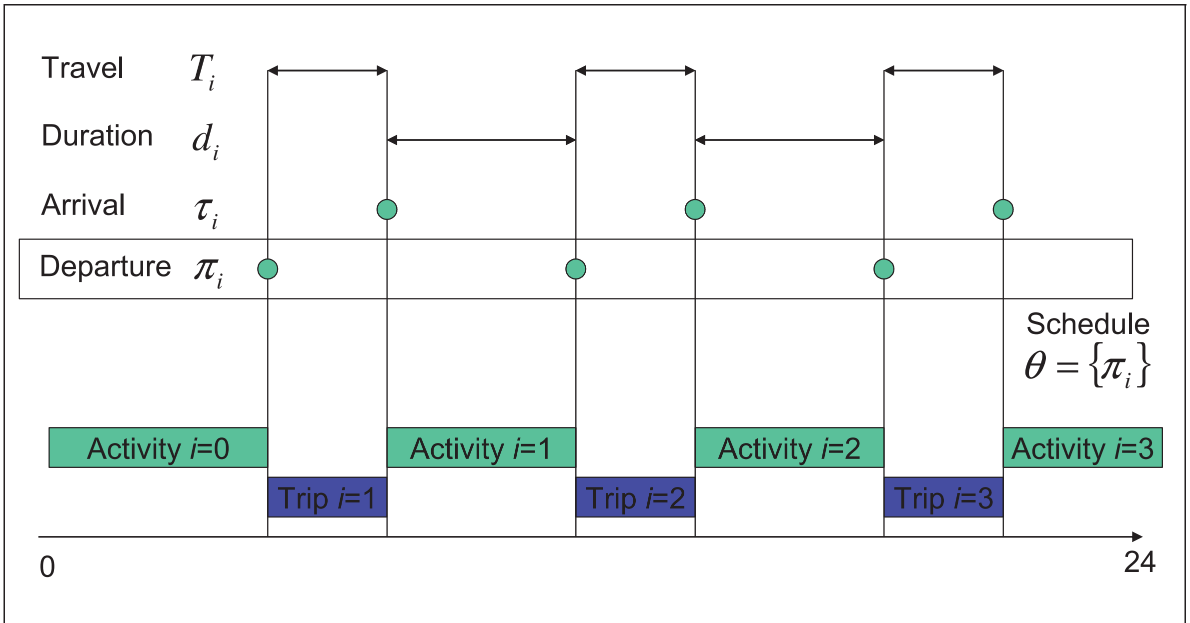


Figure 84: Consistent Individual Daily Schedule

The effect of unreliability of travel times can be directly measured by comparison of the planned and actual total daily utility of the schedule that includes all activity and travel episodes. For simplicity, but without essential loss of generality, we assume that the sequence of activity episodes and trip departure times are fixed. We will also assume that travel time delay never exceeds the planned duration of the subsequent activity; thus, activities cannot be cancelled as a result of unreliable travel time. Thus, unreliability affects only travel times and arrival times. In this context, the reliability measure can be expressed as the loss of activity participation in the following way:

Equation 47: $L = \sum_i \left(U_i^P - U_i^A\right)$,

where:

L	=	total user loss (disutility) over the whole schedule,
U_i^P	=	utility of the trip and subsequent activity with preferred arrival time,
U_i^A	=	utility of the trip and subsequent activity with actual arrival time,

where the planned and actual utilities can be written as follows:

Equation 48: $U_i^P\left(\tau_i^P\right) = a \times T_i^P + b \times C_i^P + \int_{\tau_i^P}^{\pi_{i+1}} U_i(t)dt$,

Equation 49: $U_i^A\left(\tau_i^A\right) = a \times T_i^A + b \times C_i^A + \int_{\tau_i^A}^{\pi_{i+1}} U_i(t)dt$,

where:
Equation 50: $T_i^P = \tau_i^P - \pi_i$; $T_i^A = \tau_i^A - \pi_i$.

By substituting expression (Equation 50) into formulas (Equation 48) and (Equation 49), and then, substituting formulas (Equation 48) and (Equation 49) into the basic expression (**Equation 47**) we obtain:

Equation 51: $L = \sum_i \left[a \times \left(\tau_i^P - \tau_i^A \right) + b \times \left(C_i^P - C_i^A \right) + \int_{\tau_i^P}^{\tau_i^A} U_i(t) dt \right]$,

where the last term (integral) represents the loss of activity participation, while the first two terms represent extra travel time and cost.

A logical relationship between temporal activity profiles of utilities and schedule delay cost was explored by [*Tseng & Verhoef, 2008*] that led to an insightful general framework. It can be shown that these two approaches are not independent. The schedule delay cost functions can always be consistently derived from the temporal utility profiles; thus, the schedule delay approach can be thought of as a particular transformation of the temporal utility profile approach. Interestingly, the opposite is true, i.e., temporal utility profiles could be fully restored from the schedule delay cost functions only under some specific assumptions.

To illustrate the relationship between temporal utility profile and schedule delay cost, consider two adjacent activities in the daily schedule with a trip between them as shown in **Figure 85**. In this fragment of the daily schedule, we assume that the temporal utility profile of the 1st activity is monotonically decreasing, while the 2nd one is monotonically increasing. We also number the trip as the 2nd one (according to the activity at trip destination), to be consistent with the natural numbering shown in Figure 84. With an (ideal) zero trip time between the activities, the rational individual would switch from the 1st activity to the 2nd activity at the intercept point to ensure a maximum total utility. With a non-zero trip time, the optimal strategy would be to depart at such time that the departure-time utility of the first activity would be equal to the arrival-time utility of the second activity.

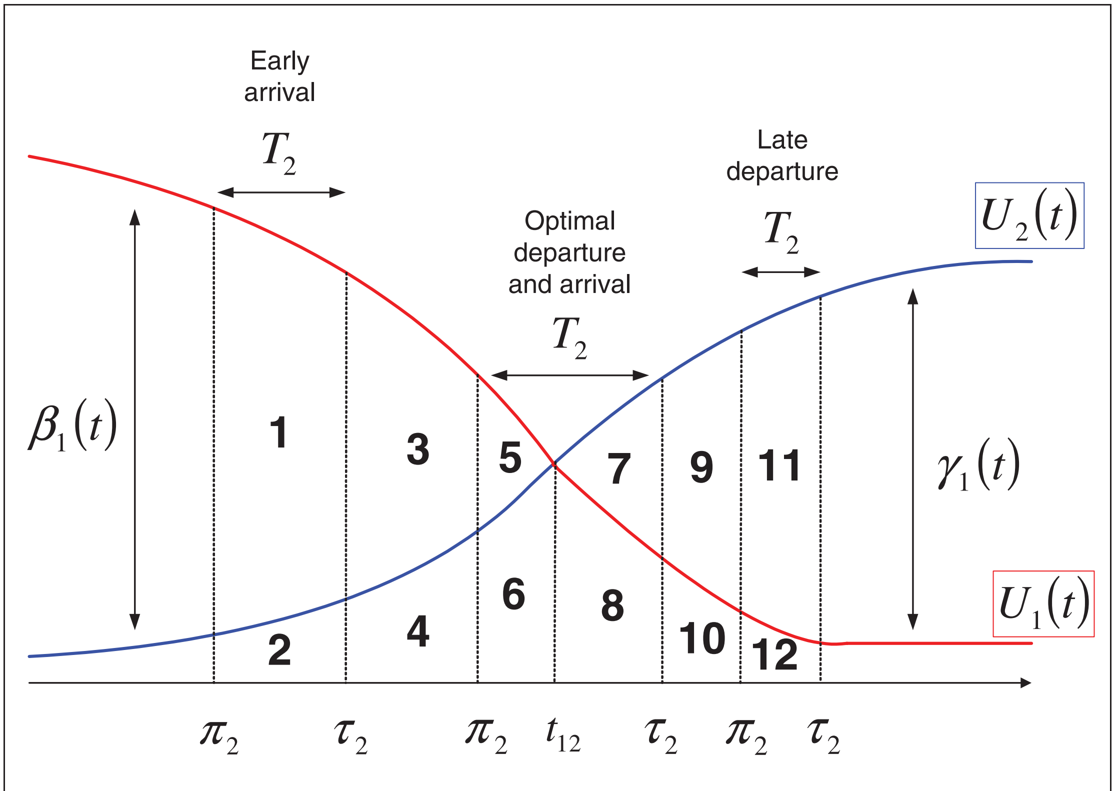


Figure 85: Example of Two Adjacent Activities

We can distinguish between three possible cases as shown in the figure:

$\pi_2 \le t_{12} \le \tau_2$ = optimal departure before the intercept point and arrival after it,

$\pi_2 < \tau_2 < t_{12}$ = arrival earlier than the intercept point,

$t_{12} < \pi_2 < \tau_2$ = departure later than the intercept point.

It is natural to specify schedule delay cost function in such a way that it should be equal to zero when the travel time is equal zero and the trip is perfectly timed at the intercept point. It is also natural to refer to the intercept point as the ideal preferred arrival time. In the general case, with non-zero travel time and a not perfectly timed trip, there are two ways to constructively derive the total trip cost from the temporal utility functions with the cost components interpreted as schedule delay cost. In both ways we calculate trip cost as a sum of the following three components:

Equation 52: $C_2(\pi_2,\tau_2)=\alpha_2(\pi_2,\tau_2)+\beta_2(\pi_2,\tau_2)+\gamma_2(\pi_2,\tau_2)$,

where:

$\alpha_2(\pi_2,\tau_2)$ = travel cost,

$\beta_2(\pi_2,\tau_2)$ = cost of arriving earlier,

$\gamma_2(\pi_2,\tau_2)$ = cost of departing/arriving late.

