MANUAL OF REGIONAL TRANSPORTATION MODELING PRACTICE FOR AIR QUALITY ANALYSIS

PREPARED BY
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ABSTRACT

Recent changes in the context of transportation planning have increased the importance of regional transportation analysis methods. In particular, the Clean Air Act Amendments of 1990 set forth requirements for detailed planning and analysis which apply to many states and metropolitan areas. This Manual, prepared for the National Association of Regional Councils as part of NARC's Clean Air Project, was designed to help transportation planning agencies, including metropolitan planning organizations, state departments of transportation, and other entities, respond to the issues raised in carrying out transportation modeling for air quality planning efforts. The Manual reviews transportation modeling today, focusing primarily on travel demand forecasting as it is practiced by regional agencies, and suggests strategies for responding to specific analysis needs and for overcoming common problems. The emphasis is on identifying issues which MPOs should consider in reviewing their models, and on recommending sound options for addressing such issues in accordance with local objectives and resource availability.

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PREFACE

Recent changes in the context of transportation planning have increased the importance of regional transportation analysis methods. In particular, the Clean Air Act Amendments of 1990 set forth requirements for detailed planning and analysis which apply to many states and metropolitan areas. This Manual, prepared for the National Association of Regional Councils as part of NARC's Clean Air Project, was designed to help transportation planning agencies, including metropolitan planning organizations, state departments of transportation, and other entities, respond to the issues raised in carrying out transportation modeling for air quality planning efforts. The Manual reviews transportation modeling today, focusing primarily on travel demand forecasting as it is practiced by regional agencies, and suggests strategies for responding to specific analysis needs and for overcoming common problems. The emphasis is on identifying issues which MPOs should consider in reviewing their models, and on recommending sound options for addressing such issues in accordance with local objectives and resource availability.

The Manual was prepared by Deakin, Harvey, Skabardonis, Inc. (DHS) with funds provided under a contract with NARC as well as with DHS internal funding. DHS Principals Greig Harvey and Elizabeth Deakin led the effort and are the Manual's senior authors. DHS Principal Alex Skabardonis and associates Henry Pancoast and Rachel Weinberger provided support for the effort. Several subcontractors also helped shape the Manual: Cambridge Systematics (Earl Ruiter, David Reinke, John Suhrbier), COMSIS (David Levinsohn), Dowling Associates (Rick Dowling, Steve Colman), Gary Hawthorn Associates (Gary Hawthorn), Parsons Brinckerhoff Quade & Douglas (David Atkins, Bruce Douglas), and Ann Stevens Associates (Ann Stevens).

While it is difficult to identify individual contributions in a complex document such as this, Greig Harvey served as lead author for the Manual, developing its outline, overseeing its development, and writing or editing the entire text, with special focus on Chapters 3 and 5. Elizabeth Deakin drafted Chapters 1 and 4 and made major contributions to Chapters 2, 3, and 5. Gary Hawthorn prepared an initial draft of the Clean Air Act materials in Chapter 2. Rick Dowling and Steve Colman prepared an initial draft of several sections of Chapter 3 and developed examples for use in the text. Earl Ruiter and Dave Reinke provided materials on auto ownership models, speed calculations, and travel surveys for Chapter 3, Dave Levinsohn provided input on TSM analysis, and Alex Skabardonis contributed materials on speed estimates in traffic assignments. Ann Stevens prepared the first draft of the glossary, and Henry Pancoast and Rachel Weinberger assembled the bibliography and organized the materials received from MPOs. David Atkins, Bruce Douglas, and John Suhrbier all contributed to the development of the outline for the Manual, as did those who later authored portions of the text.

Readers will note that the level of detail varies considerably by topic, especially in Chapter 3. Resource constraints on the preparation of the Manual dictated a synthesis of available materials rather than original work and did not provide for as extensive a re-write of some sections or as thorough a treatment of some topics as might be desirable.

Several of the topics covered in the Manual are in a state of flux (e.g., analysis procedures for conformity determinations). As a result, the Manual is being provided in loose leaf notebook format, to facilitate periodic revisions and updates.
Readers' suggestions for changes to the Manual are welcome and should be directed to the principal authors and NARC. Addresses and telephone numbers are as follows:

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Many individuals made important contributions to this document. Here we can acknowledge only some of them.

Mark Howard oversaw the development of the Manual as part of the Clean Air Project at the National Association of Regional Councils. Anne Baker, formerly of SCAG, represented NARC's Conformity Panel, and Ray Ruggieri of NYMTC represented NARC's Technical Panel; the two were instrumental in getting the project off the ground and in keeping it afloat under occasionally difficult circumstances. Later, Arnie Sherwood of SCAG, representing the NARC Conformity Panel, and Sarah Siwek of LACTC (now LACMTA), representing the NARC TCM Panel, played similar roles.

The sponsors of the Clean Air Project influenced the structure of the Manual and provided detailed reviews and extensive comments on the various drafts. Special thanks are due to Phil Lorang, Mark Simons, and Mark Wolcott of EPA; Patrick DeCorla-Souza, Alexander Elles-Boyle, Chris Fleet, Charles Goodman, and James Shrouds of FHWA; and Abbe Marner of FTA.

Literally dozens of MPO staff from around the country contributed advice, examples and written comments. Among these, Chuck Purvis of MTC, Keith Lawton of Portland METRO, Jeff May of DRCOG, and Michael Morris of NCTCOG offered a wealth of direct and insightful commentary. Purvis also lent his library and in-house instructional materials.