The first way is to derive trip cost components as follows:

Equation 53: $\alpha_2(\pi_2,\tau_2)=\int_{\pi_2}^{\tau_2}\alpha_2(t)dt=\int_{\pi_2}^{\tau_2}\max[U_2(t),U_1(t)]dt$,

(loss of maximum activity utility when traveling),

Equation 54: $\beta_2(\pi_2,\tau_2)=\int_{\tau_2}^{t_{12}}\beta_2(t)dt=\int_{\tau_2}^{t_{12}}[U_1(t)-U_2(t)]dt$,

(non-optimal 2nd activity if arrived early $\tau_2 < t_{12}$),

Equation 55: $\gamma_2(\pi_2,\tau_2)=\int_{t_{12}}^{\pi_2}\gamma_2(t)dt=\int_{t_{12}}^{\pi_2}[U_2(t)-U_1(t)]dt$,

(non-optimal 1st activity if departed late $\pi_2 > t_{12}$).

The second way uses a different structural allocation of the same total cost:

Equation 56: $\alpha_2(\pi_2,\tau_2)=\int_{\pi_2}^{\tau_2}\alpha_2(t)dt=\int_{\pi_2}^{\tau_2}U_1(t)dt$,

(loss of 1st activity utility when traveling),

Equation 57: $\beta_2(\pi_2,\tau_2)=\int_{\tau_2}^{t_{12}}\beta_2(t)dt=\int_{\tau_2}^{t_{12}}[U_1(t)-U_2(t)]dt$,

(non-optimal 2nd activity if arrived early $\tau_2 < t_{12}$),

Equation 58: $\gamma_2(\pi_2,\tau_2)=\int_{t_{12}}^{\tau_2}\gamma_2(t)dt=\int_{t_{12}}^{\tau_2}[U_2(t)-U_1(t)]dt$,

(loss of added 2nd activity in travel and late departure $\tau_2 > t_{12}$).

To verify that both ways produces the same total cost and also highlight the differences between them, we summarize all components in **Table 43**. Also, all cost components are related to the areas 1-12 of integration under the temporal utility curves shown in **Figure 85**.

Table 43: Trip Cost Components

Case	Component	Areas of Integration in **Figure 85**	
		1st way	2nd way
$\pi_2 \le t_{12} \le \tau_2$: departure earlier the intercept and arrival later the intercept	$\alpha_2(\pi_2,\tau_2)$	5,6,7,8	5,6,8
	$\beta_2(\pi_2,\tau_2)$		
	$\gamma_2(\pi_2,\tau_2)$		7
$\pi_2 < \tau_2 < t_{12}$: arrival earlier than the intercept	$\alpha_2(\pi_2,\tau_2)$	1,2	1,2
	$\beta_2(\pi_2,\tau_2)$	3,5	3,5
	$\gamma_2(\pi_2,\tau_2)$		
$t_{12} < \pi_2 < \tau_2$: departure later than the intercept	$\alpha_2(\pi_2,\tau_2)$	11,12	12
	$\beta_2(\pi_2,\tau_2)$		
	$\gamma_2(\pi_2,\tau_2)$	7,9	7,9,11

In either way of derivation, the schedule delay cost is associated with functions that represent a difference between the temporal utility profiles. The cost of early arrival is associated with the extra utility of the first activity (when it is higher than the utility of second activity). In the same vein, the cost of late arrival is associated with the extra utility of the second activity (when it is higher than the utility of first activity). In other words, schedule-related cost corresponds to participation in non-optimal activity because of the not-optimally-timed trip. This was formalized in the expressions (Equation 54, Equation 55, Equation 57, Equation 58) in the following straightforward way:

Equation 59: $\beta_2(t) = U_1(t) - U_2(t)$,
Equation 60: $\gamma_2(t) = U_2(t) - U_1(t)$.

The only difference between the two methods of derivation is in the formulation of the travel cost function and the area of integration for the schedule delay cost for a late arrival. The first way is probably more natural and appealing. In this case, travel cost is associated with the lost (maximum) utility of activity participation when traveling, while the schedule-related cost components are associated with participation in non-optimal activity. However, it operates with both departure and arrival times. Regrouping the cost in the second way allows for expression of both schedule-related cost components in terms of arrival time only. The essence of the second approach is that the extra utility of the second activity over the first activity at the time of traveling (areas 7 and 11 in **Figure 85**) is transferred from the travel cost component to the schedule delay (late arrival) component.

In the second method, the travel cost component might not look behaviorally intuitive since it is associated with the utility of first activity only. However, it should be mentioned that activity utilities are set in an arbitrary scale and only the difference between them is important. Essentially, one of the activities could be chosen as a reference point with zero utility. Thus, the difference between the two approaches is purely definitional. The second method of derivation is more convenient to operate with schedule delay functions depending on the arrival time only. Additionally, the difference between the two approaches is only important when schedule delay cost components are analytically derived from the estimated temporal utilities by formulas (Equation 53-Equation 55) and (Equation 56-Equation 58). If the schedule delay cost components as specified by formula (Equation 52) are estimated directly, the difference is irrelevant since the same explanatory variables can enter any component. However, if the schedule-related cost functions are estimated based on the arrival time only, the second approach would still be more consistent with this method of specifying the schedule delay cost function.

With the assumptions on the form of the temporal utility functions, as shown in **Figure 85** for a case of two adjacent activities in a fixed order, and with a known intercept (preferred arrival time), it is also possible to restore temporal utility profiles from the known travel cost and schedule delay functions in the following way:

Equation 61: $U_1(t)=\alpha(t)$,

Equation 62: $U_2(t)=\begin{cases}\alpha_2(t)-\beta_2(t), & \text{for } t<t_{12}\\ \alpha_2(t), & \text{for } t=t_{12}\\ \alpha_2(t)+\gamma_2(t) & \text{for } t>t_{12}\end{cases}.$

Thus, for a simple case under the assumptions explained above, there is no essential difference between the schedule-delay-cost approach and temporal-utility-profile approach. They just represent different ways of grouping the same utility/cost components. The direct analogy does not hold however, when more than two activities are considered (and not necessarily in a fixed order) or when the underlying utility profiles are more complicated and the preferred arrival times cannot be established for each trip (pair of adjacent activities) independently. In this case, utility profiles still provide a comprehensive framework for calculation of the loss of activity participation, while schedule delay cost components are bound to a particular order of activities and trips with predetermined preferred arrival time.

With certain additional simplifying assumptions the analogy between the schedule-delay-cost approach and temporal-utility-profile approach can remain valid for multiple activities/trips. Consider a situation where the sequence of activities is fixed and the daily schedule can be broken into fragments where only two activities are feasible with the preferred arrival time defined for each fragment. For example, if we have three activities in the daily pattern "home-work-home" with two trips between them, the first fragment would include (following the numbering convention in Figure 84) the 0^{th} and 1^{st} activities (home and work) and the second fragment would include the 1^{st} and 2^{nd} activities (work and home). The first fragment would include the outbound work commuting leg, while the second fragment would include the inbound work commuting leg.

Then, schedule delay cost can be derived from the utility profiles independently for each trip within each correspondent fragment by formulas (Equation 57 and Equation 58). Also, the utility profiles can be restored from the schedule delay cost of the 1^{st} trip, for the 0^{th} and 1^{st} activities and from the schedule delay cost of the 2^{nd} trip, for the 1^{st} and 2^{nd} activities by formulas (Equation 61 and Equation 62). Then, if needed, the utility profiles in one of the fragments can be shifted to ensure continuity of the entire utility profile for the 2nd activity (work) across both fragments. This technique can be applied recursively to any number of activities. It is however, extremely "fragile" and fails if one of the simplifying assumption does not hold.

Thus, the concept of temporal utility profiles, that considers travel time unreliability effects as the loss of activity-participation utility, is probably the most holistic among the three possible approaches outlined above. It offers more complete behavioral insight than the travel time variability and schedule delay approaches. It also provides a better platform for the calculation of User Benefits from travel time savings and reliability improvements, including small and discontinuous savings.

This concept, however, also has limitations. On the theoretical side, it is based on a very strong assumption that the temporal utility profiles can be measured independently for each activity, and, as a result, the daily schedule utility represents just the sum of them. In reality, the utility of one activity can be a strong function of participation and duration of the other activities. This is quite obvious with several episodes of the same or similar activity types. There are multiple effects related to saturation, satiation, and time-space/budget constraints that make the utility profiles interdependent across activity episodes. From this perspective, a microeconomic framework that distinguishes between direct and indirect utility functions holds promise. However, such a framework has not yet been operationalized in travel demand modeling.

For practical applications, this approach requires estimation of the temporal utility profiles on the demand side. This is a realistic task using econometric methods, although it might result in quite complicated structures and would require a large (household type) survey. Conceivably, application of such a model would require an explicit modeling of a planned daily schedule for each individual, taking into account expected average travel times with a subsequent network simulation, and calculation of the utility loss because of the actual travel times that are different from the expected travel times.

A.4. Advanced Time-of-Day Models with Enhanced Temporal Resolution

The model of this type that is the found in current practice was first estimated and applied as part of the Columbus ABM [*Vovsha & Bradley, 2005*]. Since then, the approach has been employed for other ABMs in Atlanta, San-Francisco Bay Area, Denver, Sacramento, San-Diego, and Phoenix. The model is essentially a discrete choice construct that operates with tour departure-from-home and arrival-back-home time combinations as alternatives. The proposed utility structure based on "continuous shift" variables, represents an analytical hybrid that combines the advantages of a discrete choice structure (flexible in specification and easy to estimate and apply) with advantages of a duration model (parsimonious structure with a few parameters that support any level of temporal resolution including continuous time). The hybrid model originally applied in Columbus had a temporal resolution of 1 hour that is expressed in 190 hour-by-hour departure-arrival time alternatives. The subsequent modifications in Atlanta and Denver used a finer temporal resolution of 30 min that can be achieved with only minor complications.

The model is applied sequentially for all tours in the individual Daily Activity Pattern (DAP) according to the predetermined priority of each activity type. The enhanced temporal resolution allows for applying direct availability rules for each subsequently scheduled tour to be placed in the residual time window left after scheduling the tours of higher priority. This conditionality ensures a full consistency for the individual entire-day activity and travel schedule as an outcome of the model.

This formulation for the variables is not restrictive since most of the household, person, and zonal characteristics in the TOD model are naturally generic across time alternatives. However, network level-of-service variables vary by time-of-day, and are specified as alternative-specific (based on the departure and arrival time of each alternative). Using generic coefficients and variables associated with either departure period, arrival period, or duration, creates a compact structure of the choice model where the number of alternatives can be arbitrarily large (depending on the chosen time unit scale) but the number of coefficients to estimate is limited to a reasonable number. Duration variables can be interpreted as "continuous shift" factors that parameterize the termination rate in such a way that if the coefficient multiplied by the variable is positive, it means that the termination rate is getting lower and the whole distribution is shifted to the longer durations. Negative values work in the opposite direction, collapsing the distribution towards shorter durations.

For a practical implementation of the proposed model, the utility functions for all (multiple) alternatives should be specified in a parsimonious way. In the ABM structure, the tour-scheduling model is placed after the destination choice and before mode choice. Thus, the destination of the tour and all related destination and origin-destination attributes are assumed known and can be used as variables in the model estimation.

The choice alternatives are formulated as tour departure from home-arrival at home hour combinations (g,h), while mode choice log-sums and bias constants are related to multi-hour departure-arrival periods (s,t). Tour duration is calculated as the difference between the arrival and departure hours ($h-g$), and incorporates both the activity duration and travel time to and from the main tour activity including intermediate stops.

The tour TOD choice utility has the following general form:

Equation 63: $V_{gh} = V_g + V_h + D_{h-g} + \mu \ln\left(\sum_m V_{s(g),t(h),m}\right)$,

where:

V_g, V_h	=	departure and arrival time specific components,
D_{h-g}	=	duration-specific components,
m	=	entire-tour modes,
V_{stm}	=	tour mode utility by mode *m*, leaving home in period *s* and returning home in period *t*,
μ	=	mode choice Logsum coefficient.

For model estimation the following practical rules can be used to set the alternative departure-arrival time combinations:

- Each reported/modeled departure/arrival time is rounded to the nearest half-hour. So, the hour "17" includes all times from 16:45 (4:45 PM) to 17:14 (5:14 PM).
- Any times before 5 (5 AM) are shifted to 5, and any times after 23 (11 PM) are shifted to 23. This results in a shift for typically relatively few cases, and limits the number of half-hours in the model to 38.
- Every possible combination of the 38 departure half-hours with the 38 arrival half-hours where the arrival half-hour is the same or later than the departure hour is an alternative. This gives 38 × 39 / 2 = 741 choice alternatives.

To specify the model as parsimoniously as possible, departure/arrival constants are only applied for seven TOD periods that can be specified, for example, as follows:

- 5 to 6 (early morning),
- 6 to 9 (AM peak),
- 9 to 12 (early midday),
- 12 to 15 (late midday),
- 15 to 19 (PM peak),
- 19 to 21 (evening),
- 21 to 23 (late night).

The network simulations to obtain travel time and cost skims can be implemented for even broader periods, for example:

- AM peak,
- Early midday,
- Late midday,
- PM peak,
- Night (including early morning, evening, and late night).

The mode-choice log-sums will be used for all relevant combinations of the five time periods above. This structure, however, is only limited by the number of traffic and transit assignments implemented at each global iteration. It could include more TOD periods for network simulation with ultimately approaching a resolution of dynamic traffic assignment. In particular, peak hour 7-8 AM can be singled out of the AM period and distinguished from the AM shoulders (6-7, 8-9). This would lead to a network simulation system with six TOD periods, which is manageable.

The predetermined hierarchy of tours by travel purpose and activity setting (individual/joint) is assumed in the scheduling procedure. This hierarchy is based on the general principle on which the most activity-based tour-based models are built. According to this principle, people first make decisions regarding their mandatory activities (work/university/school). Then, conditional upon scheduling the mandatory activities, they schedule joint non-mandatory activities – maintenance and discretionary – of which maintenance (shopping, escorting other persons, and various other household maintenance activities) is generally considered of higher priority compared to discretionary activities (leisure and eating-out). Finally, having scheduled mandatory and joint activities, each household member schedules individual activities within the residual time window remaining after making any mandatory and joint tours.

When a person undertakes several activities (tours) of the same priority in the course of the day, those tours are prioritized in a chronological order, i.e. the earlier tour is scheduled first, while the later tour is scheduled next conditional upon the departure/arrival time combination of the first tour, and also forcing the second tour to be scheduled after the first tour (even if there is an available residual window before the first tour).

By using the rules described above, all tours of each surveyed individual can be unambiguously ordered by scheduling priority. The residual time window and set of available TOD alternatives are defined for each subsequent tour conditional upon scheduling of the previously processed tours.

A.5. Explicit Modeling of Joint Travel

An explicit modeling of joint travel constitutes one of the primary advantages of the ABM paradigm. In the basic ABM structure, only joint travel for non-mandatory activities is modeled explicitly in the form of fully joint tours (where all members of the travel party travel together from the very beginning to the end and participate in the same activity). This typically accounts for more than 50% of joint travel. Other types of joint travel like carpooling of workers and escorting children can also be considered as optional extensions.

Each fully-joint tour is considered as a unit of modeling with a group-wise decision making regarding the primary destination, mode, frequency and location of stops etc. Formally, modeling joint activities involves two linked stages:

- **Generation** stage that generates the number of joint tours by purpose/activity type made by the entire household. This is the Joint Tour Frequency Model.
- **Participation** stage at which the decision whether to participate or not in each joint tour is made for each household member and tour. This is the Joint Tour Participation Model. For analytical convenience this model is broken into two sub-models: 1) travel party composition, and 2) person participation choice.

A.5.1. Household Generation of Joint Tours

For this sub-model, the number of travel purposes is limited to 4-5 non-mandatory activities (shopping, maintenance, discretionary, eating-out, visiting relatives and friends) and the observed maximum total number of fully joint tours implemented by a household during a regular workday is limited to 2-3. A simultaneous frequency-choice model can be formulated that would cover all possible frequencies and purpose combinations [*Vovsha et al, 2003*]. A structure adopted in the Columbus model (and subsequently applied in the Atlanta, San Francisco Bay Area, San Diego, and Phoenix ABMs with minor modifications) included 5 purposes and maximum of 2 joint tours that resulted in 21 alternatives – see **Figure 86.**

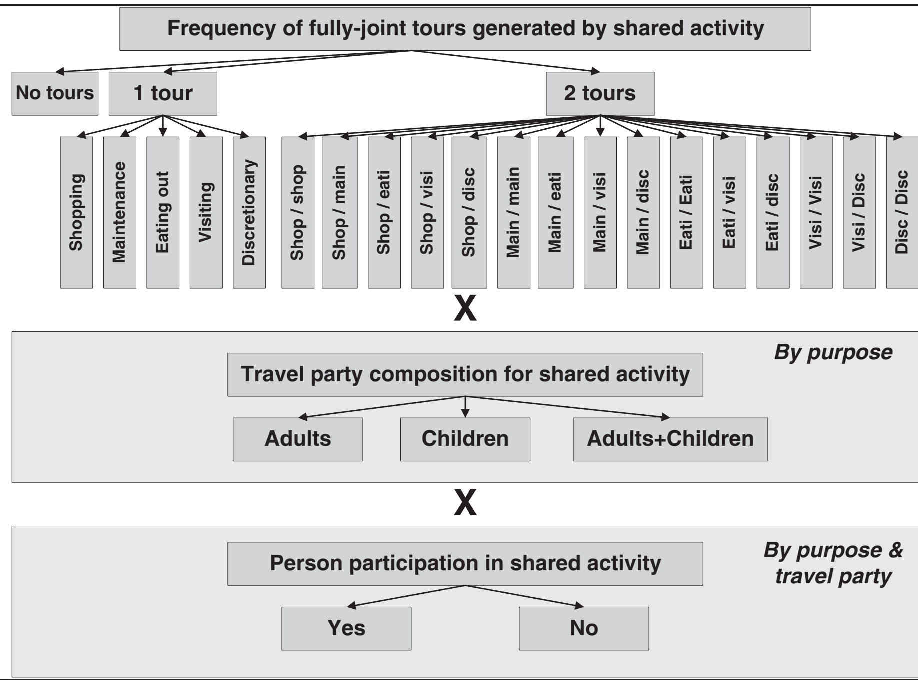


Figure 86: Model Structure for Joint Non-Mandatory Activity

Application experience of this sequential structure (tour frequency, party composition by tours, person participation by persons) in Columbus has shown that is performs well in practical terms.

A.5.2. Travel Party Composition

Travel party composition is defined in terms of person categories participating in each tour (adults and children). It results in a trinary choice model with the following alternatives as shown in **Figure 86** above:

- Adult party (including adult household members only),
- Children's party (including household children only),
- Mixed party where at least one adult and at least one child participate.

The statistical analysis and model estimation has shown a strong linkage between trip purpose and typical party compositions [*Vovsha, et al, 2003; MORPC Final Report, 2005*]. The essence of the joint party composition model is to narrow down the set of possible person participation choices modeled by the subsequent sub-model.