A number of individuals and organizations provided forums in which key elements of the model assessment (Chapter 3) and application guidance (Chapter 4) could be tested for reasonableness. These include NARC itself, through a modeling workshop held in November 1991 and a series of Clean Air Act implementation seminars held during Winter 1992-93, and the California Air Resources Board and the Transportation Engineering Graduate Program at UC Berkeley, through seminars they sponsored. Mark Brucker of EPA Region IX, Bill Hein of MTC, Larry Berkowitz of the Massachusetts Highway Department and Ken Miller of CTPS, Prof. Eric Pas of Duke University, Mark Pisano of SCAG, Ray Ruggieri of NYMTC, and Prof. Martin Wachs of UCLA all arranged for seminars or presentations.

Prof. Ryuichi Kitamura of Kyoto University and Prof. Peter Stopher of LSU gave freely of their time to discuss the literature and conveyed many useful ideas. Prof. William Garrison of UC Berkeley made an important contribution of a different kind by reminding us not to overstate the validity or the significance of transportation modeling.

The authors are particularly grateful to have had this opportunity to enrich their understanding of a topic that draws upon technical and institutional knowledge in such a complex way.

NOTICE

CHAPTER 1: INTRODUCTION

1.1 Purpose of the Manual

Recent changes in the context of transportation planning are increasing the importance of regional transportation analysis methods. The Clean Air Act Amendments of 1990 (CAA), for example, set forth detailed requirements which apply to numerous metropolitan areas, including provisions for estimating transportation emissions and evaluating the conformity of transportation plans, programs and projects to the State Implementation Plans (SIPs) for attaining air quality standards. In order to meet CAA requirements, many metropolitan planning organizations (MPOs) will need to monitor growth rates, track vehicle miles of travel, and forecast the impacts of transportation options in more precise and quantitative terms than have been necessary in the past.[1]

[1] In addition to metropolitan transportation organizations, State departments of transportation, local governments, and other entities are responsible for modeling, and this Manual is intended for their use as

While CAA requirements may pose the most immediate challenges, the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) also increases the importance of good data and models. ISTEA assigns more responsibility for transportation planning and decision-making to regional agencies and grants them greater flexibility in the use of funds. At the same time, ISTEA mandates efficient, effective transportation systems management and investment decisions and, in particular, calls for metropolitan regions to address concerns about traffic congestion and air quality. Strategic, policy-driven decision-making is to be supported by better information and analysis; specific management systems are required and the funding for planning is increased.

In many cases state and local considerations further underscore the importance of good data and analysis tools. Some regions see growing public interest in transportation as a means for economic development. Other regions are experiencing increased public attention to the environmental effects of transportation, as well as growing public concern over transportation's longer term impacts on growth and development patterns. While the specifics of these issues vary from region to region, they share the common effect of focusing attention on regional agencies' forecasting capabilities and the extent to which these tools can provide meaningful responses to the questions being posed.

Recognizing that the emerging planning context is placing new demands on regional transportation planning and analysis, MPOs have begun to review and, where necessary and feasible, to upgrade their analysis tools. For many, this is an important opportunity to implement long-desired improvements. Advances in the basic understanding of travel demand, and in the development and application of land use and transportation forecasting technologies, were made in the 1970's and '80's, but only a few MPOs had the resources at the time to implement these advances. With new mandates and new resources, many MPOs now can enhance their analysis capabilities by pursuing both data collection and model development.

Regardless of whether major updates to regional models and data bases are deemed necessary, however, many MPOs are finding that the new planning context calls for new approaches to analysis. For example, link-level speeds take on far more significance in an emissions analysis than in the typical regional transportation application. Instead of adjusting speeds to obtain reasonable volumes, as many practitioners have done in the past, it may be necessary to devote additional resources to detailed link descriptions and to model calibration. The evaluation of certain transportation control measures (TCMs), e.g., signalization and ramp metering, may require the use of traffic operations models as supplements to or in combination with regional network models. Other TCMs may require more qualitative analyses, or analyses based on empirical evidence from applications. Measures dependent on factors which are usually not included in regional models fall into this latter category: for example, non-monetary incentives (e.g., flexibility in work hours) granted to those who use alternative modes, or time-of-day pricing on toll facilities and parking designed to shift trips off the peaks. In short, new

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well.

procedures for analysis as well as additional kinds of data and methods will be required to meet the analysis needs of the 1990's.

The purpose of this Manual is to provide guidance on the issues to consider in responding to these new analysis needs, and especially in carrying out transportation modeling for air quality planning efforts. The Manual reviews the state of transportation modeling today, focusing primarily on travel demand forecasting as it is practiced by regional agencies. It identifies and discusses modeling and analysis requirements resulting from the CAA and ISTEA, and suggests strategies for responding to specific analysis needs and for overcoming common problems. Finally, the Manual identifies directions for future modeling improvements, including research and development.
The Manual has been designed to:

- explain the purposes for which regional travel models are likely to be used in the next decade, with an emphasis on the requirements of transportation - air quality planning;
- suggest a set of criteria by which model performance is likely to be judged in key applications;
- list the principal technical and procedural characteristics necessary to ensure acceptable model performance in each type of application;
- provide examples of good practice for each major element of the modeling process, recognizing the ways in which practice must vary to suit local conditions (e.g., regional size, resource availability, air pollution severity);
- provide examples of advanced practice;
- discuss the likely direction of change in the state-of-the-art, to help MPOs anticipate new analytical requirements over the next decade.

The Manual was developed under the auspices of the Clean Air Project of the National Association of Regional Councils (NARC). It greatly benefitted from the input of MPO staff as well as state and federal agency representatives and academic experts. A conference on modeling practices held in Crystal City, VA, in November 1991, attended by nearly 100 regional, state, and federal officials, academics, and consultants, set the direction for the development of the Manual. At that conference, participants had the opportunity to engage in a series of in-depth explorations of the analysis issues and concerns raised by the CAA and ISTEA, as well as by state and local transportation mandates and initiatives. Through these discussions, the key issues to be addressed in the Manual were identified, and topics of particular concern were noted. Additional meetings with NARC working groups and a technical advisory committee established specifically to guide the development of the Manual also provided for detailed review and discussion of the Manual's content.