A.5.3. Joint Tour Participation at Person Level

Frequency choice and travel party composition models discussed above generally fall quite readily into the standard discrete choice structure. Regarding the person participation model, two alternative ways to formulate the choice model have been found. The complexity of the person participation model stems from the combinatorial variety of households (especially relatively large households with, say, two workers and four children), as well as from the necessity to link participation models across household members and tours in order to logically limit the participation of each household member in joint tours.

Consider a realistic example of a household having two types of persons - two adult workers and two school children of pre-driving age. Consider a joint tour with the chosen mixed travel party. For simplicity of presentation also assume that only one adult is enough to form the party.

The first approach constitutes entire-party choice. This approach is based on explicitly listing all possible person combinations for the travel party formation. Then, the following party-formation tree can be depicted – see **Figure 87** (left side):

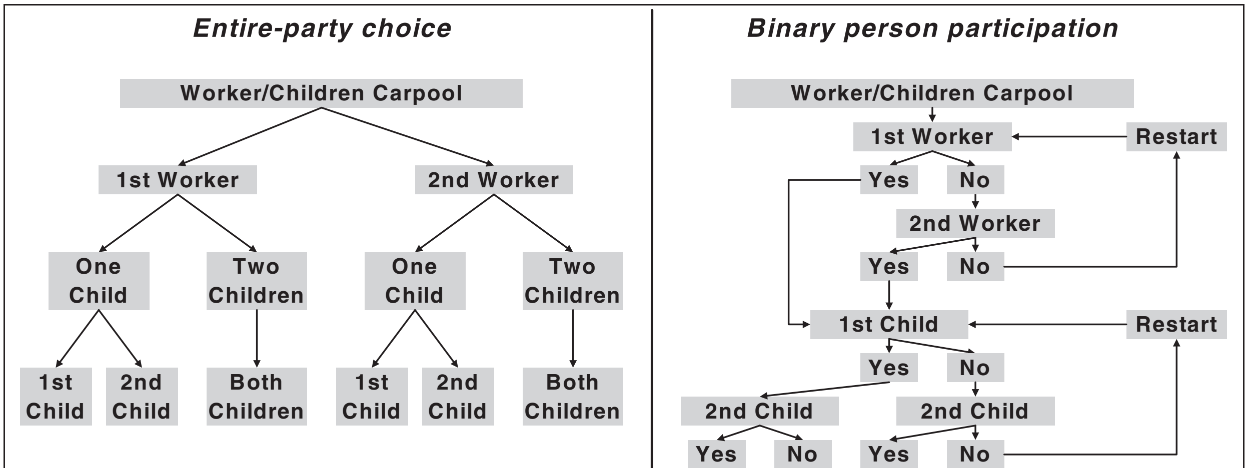


Figure 87: Travel Party-Formation Trees

In this case, six travel parties can be formed in the household. The following problematic features of the first approach have can be identified:

- The total number of alternatives in the choice set may reach hundreds if more dimensions are added to the person segmentation and/or a larger household is considered,
- The alternatives have a differential degree of similarity, thus a complicated nested structure should be applied; however, it is not clear how to organize all nesting levels in view of the multiple possible dimensions.

The second approach is based on participation choice being modeled for each person sequentially. In this alternative approach, only a binary choice model is calibrated for each activity, party composition and person type. Quantitatively different alternatives by party size are not distinguished. Thus, using the previous example, there will be two different utilities for each worker (assuming that male and female differences are important for this joint travel category) and one utility for the child. Then a sequence of binary choices is applied assuming a single possible participation for each person – see **Figure 87** (right side).

The following problematic features of the second approach are seen:

- Participation probabilities might not be independent (some particular person types or household members may tend to cooperate more), thus, this fine effect would be lost,
- There is an uncontrolled party size, including a non-zero probability for failure to form a party if all persons have chosen not to participate.

Comparing pros and cons of both approaches, we have found that the second one is more practical and operational in both model estimation and application. This approach makes travel party size automatically linked to the household size and composition. For example, the more children in the household, the more likely a bigger travel party will occur for the relevant joint travel where children are in the party composition. The case of a failure to form a travel party in model application is resolved by re-starting the Monte-Carlo simulation until the suitable travel party has been formed. This version of the model was included in the Columbus, Atlanta, and San Francisco Bay Area Models.

A.6. Evaluation of Pricing Projects: Example Application

To show how **Cost Benefit Analysis (CBA)** techniques can be applied and highlight welfare calculations, an example application is provided. While the example is on a relatively small scale (addition of a single link in a toy network), it provides useful insights.

A.6.1. Methodology

The methods used here consider multiple alternatives for travel between a single origin and two destinations. The alternatives include the choice of destination, mode (auto, bus, or walk), time-of-day (AM peak, PM peak, and off-peak), and route. **Figure 88** details the layout of this idealized network.

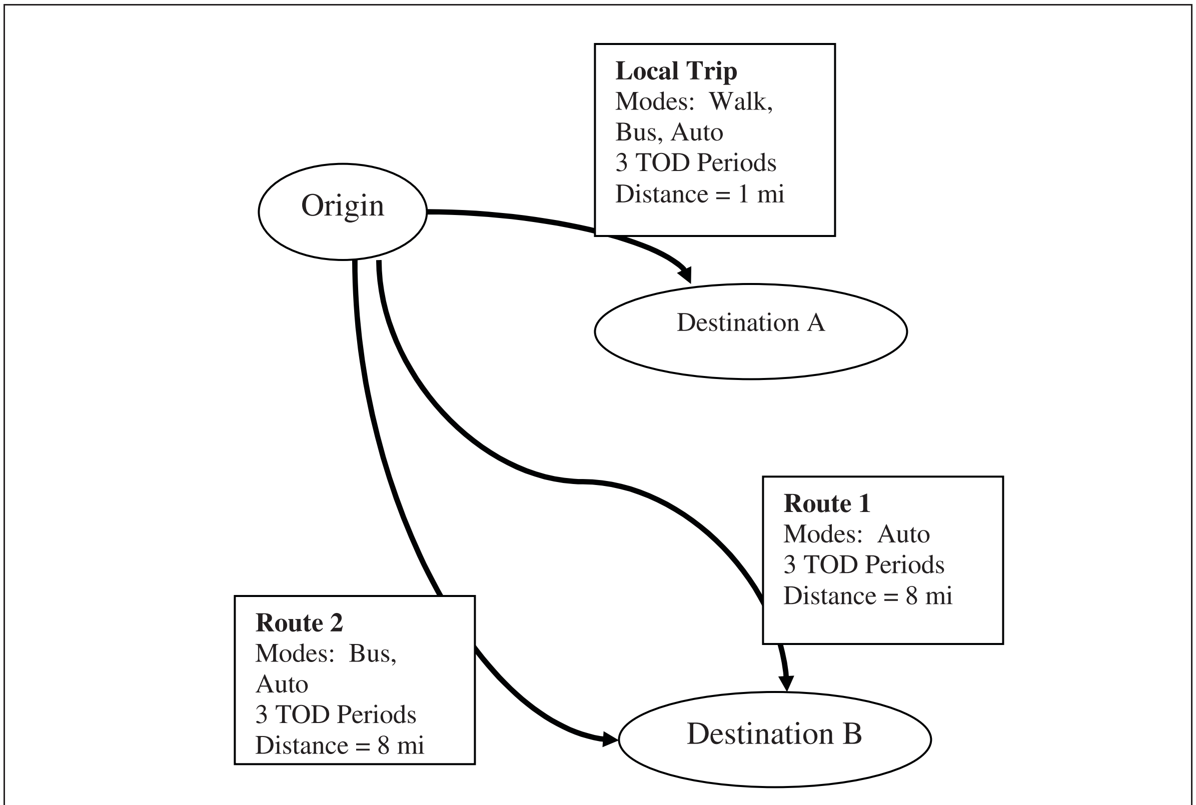


Figure 88: Idealized Network

Using a nested logit specification [*Ben-Akiva and Lerman, 1985*], so that clusters of similar options exhibit correlated error terms, and making some assumptions about cost and time sensitivity, as well as scale terms and nesting (inclusive value) parameters, one can estimate flows for each alternative. There are four distinct choice dimensions being modeled here, so the nesting structure exhibits three embedded nests. At the lowest level is route choice, followed by time-of-day, mode, and destination choices at the higher levels (Figure 89). Reasonable behavioral parameter values were selected to characterize preferences. **Figure 89** shows the overall nesting structure of the model, and the associated scale parameters.