While the Manual suggests methods and procedures for the conduct of transportation-air quality modeling under the 1990 Clean Air Act Amendments, it does not attempt to set standards for modeling. Nor in particular does it describe a single modeling approach for all MPOs or recommend specific pieces of software. Instead, the emphasis is on identifying potential problem areas which MPOs should consider in reviewing their models, and on recommending sound options for addressing such problems. The Manual is based on the premise that good practice should be designed to respond to the key issues facing the area for which the analysis is being done. Since such issues vary from place to place and over time, modeling practice also should be expected to vary. Furthermore, the modeling practice for a particular area should constitute a realistic use of available resources, and hence will tend to vary with the size of the region and with the severity of the air quality problem, among other factors - including local concerns about transportation and its social, economic, and environmental impacts.

1.2 Plan of the Manual

This Manual is organized in five chapters, including this introduction. The coverage of the remaining chapters is as follows:

- Chapter 2, The Emerging Context of MPO Analysis, discusses key issues in transportation-air quality planning, notes other key MPO analysis needs, and provides an overview of the Clean Air Act provisions of greatest concern to transportation planners.
- Chapter 3, Current Analysis Practice, presents an overview of typical approaches in current use, then discusses key model components in detail: basic concepts, data and assumptions, and methodologies. Specific topics covered include economic and population forecasts and land use allocation models; network descriptions and models; vehicle ownership models; trip generation, trip distribution/destination choice, mode split/mode choice, peaking factors/time of travel, and traffic assignment/route choice; model interrelationships; and off-model analyses. Model development and application issues, and use of models and supplemental methods to produce emissions estimates, also are discussed.
- Chapter 4, Matching Analysis Tools with Analysis Needs, covers key Clean Air Act mandated data collection and analyses, including the baseline emissions inventory, VMT tracking, and VMT forecasting. The chapter also discusses assessment issues raised by various TCM measures (ridesharing, transit, traffic engineering, pricing, time of travel measures; land use and urban design policies; other), and discusses data and analyses needed in plan, program, and project-level conformity assessments.
- Chapter 5, Looking to the Future, identifies topics that are likely to require greater attention in the coming years. The chapter discusses MPO resource needs; data requirements; high-payoff model improvements; and research priorities.

Appendices to the Manual present a glossary of terms and a detailed bibliography.

CHAPTER 2: THE EMERGING CONTEXT OF MPO ANALYSIS

In the past two years, a broad set of developments has drawn attention to the strengths and weaknesses of regional transportation models. In virtually every case, questions have arisen not because of a model's failure to perform acceptably in conventional studies, but because of difficulties in extending the scope of travel demand analysis. Debates over regional transportation policy have expanded to include a range of questions about long-term investment policy: Whether or not to invest in certain areas, whether to focus on highways or emphasize transit, what to expect from demand management, and so on. Transportation models, as tools of the trade, are looked to for reasoned and reliable information on the policy issues transportation decision-makers face.

Transportation-air quality planning is a key area where heavy demands are being placed on transportation models, but other policy debates and investment opportunities also call for models which can capture both the effects of broad strategic alternatives and the specific impacts of proposed projects. In this chapter a brief overview of transportation-air quality planning analysis requirements is presented, followed by an outline of other analysis needs which point to the desirability of model improvements. The chapter ends with a more detailed review of the requirements of the Clean Air Act Amendments of 1990 (CAA) related to transportation.

2.1 Transportation-Air Quality Planning Analysis Requirements: An Overview

Clean air legislation has been a major source of renewed interest in (and concern about) regional transportation data and models. These data and models will play important roles in mobile source inventory preparation and updates and mobile source emissions monitoring and tracking. The data and models also will be key to transportation control measure (TCM) analyses and to evaluations of the conformity of transportation plans, programs, and projects to the State Implementation Plan (SIP) for attainment of the National Ambient Air Quality Standards (NAAQS) for ozone (03), carbon monoxide (CO), oxides of nitrogen (NOx), and particulates (PM10 - particulate matter of less than 10 microns).

2.1.1 Mobile Source Inventories

Emissions inventories will be a key determinant of the emphasis on transportation activities in air quality planning, since the updated inventories will be used to establish the relative contributions, current and projected, of mobile sources and stationary sources,-as well as to help identify and evaluate potential control measures. Although emissions inventories can be prepared in various ways, most mobile source emissions inventories will draw upon regional models and data.

In order to assemble inventories of mobile source emissions, accurate information specific to each region[2] is needed about the nature and extent of vehicular travel. Mobile source inventories must be produced for calendar year 1990 (the base year), for the projected attainment year, and in some cases for one or more years in between. Items on which inventory estimates are based include the following (the MOBILE emissions factor model promulgated by the US Environmental Protection Agency (EPA) and the EMFAC software used in California vary as to the specifics):

[2] Here, the term “region” generally refers to a metropolitan area (as in “regional council”.) Federal agencies also use the term “region” in some contexts to refer to a multi-state area; that usage does not appear in this document.

- Vehicle-miles traveled (VMT) - the number of miles traveled by vehicles of various types, preferably for each link of the highway system (or at least for each grid cell in a regional photochemical dispersion model).
- Speed - the average speed for vehicles on each link in the highway system. For many analyses this is needed by time of day.
- Vehicle fleet characteristics - the number of vehicles of each type "garaged" in the region. The vehicle types include various categories of light-duty and heavy-duty vehicles, by age and other characteristics.
- Vehicle trips - the number of trips originating and ending in each geographic subarea, grid cell or zone (needed for EMFAC).