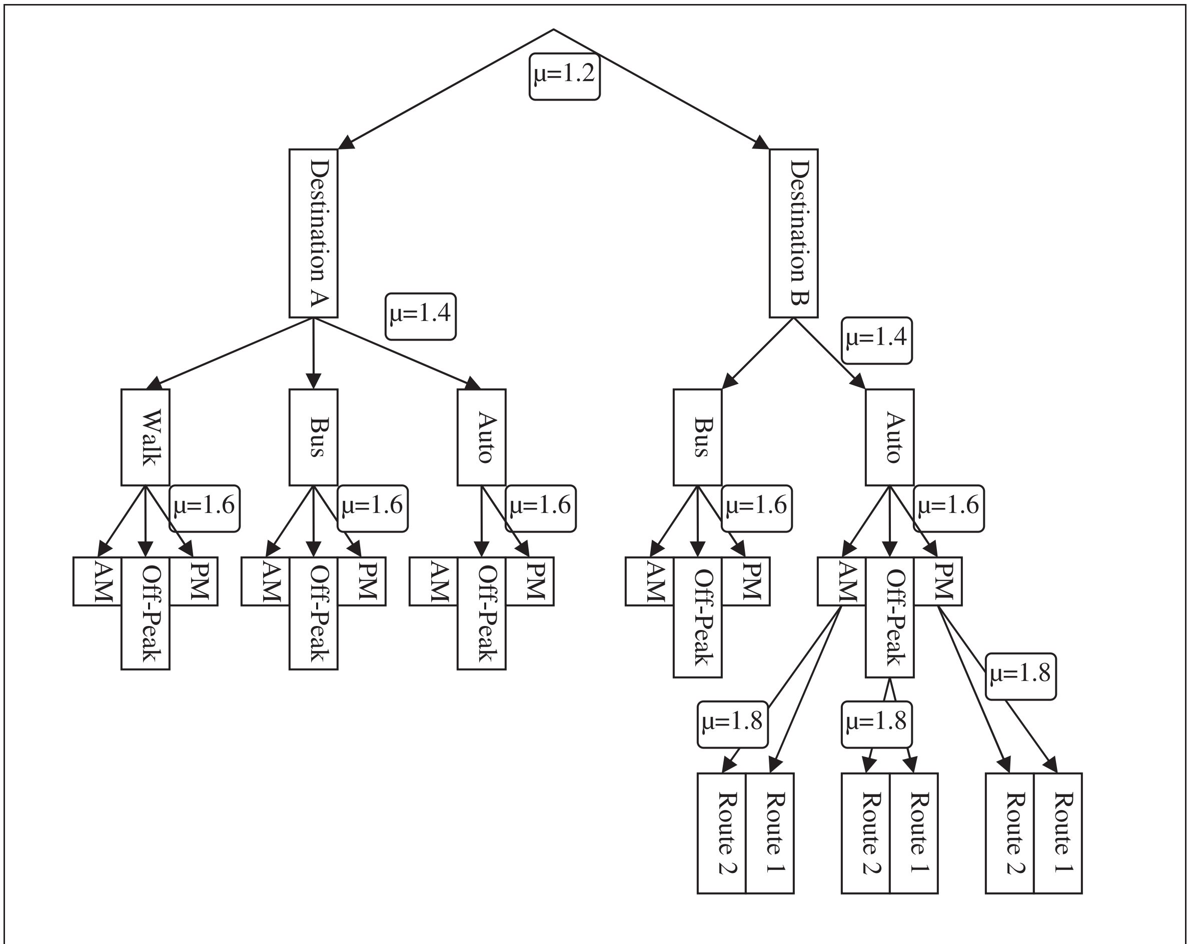


Figure 89: Nested Logit Model Structure and Parameters

Two destination options (A and B) are available for each user. Destination A represents a location close to the origin (1 mile), while destination B lies much farther away (8 miles). However, the assumed attractiveness of destination A is much less than that of B (10 versus 200 – much like a local versus regional activity center). Further, the free-flow speed to A via automobile is only 10 mph, as compared to 60 mph to B. The two routes to destination B (existing and new) are assumed to be identical in their physical characteristics, and the Bureau of Public Roads (BPR) link performance function (Equation 1) was used to compute travel times as a function of free-flow times, capacities, and volumes, with alpha (α) and beta (β) parameters of 0.85 and 5.5, respectively (as suggested by *Martin and McGuckin, 1998*):

Equation 64: $t_l = t_{free,l}\left(1+\alpha\left(v_l/c_l\right)^{\beta}\right)$, where t_l is travel time on link *l*, $t_{free,l}$ is free-flow travel time on link *l*¸ v_l is demand for link *l*, and c_l is link *l*'s capacity flow volume.

For destination A, capacity is assumed to be unlimited, which is reasonable when such trips use a local street network with multiple paths (and relatively low demand, as compared to supply).

In the second level of the nest, three mode alternatives are available, though the walk mode is only available to destination A. Walk speed is assumed to be 4.47 mph, and bus speed is assumed to be the same as the auto mode (In the case of travel to destination B, buses are assumed to travel on route 2 – the tolled route, though bus passengers do not pay the toll.). However, a flat 15 min penalty is added to bus times to represent its added wait, access, and egress times. Furthermore, the bus fare is set at $0.50 per trip, buses on the network are assumed to be equivalent to 2.0 passenger cars (as suggested by the Highway Capacity Manual [*TRB 2001*]), and buses are assumed to ride "full", at 20 persons of capacity. For the auto mode, a fixed operating cost of $0.20/mile is assumed. Last, in calculation of utilities for each alternative, alternative specific constants (ASCs) are assumed for each mode: 0.0 for auto, -1.1 for bus, and -1.3 for walk. These values were selected to represent reasonable preference structures and are simply for illustrative purposes.

The last two levels of the nesting structure are for time-of-day (TOD) and route choices (though choice of route is only available to those driving to destination B). Three TOD alternatives are available and link capacities to destination B are assumed to vary by the number of hours in each time period (which assumes uniform assessment of all traffic within each period). AM peak is assumed to last 3 hours (6-9 am) and PM peak is assumed to last 4 hours (3-7 pm). Instead of giving the off-peak (OP) period the remaining 17 hours of the day, it is assumed that most OP travel will occur between the AM and PM peaks; thus, the OP period lasts 6 hrs. If 2,000 passenger cars per hour per lane (pcphpl) is assumed for freeway capacity, and each route to B has two lanes, then capacities on both routes are the same for each TOD: 12,000 passenger cars equivalents in the AM, 24,000 in the OP, and 16,000 in the PM. In computing utilities, ASCs for each TOD alternative are assumed to be 0.0, -0.3, and 0.2 for the AM peak, OP, and PM peak, to reflect relative preference for travel during the PM and then AM periods, respectively.

Several other assumptions are needed here as well. The total number of system users is assumed to be 125,000, segmented into two groups. Low value of travel time (VOTT) users make up half of the population (with a $6/hour VOTT), and high VOTT users make up the other half (with a $12/hour VOTT). Finally, it is important to discuss the scale parameters (also known as inclusive value coefficients) in each level of the nested model. While scaling parameters need not be the same for two different nests at the same level in the nesting structure, all were assumed to be the same here for simplicity. For example, the scale parameters across TODs for walk mode to A are assumed to be the same as the scaling parameter across TODs for bus mode to B. Consistent with McFadden's random-utility theory the scale parameters for the route choice, TOD, mode and destination choice nests were assumed to be 1.8, 1.6, 1.4, and 1.2, respectively. In contrast to most nested logit specifications (where the top level nest enjoys a 1.0 scale factor), the top level scaling parameter is assumed here to be 1.2. The reason for this is that the coefficient on cost in the utility equations is set equal to -1 (as will be shown below). In this way all top-level utility values are in terms of dollars already. An equivalent formulation emerges when setting the top-level scaling parameter to 1.0 (as is customary) and adjusting other parameters accordingly. Such formulations require subsequent conversion of utility values to dollars, however.

As shown in Figure 89 with a scale parameter (μ_1) of 1.8 in the lowest nest (driving to destination B via route 1 or route 2), 1.6 (μ_2) in the next lowest nest (AM versus PM versus OP TOD), 1.4 (μ_3) in the second highest level nest (walk versus bus versus auto), and 1.2 (μ_4) in the upper level nest (destination A versus destination B), equilibrium destination, mode, TOD, and route shares, and travel times and tolls were estimated for a variety of pricing scenarios. The associated equations, for generalized trip costs, systematic utilities, inclusive values (scaled Logsums) of the nested choices and choice probabilities are as follows:

Equation 65: $GC_{i,dmpr} = VOTT_i \cdot t_{dmpr} + \tau_{dmpr} + OC_{dmpr}$

Equation 66: $V_{i,dmpr} = [\ln(Attr_d) - \ln(Attr_B)] + ASC_m + ASC_p - GC_{i,dmpr}$

Equation 67: $\Gamma_{i,dmp} = \frac{1}{\mu_1} \ln[\exp(\mu_1 V_{i,dmp,route1}) + \exp(\mu_1 V_{i,dmp,route2})]$

Equation 68: $\Gamma_{i,dm} = \frac{1}{\mu_2} \ln[\exp(\mu_2 \Gamma_{i,dm,AM}) + \exp(\mu_2 \Gamma_{i,dm,OP}) + \exp(\mu_2 \Gamma_{i,dm,PM})]$

Equation 69: $\Gamma_{i,d} = \frac{1}{\mu_3} \ln[\exp(\mu_3 \Gamma_{i,d,Walk}) + \exp(\mu_3 \Gamma_{i,d,Bus}) + \exp(\mu_3 \Gamma_{i,d,Auto})]$

Equation 70: $\Pr_{i,d} = \frac{\exp(\mu_4 \Gamma_{i,d})}{\sum_{l \in D} \exp(\mu_4 \Gamma_{i,l})}$

Equation 71: $\Pr_{i,dm} = \Pr_{i,d} \frac{\exp(\mu_3 \Gamma_{i,dm})}{\sum_{l \in M} \exp(\mu_3 \Gamma_{i,dl})}$

Equation 72: $\Pr_{i,dmp} = \Pr_{i,dm} \frac{\exp(\mu_2 \Gamma_{i,dmp})}{\sum_{l \in P} \exp(\mu_2 \Gamma_{i,dml})}$

Equation 73: $\Pr_{i,dmpr} = \Pr_{i,dmp} \frac{\exp(\mu_1 \Gamma_{i,dmpr})}{\sum_{l \in R} \exp(\mu_1 \Gamma_{i,dmpl})}$

Here *GC* is the generalized cost, *V* stands for systematic utility of the alternative (as measured in dollars), Γ denotes the inclusive value or expected maximum utility for an upper level alternative, *Pr(·)* represents the probability of a particular choice, *i* denotes user group (either low or high VOT), *d* stands for the destination of interest (either A or B), *m* represents the mode of interest (walk, bus, or auto), *p* denotes the TOD (AM, OP, or PM), *r* is the route (either 1 or 2), *D* is the set of destination alternatives, *M* is the set of mode alternatives, P is the set of TOD alternatives, and R is the set of route alternatives. Here, VOT denotes the value of travel time for the associated traveler group, μ_1, μ_2, μ_3, and μ_4 serve as the scaling parameters for the route, TOD, mode, and destination nests, respectively, τ represents out-of-pocket charges (for toll or bus fare) and has no coefficient (so that utilities are in dollars), *OC* is the out-of-pocket operating expenses (set to zero for bus and walk modes), *t* denotes the travel time, *ASC* represents the alternative specific constants for mode and TOD alternatives, and *Attr* is the attractiveness value of each destination.