While default estimates are available for many of these items (usually based on national or state averages), regional travel surveys and outputs from regional travel models are frequently used to help prepare the emissions inventory. The base year inventory may be estimated directly from traffic counts and other available data, but projections of future year inventories are difficult without the aid of a regional travel model. In practice, base year inventories are often developed in whole or in part from model runs as well, because of the limitations of centrally available traffic data in many urban areas.

More refined emissions estimates could be prepared using data from travel models. For example, running emissions, comprising up to half of the volatile organic compound (VOC)[3] and CO mobile source output, are proportional to miles traveled, with per-mile rates that vary significantly with speed. Start-up emissions (both cold start and hot start), comprising about half of the CO inventory and one-third of the VOC inventory for mobile sources, occur in the first several minutes of vehicle operation; hot soak emissions occur when the vehicle is turned off at the end of the trip. The count of garaged vehicles determines the localized output of diurnal VOC emissions. All of these elements of the mobile source emissions inventory can be estimated from data taken from travel surveys and models.

Current research by EPA and the California Air Resources Board suggests that two other factors may be a significant portion of VOC and CO running emissions, and hence may need to be accounted for as well:

- Occurrences of high acceleration - the average duration and number of instances of high acceleration (such as might occur at a freeway ramp metering light) in each grid cell.
- Occurrences of extended idling and delay - such as might occur on congested highway segments or at toll booths - by link, or by grid cell or zone.

Most transportation models currently do not explicitly account for these occurrences (microscopic traffic operations simulation models are the exception), but in the future such details may need to be taken into account.

2.1.2 VMT Estimation and Tracking

[3] In California the term reactive organics (ROG) is commonly used.

In future years the VMT estimates on which plans are based will be compared to "actual" VMT estimates derived from field studies or other sources. The Clean Air Act Amendments provide much incentive for an MPO to develop the most reliable VMT (and other) data and forecasts it possibly can. Over-predictions of VMT and other travel indicators will lead to overestimation of the need for emissions controls. Under-predictions could result in difficulties in making conformity findings and achieving air quality progress goals, which in turn could trigger a need to apply drastic mitigation measures when problems become apparent (possibly more extensive and expensive than additional controls would have been at the outset).

Current guidance from EPA (US Environmental Protection Agency, 1992a) calls for data from the Federal Highway Administration-sponsored Highway Performance Monitoring System (HPMS) to be used in estimating current VMT - though at the present time in some areas there are too few sample counts for this data base to be wholly reliable and alternative methods will be applied instead of or in addition to using HPMS data. Forecasts will in general be based on growth rates derived from regional travel models.

A major concern is that past model-based projections of VMT, trips, and vehicle ownership have tended to be low. For example, trends data in some regions indicated VMT growth of 3-4 percent, while models predicted VMT growth of only 1-2 percent. In addition, errors often have been concentrated in fast-growing parts of the region (typically the suburbs) and among certain categories of traveler (in particular, women.) This has led air quality agencies to seek a better understanding of travel forecasting methods and their performance, and to ask for assurances that the sources of past errors have been understood and corrected. Periodic comparisons of traffic counts and other measured data with forecasts are expected to provide a basis for model evaluation, problem diagnosis and correction.

Instead of refining model-based estimates, an alternative would be to simply base VMT, trips, and vehicle ownership estimates on extrapolations from past trends. However, using extrapolations in air quality planning and model-based estimates in other aspects of the transportation planning process could lead to awkward divergences in estimates (unless transportation model results were adjusted to agree with trend projections). This could entail some risk for an MPO. In addition, model-based projections of growth can take into account numerous details concerning changes in the composition, location, and magnitude of population and employment, whereas most extrapolations are much simpler and hence much less rich in their reflection of factors underlying posited changes. Thus model improvements designed to improve forecasts of VMT and other travel indicators seem the preferable route to most analysts, even though such improvements may be relatively costly and time-consuming.

2.1.3 Conformity Analyses

The conformity provisions of the Clean Air Act Amendments will pose one of the biggest challenges most metropolitan transportation organizations will face in transportation-air quality planning and analysis. Both federal actions and certain activities of the MPOs themselves are subject to the conformity provisions, which basically require that plans, programs, and projects must conform to the applicable State Implementation Plan (SIP) for achieving clean air, and must be found not to lead to new violations of the National Ambient Air Quality Standards, exacerbate existing violations, or interfere with attainment of the standards or compliance with interim emissions reduction requirements.

The conformity provisions focus a spotlight on models' credibility in estimating medium- to long-run plan and program impacts. For example, under the interim guidelines for determining the conformity of transportation plans and programs to SIP assumptions and commitments, the MPO is required (among other things) to compare the full Transportation Improvement Program (TIP) for the non-attainment area with a no-build scenario. Once a revised SIP is approved, the comparison will be to motor vehicle emissions estimates and necessary reductions contained in the SIP. Both types of analyses are likely to be subjected to close scrutiny by environmental and other interest groups, who will seek a demonstration that all phenomena which plausibly could affect such a comparison have been taken into account.

2.1.4 TCM Analyses

Under the CAA Amendments of 1990, only the more heavily polluted metropolitan areas are required to include transportation control measures (TCMs) in their SIPs (see Section 2.3). However, many other areas are required to include TCMs under state law (e.g., California nonattainment areas), or will do so by choice after considering the available pollution control options. ISTEA further encourages the consideration of TCMs and related strategies. As a result, estimates of TCMs' effectiveness will be sought by numerous regions.

The inclusion of TCMs in regional transportation modeling has often proven to be a complex matter. Capital investments which also happen to be TCMs (such as transit extensions or HOV lanes) generally can be adequately represented in regional model systems, but many other TCMs (e.g., rideshare incentives offered in some corridors only, transit subsidies available only in some areas or to some users) are likely to place heavy demands on regional travel data and models. Moreover the typical regional model is unequipped to handle a plethora of TCMs, including signal timing, ramp metering, elements of employer-based demand management programs, many land use and urban design measures, and (sometimes) pricing strategies.

Evidence from a variety of TCM implementation experiences has been compiled as a basis for initial screening of TCMs, and simple sketch planning methods sometimes embody this evidence in spreadsheets. While these methods are useful if carefully applied and thoughtfully interpreted, the use of “transfer of experience” approaches to justify TCMs has proven vulnerable to challenges, for example by business groups that are unhappy about proposed employer-based requirements and by environmental groups distrustful of benefits claimed for added HOV lanes and traffic flow improvements. Hence MPOs may find that they either will have to extend the behavioral reach of their models (e.g., by adding explanatory variables that are relevant to TCMs) or will have to find ways of grafting credible off-model (or supplementary model) estimates of TCM impact onto conventional model results.

2.2 Other MPO Analysis Needs

Clean Air Act transportation analysis requirements are pressing, but they are not the only (or perhaps even the most critical) forces for change in regional travel modeling. Other developments include the following:

- Provisions of the Intermodal Surface Transportation Efficiency Act (ISTEA) permit much greater state and local discretion in allocating funds between transit and high-ways and among levels of the highway system. This will intensify the concern over how well models capture the long-run effects of distinctly different infrastructure alternatives - on travel time and cost, and on location patterns - particularly for comparisons between transit-oriented and highway-oriented programs.
- Congress has broadened the scope of citizen suits under the Clean Air Act, and for the first time the US Secretary of Transportation can be a legal target. There is reason to anticipate that shortcomings in meeting the analysis requirements of the Clean Air Act may result in legal actions against MPOs and other entities which approve allegedly "deficient" plans - environmental groups have already put several agencies on notice to this effect.
- Computer work station technology has brought travel demand analysis within reach of groups outside the traditional transportation planning community. For example, environmental groups in Boston, Los Angeles, Portland (OR), and the San Francisco Bay Area have shown an interest in developing independent transportation modeling capabilities. While, conceptually, it might be good to have competing analyses of difficult policy questions, competing models will present problems for MPOs unless it can be shown that "official" MPO models are equally or more current, comprehensive, and accurate.
- Increasingly, concerns are raised about whether project-level analyses are consistent with the analyses conducted at the regional level. A typical question might involve whether project assumptions in an environmental document agree with assumptions made in the earlier TIP analysis. Because of differences in analytical and reporting detail between project analyses and regional model system analyses, it can be quite difficult to determine this. In particular, facilities often are not represented in enough detail in the regional model system to support clear determinations of project consistency. This has led to pressure for greater detail in regional networks (and more careful and disaggregate reviews of accuracy), so that most facilities of local import also will be found on the regional system with plausible volumes and speeds.

All of these developments suggest that it would be prudent for MPOs to review their analysis capabilities and make improvements where warranted. Such an exercise can be expected to reveal many legitimate issues that cannot be resolved at the current state-of-the-art or with available resources. Thus, the result of a review is likely to include a program for immediate action with existing resources, a program for longer-term action with enhanced resources, and a program of research. The short-term programs might be undertaken by each individual MPO, whereas the longer-term actions and research efforts might be a joint effort of MPOs with pooled resources and/or federal and state assistance.

2.3 Review of Clean Air Act Transportation Requirements

As the overview of transportation-air quality planning analysis requirements has illustrated, the Clean Air Act Amendments of 1990 affect transportation planning in a variety of ways. Because of the importance of this legislation for many MPOs, a detailed review of key provisions is presented in this section.

2.3.1 General Provisions

The Clean Air Act (CAA) Amendments of 1990, like the Amendments of 1970 and 1977, rely on a combination of locally-developed State Implementation Plans (SIPs) and federally mandated controls for attainment of national ambient air quality standards for ozone (0_3), carbon monoxide (CO), oxides of nitrogen (NO_x), and particulates (PM10) by statutory deadlines. However, the 1990 Amendments greatly expand and add specificity to the requirements for ozone and carbon monoxide nonattainment areas. They also establish for the first time deadlines which vary with the pollutant and the severity of the pollution problem, with later deadlines but more extensive requirements for the more polluted areas.

Titles I and II of the Clean Air Act set forth air pollution prevention and control and emissions standards for moving sources, respectively. Among other things, Title I establishes the process for designating and classifying nonattainment areas; authorizes EPA to determine nonattainment area boundaries; defines nonattainment area classifications; establishes deadlines and requirements to match the severity of pollution; sets forth plan development procedures and review criteria; and defines criteria and schedules for imposing sanctions (highway and emission offsets) and for promulgating Federal Implementation Plans (FIPs).

Title II directs the federal government to require a variety of mobile source controls, including tighter hydrocarbon, carbon monoxide, and NO_x tailpipe emission standards to be phased in for cars and trucks beginning with 1994 models; reduced new-car evaporative emissions during refueling; more tightly controlled fuel quality (e.g., controlled for volatility and sulfur content); mandated re-formulated gasoline (beginning in 1995) for the most severely polluted ozone nonattainment areas; oxygenated fuels during winter months for areas designated as Moderate or Serious for nonattainment of carbon monoxide standards; and a clean fuel pilot program for Los Angeles. Transportation planners will depend, to a very large extent, on the emissions reductions which should result from Title II programs, and will follow the provisions of Title I to develop such other measures as may be needed to meet the ambient air quality standards by the applicable deadlines.