Two routes exist only if auto mode and destination B are chosen. In the other cases, route 2 can simply be assumed to have some arbitrarily large disutility (or travel cost) associated with it such that route 2 is not chosen. Since utility is unobserved, forcing the cost coefficient to equal one necessitates the use of two (non-unitary) scale factors (one for each nest). This offers greater transparency in dimensioning, but is in some contrast to most NL specifications (where μ is set equal to 1 in the upper [or lower] nest).

Estimates of the **Consumer Surplus (CS)** of each tolled scenario were computed as well. In general, the CS can be measured between any two scenarios, but we will look primarily at the CS measured in reference to the base scenario – where only one of the two routes to destination B is available. In other words, the base scenario is a "do nothing" scenario where no new roads are built to destination B. The CS computation is as follows:

Equation 74:

$$CS_i = \frac{1}{\mu_4}\left(\ln\left[\sum_{k\in D}\exp\left(\mu_4\Gamma^1_{i,k}\right)\right] - \ln\left[\sum_{k\in D}\exp\left(\mu_4\Gamma^0_{i,k}\right)\right]\right)$$

Equations from **Equation 65** through **Equation 74** were applied for both traveler types, recognizing the distinctive values of time for each.

A.6.2. Application Results

An assortment of tolled and non-tolled scenarios was investigated. Each scenario was run to find equilibrium travel times and tolls on all network links. A base scenario is developed so that only one of the two routes to destination B exists. In addition, another non-tolled scenario is constructed such that both routes to destination B exist, but neither is tolled (i.e., build a new road without tolls). Six distinctive tolled scenarios were also considered, for a total of eight scenarios (These scenarios are in no way exhaustive and simply serve to illustrate key policy cases.). The simplest of these involve the building of a new road with a flat toll assessed (both $0.05 per mile and $0.10 per mile tolls are considered here). Optimal toll levels were sought, to maximize expected net benefits, across all 125,000 travelers (relative to the non-tolled scenario). Moreover, this scenario was extended to the case where optimal toll levels are assessed on both routes to destination B. Finally, revenue maximizing tolls were considered on the new route as well as on both routes to destination B. Unfortunately, throughput maximization cannot be undertaken here since a maximum flow is not defined by the BPR function. The BPR function suggests that demand equals flow, and, since demand is unbounded to the right (i.e., demand can grow toward positive infinity), flow is also unbounded to the right. The results of these applications emerge from relatively straightforward network equilibration and optimization procedures, and are discussed below.

A.6.2.1. Traveler Choices and Network Effects

Under the above assumptions, equilibrium base conditions (where only one route to destination B exists) result in volume–to-capacity (V/C) ratios for peak and off-peak periods of 1.08 (for both AM and PM peaks) and 0.98, respectively, to destination B. This results in 19 minute and 15 minute peak and off-peak travel times to destination B, which are quite high relative to its 8-minute free-flow travel time.

Of course, what is of interest is how this compares to scenarios in which a second route (to destination B) is added (essentially doubling corridor capacity). In each case of an **added route to destination B**, substantial delay reductions emerge. When the new route is not tolled, V/C ratios, and thus travel times, to B are lower. Travel times are just under 14 minutes in the peak periods and 10 minutes in the off-peak period (Table 1), saving travelers about 5 minutes per trip in all TODs. If a **flat toll** of $0.40 (equivalent to 5¢ per mile) is assessed **on the new route** to destination B, lower V/C ratios are experienced on the tolled route (in comparison to the non-tolled case); and V/C ratios are higher on the non-tolled route (as compared to the non-tolled case), but lower than the base (no-build) scenario. If a flat toll of $0.80 (equivalent to 10¢ per mile) is assessed on the new route to B, similar results emerge, but with more significant differences. Thus, in comparison to the non-tolled scenario, travel times to destination B in these two tolled scenarios fall by about 2 minutes, to 3.5 minutes per trip in peak periods (for the 5¢ and 10¢ per mile settings, as shown in **Table 44**), however, traffic shifts to the non-tolled route, where travel times rise.

Table 44: Travel Times, Tolls, V/C Ratios, and VMT across Scenarios

Parameter	Link	TOD	Base (1 Link to Dest. B)	Build 2nd Link (No Toll)	Link 2 Tolled				Both Links Tolled	
					5 cent/mi Toll	10 cent/mi Toll	Welfare Maximizing Toll	Revenue Maximizing Toll	Welfare Maximizing Toll	Revenue Maximizing Toll
Travel Time (min)	Link 1	AM	19.12	13.69	14.26	14.94	14.43	15.55	9.40	8.44
		MID	14.20	9.69	10.11	10.67	10.16	11.14	8.70	8.02
		PM	19.26	13.81	14.39	15.07	14.56	15.68	9.43	8.45
	Link 2	AM	N/A	13.72	11.85	10.28	9.44	8.52	9.20	8.77
		MID	N/A	9.71	8.51	8.06	9.00	8.03	8.67	8.03
		PM	N/A	13.84	11.97	10.38	9.45	8.54	9.21	8.81
Toll ($)	Link 1	AM	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$1.13	$1.70
		MID	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.58	$1.36
		PM	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$1.14	$1.71
	Link 2	AM	N/A	$0.00	$0.40	$0.80	$0.89	$1.33	$1.20	$1.63
		MID	N/A	$0.00	$0.40	$0.80	$0.26	$0.99	$0.60	$1.36
		PM	N/A	$0.00	$0.40	$0.80	$0.91	$1.35	$1.21	$1.64
V/C Ratio	Link 1	AM	N/A	0.97	0.99	1.00	0.99	1.02	0.75	0.61
		MID	N/A	0.78	0.81	0.84	0.81	0.87	0.66	0.36
		PM	N/A	0.97	0.99	1.01	0.99	1.02	0.75	0.61
	Link 2	AM	1.08	0.96	0.89	0.80	0.73	0.60	0.70	0.62
		MID	0.98	0.77	0.62	0.42	0.70	0.35	0.65	0.36
		PM	1.09	0.96	0.89	0.81	0.73	0.60	0.70	0.63
VMT (1,000 veh-mi/day)	All Auto Links	AM	125	195	190	185	176	168	152	136
		MID	201	303	280	249	297	242	259	148
		PM	168	261	255	248	235	225	204	183
		Total	494	759	726	682	708	636	615	467

In the case of **welfare maximizing tolls**, two scenarios were investigated: one where only the **new route** to destination B is tolled and one where both the new and old routes to destination B are tolled. I(Note: Welfare maximizing tolls refer to toll levels that result in the maximum social welfare, which includes traveler perceived costs and benefits, along with generated revenues.) In the case of one tolled route, the welfare-maximizing toll on that route (at system equilibrium) is found to be $0.89 in the AM peak, $0.91 in the PM peak, and $0.26 in the off-peak period (**Table 44**). Both peak periods' optimal tolls are higher than the flat tolls considered above, while the off-peak period toll is somewhat less, since it is less attractive to travelers (and thus was assigned a negative ASC). These tolls result in travel times on the new route that are almost the same for peak and off-peak periods (just 9 minutes during the off-peak and about 9.5 minutes during the two peaks), in clear contrast to the flat tolls discussed above. If welfare maximizing tolls are charged on **both routes** to destination B, tolls rise (to about $1.10 to $1.20 in the peak periods and about $0.60 in the off-peak period, as shown in **Table 44**). While tolls may be high, travelers enjoy significant travel time benefits when driving to destination B. No travelers destined for B experience more than a 9.5 minute travel time.

If road managers instead wish to **maximize revenue** on the **new route**, optimal tolls will be $1.33 in the AM peak, $0.99 in the off-peak, and $1.35 in the PM peak (**Table 44**). If one maximizes revenues by tolling **both routes** to destination B, the lowest travel times emerge, since fewer travelers choose destination B, due to tolls on the order of $1.60 to $1.70 in the peak periods and $1.35 in the off-peak period (as shown in **Table 44**), much higher than in any of the other scenarios. These higher tolls result in a substantial VMT reduction. In fact, maximizing revenue on both routes is the only scenario in which VMT drops relative to the base (No Build) scenario (5.4% less). All other scenarios exhibit a substantial increase in VMT relative to the base, ranging from a 24.6% increase (in the case of welfare maximizing tolls on both routes) to a 53.4% increase when neither route to destination B is tolled.

A.6.2.2. Welfare Results

Equation 74 specifies equivalent variation or average traveler welfare change as measured relative to the one-route (to destination B) base scenario, in units of dollars per traveler. A positive welfare change means that users benefit (on average) from the policy, whereas a negative welfare change indicates user losses. In addition to traveler welfare impacts, revenues resulting from each tolling scenario must be considered here. **Table 45** presents the predicted traveler welfare change and revenue streams for each of the scenarios previously discussed.

Table 45: Revenues and Welfare Results by Scenario

Measure	VOT	Build 2nd Link (No Toll)	One Link Tolled				Both Links Tolled	
			5 cent/mi Toll	10 cent/mi Toll	Maximum Welfare Toll	Maximum Revenue Toll	Maximum Welfare Toll	Maximum Revenue Toll
Welfare Change from Base ($/traveler/day)	Low VOT	$0.63	$0.54	$0.45	$0.52	$0.39	$0.24	$0.00
	High VOT	$0.69	$0.63	$0.53	$0.63	$0.46	$0.48	$0.24
	Average	$0.66	$0.58	$0.49	$0.57	$0.42	$0.36	$0.12
Daily Welfare Change ($/day)	Low VOT	$39.6K	$33.9K	$28.4K	$32.3K	$24.3K	$15.2K	$0.13K
	High VOT	$42.9K	$39.1K	$33.3K	$39.1K	$28.4K	$30.2K	$15.1K
Total User Benefit ($/day)		$82.5K	$73.0K	$61.7K	$71.4K	$52.7K	$45.4K	$15.3K
Toll Revenue ($/day)		$0	$15.9K	$26.0K	$23.0K	$30.9K	$65.9K	$81.1K
Net Welfare (User Benefit plus Revenue in $/day)		$82.5K	$88.9K	$87.7K	$94.4K	$83.6K	$111.3K	$96.4K

As shown in Table 45, generated revenues range from $0 in the Build, No Toll route scenario to $81,000 per day in the Revenue Maximizing, Both Routes Tolled scenario. In discussing traveler welfare, it is not so surprising that in all of the scenarios with the new route to B, welfare change estimates are positive (even for the Revenue Maximizing, Both Routes Tolled scenario where VMT falls), meaning net benefits exist for all travelers. This is due to the highly congested conditions of the one-route base scenario, and the simple result that doubling capacity to destination B allows for great congestion relief.

The greatest welfare improvements for travelers emerge in the no-toll scenario ($0.63 and $0.69 per traveler per day for low- and high-VOT travelers, respectively, and $82,500 total per day). However, when toll revenues are considered in addition to traveler welfare, this no-toll scenario offers the lowest net welfare overall. Even when tolls are set to maximize revenues on one or both routes, net welfare is greater than the no-toll scenario. These welfare benefits are useful to highlight for all stakeholders.

Of course, the greatest net benefits emerge when all "goods" are priced optimally – so that tolls are set to maximize welfare on **both** routes (net welfare of $111,300 per day). If a no-toll route to destination B must be provided, the best option emerges from the welfare maximizing scenario with a single route tolled (net welfare of $94,400 per day). Clearly, there are benefits for both low-and high-VOT travelers and high-VOT travelers benefit more, but the disparity between the two traveler types is larger when both routes are tolled (differences of $6,800 in traveler benefits with one route tolled and $15,000 with both tolled). A similar result is found when tolls are set to maximize revenues. The difference between low- and high-VOT travelers when one route is tolled is $4,100 per day ($24,300 versus $28,400) while the difference when both routes are tolled is $15,000 per day ($100 versus $15,100), again supporting the notion that the impacts are more evenly distributed when one route is left non-tolled. In fact, if equity is measured as the difference in welfare between low- and high-VOT travelers, the least equitable scenario occurs with welfare maximizing tolls on both routes (though the equity is almost the same for the revenue maximizing tolls on both routes). The availability of substitute travel options may be essential in maximizing user benefits under tolling (and other) policies while wooing supporters across all demographic classes. Of course, such welfare calculations do not account for the costs of construction of the new facility nor do they account for the operation of tolling technology needed for scenarios with tolling implemented.

As a point of comparison, **Rule-of-Half (RoH)** results can also be computed – relative to the base scenario and relative to the Build, No Toll route scenario. It is important to recall that, in general, one cannot use the RoH when new alternatives are added, since the price associated with zero demand for the new alternative in the base scenario (i.e., where the demand curve intercepts the price axis) is unknown. Thus, price changes cannot be measured. However, this idealized example (with perfect route substitution) allows one to assume that link capacity to destination B is simply doubled (instead of an entirely new link being added to the network). Alternatively, one can view the situation as one where both links are present in the base case, neither tolled, and the capacity on the new/second link is negligible, so no travelers use that link until it is expanded. Either way, however, the RoH approach (relative to the No Build scenario) neglects the fact that a new alternative is being added New alternative convey a variety of unobserved benefits in individual utility perceptions, offering subtle but often substantial benefits.

Under this approach, the RoH can be used to approximate welfare changes relative to the No Build or base scenario. When the Build, No Toll scenario is used as the base, the RoH can be used in the standard fashion.

Table 46 shows the results of the RoH analysis in terms of daily welfare change from the base. Welfare changes resulting from the logsum analysis are also provided. When the single non-tolled route scenario is considered the base, the RoH calculation produces very different results than the logsum approach. In each scenario, the RoH estimates are lower than logsum estimates; they range from about 33% lower (for maximum-revenue tolls on a single link) to over 100% lower (for maximum revenue tolls on both links, where welfare estimates become negative under the RoH). This is due mostly to the fact that the addition of a new alternative provides the opportunity for a new choice, with a random utility component (the Gumbel error term, reflecting unobserved factors). Thus, even if the added alternative did not appear to offer generalized travel cost benefits, it would still offer benefits. As mentioned earlier (under the RoH discussion), such benefits are neglected in the RoH framework. In addition, RoH estimates perform best for policies resulting in small travel cost and time changes. Here, the new link offers extensive congestion relief to the corridor, so the RoH's linear-demand assumption is problematic.

However, when the Build, No Toll route scenario serves as the base case, the RoH estimates lie very close to the Logsum-based estimates, differing by no more than 2.4%.

Table 46: Traveler Welfare Changes Using RoH versus Using Logsum

Measure by VOT		Build 2nd Link (No Toll)	One Link Tolled				Both Links Tolled	
			5 cent/mi Toll	10 cent/mi Toll	Maximum Welfare Toll	Maximum Revenue Toll	Maximum Welfare Toll	Maximum Revenue Toll
Single Non-Tolled Link Scenario as Base								
RoH Approach	Low VOT	$23.2K	$19.9K	$17.0K	$19.8K	$15.8K	$2.3K	-$10.3K
	High VOT	$31.0K	$27.7K	$23.2K	$27.7K	$19.4K	$20.1K	$7.0K
	Total	$54.3K	$47.6K	$40.2K	$47.5K	$35.2K	$22.4K	-$3.4K
Logsum Approach	Low VOT	$39.6K	$33.9K	$28.4K	$32.3K	$24.3K	$15.2K	$0.1K
	High VOT	$42.9K	$39.1K	$33.3K	$39.1K	$28.4K	$30.2K	$15.1K
	Total	$82.5K	$73.0K	$61.7K	$71.5K	$52.7K	$45.4K	$15.2K
Build 2nd Link (No Toll) Scenario as Base								
RoH Approach	Low VOT	N/A	-$5.7K	-$11.3K	-$7.3K	-$15.6K	-$24.0K	-$38.1K
	High VOT	N/A	-$3.8K	-$9.5K	-$3.7K	-$14.3K	-$12.5K	-$27.5K
	Total	N/A	-$9.5K	-$20.8K	-$11.0K	-$29.9K	-$36.5K	-$65.6K
Logsum Approach	Low VOT	N/A	-$5.7K	-$11.2K	-$7.3K	-$15.3K	-$24.4K	-$39.5K
	High VOT	N/A	-$3.8K	-$9.5K	-$3.7K	-$14.5K	-$12.7K	-$27.8K
	Total	N/A	-$9.5K	-$20.7K	-$11.0K	-$29.8K	-$37.1K	-$67.2K

Note: Revenues are not added to these estimates of traveler welfare changes

A.6.2.3. Accounting for Highway Cost

In order to more fully evaluate the scenarios as investment alternatives, it is necessary to recognize the costs associated with building and operating a new roadway. *Litman's, 2006* review of the literature suggests that freeways in urban areas cost on the order of $5 million to $10 million per lane-mile, which includes land acquisition, pavement, and intersection reconstruction. (Note that the costs of building a new road in a non-urban area would be substantially lower). Assuming the cost is $5 million per lane-mile, an 8-mile, 2-lane freeway will cost $80 million. If one also assumes that routine annual maintenance costs of highways are $14,000 per lane-mile (assumed from a range from $13,100 to $14,600 as suggested by *FDOT, 2003*) and toll road management costs are $50,000 per lane-mile per year, a single toll facility will cost $1.02 million per year, and two toll facilities will cost $1.82 million per year. Total operating expenses and number of toll road lane-miles for NTTA (NTTA, 2003), New Jersey Turnpike Authority (NJTA, 2003), and San Joaquin Hills Transportation Corridor Agency [*SJHTCA, 2003*] were used to find average management costs for toll roads. All three were on the order of $100,000 per lane-mile, but these systems are mature, and rely on past technology. With new, paperless systems, management costs of $50,000 per lane-mile were assumed to be reasonable here.

Finally, if it is assumed that calculated revenues are for weekdays only and weekend days generate only half that of weekdays, daily revenues can be multiplied by 313 to find yearly revenue streams in each scenario. Given these assumptions, it is possible to perform a cost-benefit analysis of traveler welfare, system expenditures and toll revenues. (For purposes of policymaking, more comprehensive analysis may also be pursued, including estimation of bus service subsidies, emissions effects, and crash costs.)

The analysis of financing the new road is performed in two ways. First, it is assumed that all toll revenues go toward the construction and management costs of the new road, after discounting future revenues at 5% per year. Note that a rate of 7% may be more appropriate for the facility investigated here (as per *OMB, 2003 suggestions*), but this example is for illustrative purposes only. In the scenario where the new road is built without tolls, there are no revenues, but one can still compute costs and traveler benefits, which results in a net benefit of about $0.52 per traveler per day (one-way), or $20.4 million per year (if costs are financed via a 5-percent 30-year loan.