Sections 110 (Implementation Plans) and 172 (Nonattainment Plan Provisions In General) of Title I cover requirements which apply to all nonattainment areas' State Implementation Plans. These sections of the Amendments set forth objectives and procedures for SIP adoption and revision, and require enforceability and timely implementation of control measures.

Section 110(a)(2) states that each implementation plan shall:

- include enforceable control measures and schedules for compliance necessary to meet the Act's requirements.
- provide necessary assurances that the state (or general purpose local governments or regional agencies) will have adequate personnel, funding, and authority under state and local law to carry out the implementation plan (and is not prohibited by any provision of federal or state law from carrying out the implementation plan.)
- provide necessary assurances that, where the state has relied on a local or regional government agency for the implementation of any plan provision, the state has responsibility for ensuring adequate implementation of such plan provision.
- meet requirements for intergovernmental consultation and participation in plan development, and for enhanced public notification on pollution and health, public awareness of control measures, and public participation in regulatory actions.

Section 172© requires that nonattainment areas' SIP revisions must:

- provide for the implementation of all reasonably available control measures as expeditiously as practical.
- require reasonable further progress (RFP) - defined as "such annual incremental reductions in emissions as...may reasonably be required...for ensuring attainment of the...standard by the applicable date."
- include contingency measures to take effect without further action by the state or EPA, if the plan fails to make RFP, or to attain the standard by the applicable attainment date.

Other provisions of Title I establish due dates and deliverables. The time allowed for the first major submissions under the 1990 Amendments is short. Updated emission inventories, including current and projected mobile source contributions to total emissions, were due in November 1992. Revised SIPs also were due in November 1992 in CO nonattainment areas (at the same time as the updated emissions inventories), and in November 1993 for ozone nonattainment areas. These plans must include control measures as needed to demonstrate attainment by the applicable deadline(s).

Beyond these tight initial deadlines, the Amendments emphasize a continuous transportation-air quality planning and decision-making process. Updates of state and local planning procedures, renewals of assignments of responsibility, and provisions for involvement of elected officials are mandated. Nonattainment areas must periodically assess VMT, vehicle trip levels, congestion, and emissions, and based on their findings must prepare SIP revisions as needed to offset emission levels which exceed those assumed in the SIP. EPA's Transportation-Air Quality Planning Guidelines are to be updated as necessary to maintain a continuous planning process, and must include methods for reviewing plans on a regular basis. Determinations of the conformity of transportation plans, programs, and projects to the SIP must be made not less frequently than every three years, with revisions to transportation proposals as needed. Finally, the U.S. Department of Transportation (DOT) and EPA must submit a report to Congress every three years beginning in 1993, assessing how well federal, state and local air quality-related transportation programs are achieving the goals of, and compliance with, the Clean Air Act.

2.3.2 Emissions Inventories and Emissions Budgets

One SIP revision activity of critical interest to transportation agencies is the determination of emission reduction targets for transportation. Based on the updated emissions inventories, the respective contribution of stationary and mobile sources to total emissions and pollution levels will be determined. This will result in an "emission reduction budget" being assigned to mobile sources, i.e., to the transportation sector.

Emission reduction budgets will indicate the clean-up burden that will be placed on transportation plans and programs, as well as the extent to which transportation control measures (TCMs) will be needed. Also, staying within this budget will be one of the tests of transportation plan and program conformity with the SIP. If unrealistically large emission reduction targets are assigned to transportation sources and placed in the SIP, conformity demonstrations will be difficult to make; without such demonstrations of conformity, projects could be delayed or stopped. Thus it is in the best interest of transportation agencies, including state DOTs and MPOs and interested local agencies, to participate in the evaluation of relative emission contributions and the needed mix of stationary and mobile source controls.

2.3.3 Transportation Control Measures

Transportation control measures (TCMs) are required only for some nonattainment areas and for some circumstances under the 1990 Amendments. Otherwise the choice of whether to use TCMs and what TCMs to use is discretionary with state and local officials, as long as the overall set of control measures can reduce emissions to show attainment by the applicable deadlines). Nevertheless, many areas will need to analyze a range of TCMs, as many are likely to need to implement at least some of them in order to meet interim milestones as well as ultimate deadlines.

Metropolitan planning organizations will play a key role in analyzing TCMs and in recommending which ones should be included in the SIP. MPO roles are further underscored by the Intermodal Surface Transportation Efficiency Act (ISTEA), which gives MPOs increased responsibility for and control over the programming of projects within their boundaries, and in nonattainment areas provide special funds for TCM implementation (congestion management/air quality funds).

Once TCMs are adopted in an approved SIP, their timely implementation will be a key criterion in future conformity determinations. If TCM implementation does not proceed on schedule, conformity demonstrations could be difficult to make, with the result that projects requiring federal approval or assistance could be delayed or stopped.

EPA has issued several documents to assist in the planning, analysis, and implementation of TCMs, including an update of its 1978 Transportation-Air Quality Planning Guidelines as well as information on the 16 TCMs listed in Section 108 (Cambridge Systematics et al., March 1992). These documents can serve as valuable starting points for MPOs in deciding how to proceed with TCM evaluation.

The Transportation-Air Quality Planning Guidelines produced by EPA cover planning and programming activities necessary to respond to CAA transportation requirements. Developed with input from US DOT and state and local officials, this document's primary purpose is to provide guidance for the planning and implementation of transportation measures needed to achieve emission reductions in accordance with CAA requirements. The guidelines include information on how to:

- identify and evaluate alternative planning and control activities;
- review plans on a regular basis as conditions change or new information is presented;
- identify funds and other resources necessary to implement the plan, and obtain interagency agreements on providing such funds and resources;
- assure participation by the public in all phases of the planning process; and
- carry out a continuous planning process.

The TCM information documents provide general guidance on the emission reduction potential of each type of TCM, discuss other benefits and costs of TCMs, and identify implementation issues. This information is intended to serve as a starting point for TCM evaluation. It is not, however, a substitute for locally-conducted analyses of TCMs, nor for local consultation on various measures' acceptability. State and local transportation and air quality officials must determine what measures are "reasonably available" (i.e., are cost-effective and feasible) in their urban area based on the characteristics of the region's transportation systems, its population and employment characteristics, its institutional and financial capacities, and community responses to the various proposals.

2.3.4 Conformity

Section 176© of the CAA requires departments, agencies, and instrumentalities of the federal government to assure that activities which they engage in, assist, approve, fund, license, or support in any way are in conformity with applicable State Implementation Plans. Similar requirements apply to metropolitan planning organizations in approving projects, programs, and plans. EPA, with DOT's concurrence, is responsible for promulgating criteria and procedures for demonstrating and assuring conformity.[4]

The CAA states that conformity to a SIP means conformity to the plan's purpose of eliminating or reducing the severity and number of violations of the National Ambient Air Quality Standards, and that activities will not cause or contribute to a new violation of any standard, increase the frequency or severity of an existing violation, or delay timely attainment of any standard or interim milestone. In addition, transportation plans and programs can be found to conform only if: (1) emissions from such plans and programs are consistent with emissions projections and reductions assigned to those transportation plans and programs in the SIP, i.e., are consistent with the emissions budgets or targets;

[4] EPA and DOT issued interim conformity guidance on 6/7/91. Final guidance, due 11/15/91, was under review at the time of this writing.

and (2) the plans and programs provide for timely implementation of SIP TCMs consistent with SIP schedules.[5]

2.3.5 Sanctions

Sanctions for failure to comply with the CAA, including the withholding of funds for certain highway projects, were an option under the 1977 Amendments, but EPA imposed these sanctions in a very limited fashion. For example, since 1980, EPA imposed highway sanctions in just seven states, and in five of these states the sanctions were applied to just one urban area. Moreover in three of the seven states, the sanctions were in effect for less than two months; in two others they were in effect for less than two years. Overall, few highway projects were delayed and few federal highway dollars were withheld.

Highway sanctions may increase in importance under the 1990 Amendments. First, because certain other sanctions were deleted, highway funding restrictions could become the primary sanction available. Second, highway sanctions can now be applied statewide under certain circumstances. Third, while sanctions formerly were applied only when an area failed to submit, or make reasonable efforts to submit, a SIP, sanctions now may be triggered when EPA disapproves a SIP or a state fails to make any submission required by the Act or implement any provision in an approved SIP. Moreover, highway sanctions can be imposed for failures not related to transportation or mobile sources (e.g., for failures related to stationary source measures). Finally, EPA discretion in determining when to impose sanctions has been reduced, with the Amendments making more explicit the criteria that could result in highway funding restrictions and prescribing a relatively limited list of projects that can be exempted from sanctions (high occupancy vehicle (HOV) incentives, single-occupancy vehicle (SOV) disincentives, and congestion relief measures.)

2.3.6 Specific Requirements for Ozone Nonattainment Areas

[5] Conformity determinations differ in the interim period (until a SIP revision is approved) and thereafter. In the current, interim period, plans and programs must show expeditious implementation of TCMs and contributions to annual emissions reductions; projects must come from conforming plans and programs and, for projects in CO nonattainment areas, eliminate or reduce the severity and number of CO violations in their vicinity. Once SIP revisions are approved, conformity will be based on consistency with the area-wide transportation emissions budget for the area plus TCM implementation.

Specific requirements apply to ozone nonattainment area SIPs, in addition to the general SIP requirements described earlier. Deadlines and other requirements are based on the severity of ozone pollution.[6] Requirements are cumulative and escalate in stringency by nonattainment area classifications as the severity of pollution worsens. The six classifications, corresponding design values, and attainment dates are as follows:

Classification	Design Value (PPM)	Attainment Date
Marginal	.121 - .138	11/15/93
Moderate	.138 - .160	11/15/96
Serious	.160 - .180	11/15/99
Severe 1	.180 - .190	11/15/05
Severe 2	.190 - .280	11/15/07
Extreme	.280 and above	11/15/10

Based on the information available at the time of this writing there are 42 areas classified as Marginal, 31 classified as Moderate, 14 as Serious, nine as Severe, and one as Extreme for ozone nonattainment.

Areas with the worst air quality must implement the greatest number of and the most stringent controls. For example, areas classified as Moderate must require Reasonably Available Control Technology (RACT) for stationary source controls on new and existing 100-ton sources of volatile organic compounds (VOC) (not covered by EPA Control Technique Guidelines); Serious areas must require RACT on 50-ton sources; Severe areas must control 25-ton sources, etc. Emissions from new sources are subjected to increasingly more stringent offset requirements, ranging from a 1.1 to 1 offset in Marginal areas to a 1.5 to 1 offset in Extreme areas. Vehicle inspection/maintenance programs similarly must be more rigorous in the more polluted areas.

An area's classification also determines the number and stringency of transportation requirements, covering both the planning and programming of transportation control measures imposed by the Act.

[6] Note that the ozone is not directly emitted but forms in the atmosphere through a photochemical reaction involving VOC and NO_x, emissions. Accordingly, the emissions inventories of concern in ozone nonattainment areas are for VOC and NO_x. States must submit comprehensive inventories of actual emissions from all VOC and NO_x sources in accordance with EPA guidance. The initial due date for the emissions inventory is 11/15/92. Updates are required every three years.

Reasonable Further Progress (RFP) requirements may be among the most difficult for MPOs to meet. Ozone areas classified Moderate and above must submit SIP revisions by 11/15/93 that demonstrate the achievement, by 11/15/96, of a 15 percent VOC emission reduction from a 1990 baseline (defined as an area's total, actual VOC and NO_x emissions during 1990.) In addition, emissions due to growth must be offset. Reductions from several federal mobile source control programs promulgated before the 1990 Amendments were adopted, including tailpipe standards, evaporative emissions controls, and fuel volatility standards, may not be credited toward the 15 percent reduction.

Less than a 15 percent 1990-1996 reduction would be acceptable only if the 1993 SIP revisions (1) implement new source review requirements applicable to Extreme areas, (2) apply RACT to all existing major sources, (3) implement all measures that can be feasibley implemented in the area, in light of technological feasibility, and (4) demonstrate that the plan contains control measures achieved in practice by similar sources in nonattainment areas of the next higher classification.

Additional RFP requirements apply for those areas classified as Serious or worse. A SIP revision due 11/15/94 for such areas must demonstrate an additional VOC reduction of 3 percent annually, averaged over each consecutive three-year period after 1996 until attainment. This RFP requirement also excludes major federal mobile source control measures promulgated prior to 1990. However, reductions from federal measures promulgated after 1990 could be credited toward the annual 3 percent reductions required after 1996. Reductions of less than a 3 percent annual average can be allowed only if conditions (3) and (4) listed above are met.

Neither the required reductions nor the alternative conditions are expected to be easy to meet, and many areas are likely to need to implement TCMs to meet RFP requirements.

The scheduled emission reduction requirements applying to Serious, Severe, and Extreme ozone nonattainment areas are called milestones. The first milestone is the 15 percent reduction from 1990 VOC levels, to be accomplished by 1996; the next milestones are the 3 percent annual average reductions over each consecutive three-year period thereafter, until attainment is demonstrated (subject to the options for lesser reductions if other conditions are met, as described earlier.) Areas must demonstrate to EPA that these milestones have been met. Areas failing to submit a compliance demonstration or to meet a milestone must choose one of the following: (1) re-classify to the next higher category and implement more stringent requirements, (2) implement additional control measures from the applicable contingency plan, which could include TCMs, or (3) adopt an economic incentive and transportation control program.

Table 2.1: TCMs Listed in Section 108(f) of the 1990 Amendments	
1.	Programs for improved public transit
2.	Restriction or construction of certain lanes or roads for use by buses or HOVs
3.	Employer-based transportation management programs, including incentives

4.	Trip reduction ordinances
5.	Traffic flow improvement programs that achieve emissions reductions
6.	Fringe and corridor parking facilities serving HOVs and transit
7.	Programs to limit or restrict vehicle use downtown or in other areas of emission concentration, particularly during peaks
8.	HOV/ridesharing service programs
9.	Time or place restrictions of road surfaces or areas to bikes and pedestrians
10.	Bike storage, lanes, and other facilities, public and private
11.	Programs to control extended vehicle idling
12.	Programs to reduce extreme cold start emissions
13.	Employer-sponsored programs to permit flexible work schedules
14.	Localities' SOV trip reduction planning and development programs for special events and major activity centers including shopping centers
15.	Pedestrian and non-motorized transport facility construction and reconstruction
16.	Programs for voluntary removal of pre-1980 vehicles.

Section 182(g)(4), dealing with the consequences of missing VOC milestones, states that an economic incentive program may include state-established emission fees, a system of marketable permits, fees on the sale and manufacture of products the use of which contributes to ozone formation, and incentives and requirements to reduce vehicle emissions and vehicle miles-traveled in the area, including any of the transportation control measures identified in Section 108 (f). Revenues from such a program are to be used to handle administrative costs (not more than 50% of total revenues) and/or to provide emission reduction incentives and assist in the development of lower-polluting control technologies and products.

Milestone requirements may trigger TCMs in areas classified as Serious or worse.[7] Section 182(c)(5) of the 1990 Amendments states that beginning in 1996 and every third year thereafter, such areas must

[7] As noted earlier, TCMs are required only for some areas and for some circumstances under the 1990 Amendments. Areas designated as Marginal or Moderate for ozone nonattainment are not

submit a demonstration as to whether current aggregate vehicle mileage, aggregate vehicle emissions, congestion levels, and other relevant parameters are consistent with those used for the area's demonstration of attainment. If levels are found to exceed those projected in the attainment demonstration, a SIP revision must be submitted within 18 months to reduce projected emissions to levels consistent with those in the attainment demonstration. Such a SIP revision must include transportation control measures including, but not limited to, measures selected from those listed in section 108(f) (Table 2.1).

Probably reflecting concerns about TCMs, the Amendments indicate that in selecting TCMs states should ensure adequate access to downtown and other commercial areas, and avoid measures that increase or relocate emissions and congestion rather than reduce them. This language also appears in the section for Severe areas.

TCM requirements apply earlier to areas classified as Severe or worse. For these areas the 1992 SIP revisions must identify and adopt transportation control strategies to offset emission increases due to growth in VMT and vehicle trips, to achieve, in combination with other controls, the required periodic emission reductions, and to demonstrate attainment.

Employer Trip Reduction Programs also are required in Severe areas and must be included as part of the areas' 11/15/92 SIP revisions. This is the only TCM whose implementation is specifically required in the 1990 Amendments. At a minimum, employers with 100 or more employees must implement programs to reduce work-related employee VMT and vehicle trips, and must increase the average vehicle occupancy of employee work trips by at least 25 percent above the area average. Employer plans, due by 11/15/94, must "convincingly" demonstrate compliance by 11