Table 47 presents the results of this first step of the analysis, including total and net annual revenues (after covering construction loan costs and toll road management), and time period it takes to fully recover construction and management costs (assuming an annualized payback). When the new road is built but not tolled, a repayment period clearly cannot be computed (since there are no toll revenues), and in the case of a flat 5¢/mile toll, toll revenues are not enough to cover all costs when future revenues are discounted at 5%. In each of the other scenarios, the repayment period is rather modest (about 20 years or less), with the minimum payback duration (less than 4 years) resulting from tolling of both routes. Of course, once the costs of building, maintaining, and managing the new road have been recovered, future revenues can go toward any number of things, including credits to travelers, other infrastructure improvements, or the improvement of transit services.

Table 47: Repayment Period Results for New Road Investment

Measure	Build 2nd Link (No Toll)	One Link Tolled				Both Links Tolled	
		5 cent/mi Toll	10 cent/mi Toll	Maximum Welfare Toll	Maximum Revenue Toll	Maximum Welfare Toll	Maximum Revenue Toll
Toll Revenues[1]	$0	$4.98M	$8.15M	$7.18M	$9.68M	$20.62M	$25.38M
Maint. Cost[2]	$0.224M	$0.224M	$0.224M	$0.224M	$0.224M	$0.224M	$0.224M
Manage. Cost[3]	$0	$0.8M	$0.8M	$0.8M	$0.8M	$1.6M	$1.6M
Net Revenue[4]	$0	$3.96M	$7.12M	$6.16M	$8.66M	$18.80M	$23.56M
Repay. Time[5]	N/A	N/A	16.9 yrs	21.5 yrs	12.7 yrs	4.9 yrs	3.8 yrs

[1]Revenue generated for a year assumes 261 weekdays and 104 weekend days per year, where weekend-day revenues are one half those of regular weekdays. Values are shown in millions of $/year.
[2]These are roadway maintenance costs for the new highway in millions of $/year.
[3]These are tollway management costs in millions of $/year.
[4]Net revenue is the difference between total revenue and the sum of maintenance and toll management costs, shown in millions of $/year.
[5]Repayment time is the time (in years) it takes to pay off an $80 million loan using all of the net revenues generated by the scenario. Here, a discount rate for future revenues is assumed to be 5%.

In the second step of the analysis, a more standard approach to CBA is taken where costs and benefits that accrue over time are discounted to find equivalent NPVs. First, it is assumed that the construction of the new road will be paid for by a 30-year loan with 5% interest rate and fixed yearly payments. This amounts to annual payments of approximately $5.2 million (not including maintenance and management costs, which are subtracted from net revenues before applying them to loan payments). In addition, other costs include the annual maintenance and management costs, and benefits include yearly toll revenues and traveler benefits. Once all annual costs and benefits are computed, the NPV of each can be found (by discounting at the assumed rate of 5% per year) and summed to determine a project's total NPV. **Table 48** shows the results of this analysis. Note that the NPV of all costs includes only construction costs and the NPV of all benefits includes all other benefits and costs per *FHWA, 2003* guidance in computing B-C ratios. As shown in **Table 48**, each scenario enjoys very high NPV values (due to heavy congestion in the base scenario) ranging from $306.6 million in the case of revenue-maximizing tolls on a single route to $427.4 million in the case of welfare-maximizing tolls on both routes. Since the NPV of costs is the same for each alternative, the scenario rankings based on total NPV and B-C ratio are identical.

Table 48: Cost-Benefit Analysis Results for New Road Investment

Measure	Build 2nd Link (No Toll)	One Link Tolled				Both Links Tolled	
		5 cent/mi Toll	10 cent/mi Toll	Maximum Welfare Toll	Maximum Revenue Toll	Maximum Welfare Toll	Maximum Revenue Toll
Construction Costs[1]	$5.2M	$5.2M	$5.2M	$5.2M	$5.2M	$5.2M	$5.2M
Maint. Costs[1]	$0.22M	$0.22M	$0.22M	$0.22M	$0.22M	$0.22M	$0.22M
Manage. Costs[1]	$0	$0.8M	$0.8M	$0.8M	$0.8M	$1.6M	$1.6M
Revenue[1]	$0	$4.98M	$8.15M	$7.18M	$9.68M	$20.62M	$25.38M
Traveler Benefits[1]	$25.8M	$22.8M	$19.3M	$22.4M	$16.5M	$14.2M	$4.8M
Yearly Costs[2]	$5.2M	$5.2M	$5.2M	$5.2M	$5.2M	$5.2M	$5.2M
Yearly Benefits[2]	$25.6M	$26.8M	$26.4M	$28.5M	$25.1M	$33.0M	$28.3M
NPV of Costs[3]	$80.0M	$80.0M	$80.0M	$80.0M	$80.0M	$80.0M	$80.0M
NPV of Benefits[3]	$393.3M	$412.0M	$406.6M	$438.5M	$386.6M	$507.4M	$435.4M
Total NPV	$313.3M	$332.0M	$326.6M	$358.5M	$306.6M	$427.4M	$355.4M
B-C Ratio	4.917	5.150	5.082	5.482	4.832	6.343	5.443

[1]All values are shown in millions of $/year. Construction costs are computed assuming a 5% interest rate on 30-year loan. Revenues and traveler benefits are computed assuming 261 weekdays and 104 weekend days per year, where weekend-day revenues and traveler benefits are one half those of regular weekdays.
[2]Yearly costs include only construction costs and yearly benefits include maintenance and management costs, revenue, and traveler benefits. All values are shown in millions of $/year.
[3]NPVs are calculated using a discount rate of 5% per year.

Of course, the NPV of each scenario depends greatly on the assumed discount rate of 5%, though, in this case, the rankings of scenarios will be the same regardless of chosen discount rate (since annual demand, costs and benefits are simply assumed constant over the 30 year period of analysis). However, it is of interest to understand the sensitivity of NPV to the chosen discount rate. The welfare-maximizing tolls on a single route yield a NPV of $358.5 million, when discounting at 5% per year (as shown in **Table 48**). If the discount rate is changed to 3%, the NPV estimate rises to $457.2 million (28% greater than discounting at 5%). In contrast, if the discount rate is 7%, the NPV estimate falls to just $289.4 million (19% less than the original). Thus, for even small deviations in the discount rate, large fluctuations in the estimated NPV may result.

A.6.2.4. Summary

The example application provided here illustrates how Logsums can be used as a measure of traveler welfare, and how cost-benefit analysis can be used as a tool for project evaluation in toll road settings. In addition, theRoH estimates of welfare change were illustrated, in order to demonstrate how close and how far they can be from the Logsum measure (when wholly new routes/alternatives are added versus existing routes are tolled). As shown in eight numerical examples, with two distinctive (and latently heterogeneous) traveler types, congestion levels can be largely reduced in the presence of pricing (even with flat tolls), and estimated net welfare effects can be significant (even when tolls are set to maximize revenue). While disparities exist between the welfare benefits of low- and high-VOT travelers, these are lessened when a no-toll or low-tolled option is preserved. The results also show how congestion pricing can provide a means to finance new highways along previously congested corridors. In the congested-corridor context examined here, it was found that all but one pricing policy led to revenues that could fully finance the infrastructure costs within 30 years, with excess revenues. Such excess revenues can be used for any number of things.

Of course, the analysis provided here illustrates only key concepts with an idealized set of scenarios. Nonetheless, it shows how a variety of pricing policy options exist for those willing to invest in new transportation infrastructure that offers travel time savings. The tools and techniques highlighted here illustrate practical methods for identifying welfare-enhancing and cost-recovering investment opportunities. These techniques recognize demand elasticity across times of day, destinations, modes and routes, which are standard features of most travelers' choice sets, but which are too often lacking in most analysts' toolkits and not applied.

A.6.3. Conclusions and Recommendations

The topics covered in this appendix seek to aid planners and decision makers in using transportation models to inform the decision-making process, with emphasis on toll road projects. Traveler welfare calculations were discussed at length, with a focus on logsum calculations across discrete alternatives. Such measures of traveler welfare provide the most rigorous estimates when demand estimates are a consequence of discrete choice models, such as with the MNL and NL specifications. However, they are not appropriate in model specifications, where multiple choice dimensions are modeled in a largely sequential and less integrated fashion. In such cases, the RoH may instead provide reasonable estimates of welfare changes, at least when existing road policies are only modified (e.g., tolling is added to existing systems). When choice alternatives are added (such as new roadways), however, the RoH is inappropriate.

CBA techniques are invaluable in weighing attributes of different alternatives, and a variety of measures (e.g., B-C ratios, NPVs, and IRRs) can support objective results. The NPV approach may be the most robust of the CBA measures discussed here, since it offers a quantity for direct comparison across potential projects, with obvious dollar–value implications. Of course, it can be difficult to measure all project impacts in monetary terms (as discussed by *Small, 1999*) and each project is unique; thus ultimately, there is no substitute for expert judgment in toll road project evaluation, as a complement to such calculations.

As discussed, discount rate selection is a component of all cost-benefit analyses, meriting serious consideration. *OMB, 2003* guidelines suggest a real rate of 7% for public projects. However, it is especially important for toll road projects in order to properly evaluate the implications of the chosen discount rate (whatever it is), adjusting it up and down by 2, 3, or even 5 percentage points. Robust investment decisions and tolling policies should rank near the top (of all potential policies) across various discount rates (though NPV generally vary substantially across discount rates).

Toll rate selection is a critical component of toll project evaluation. Three methods for rate selection were discussed here: welfare maximization, revenue maximization, and throughput (flow) maximization. While each is distinct and can result in very different toll levels, different stakeholders will prefer different objectives, and it can be valuable to explore the implications of all three approaches. Such investigations allow planners and policymakers to quantify the relative closeness of a project's/policy's expected welfare, revenue, and throughput, to optimal levels. More robust policies will perform relatively well across multiple measures. In the end, of course, the pursuit of social welfare maximization is a meaningful goal likely to appeal most to the traveling public and policymakers.

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation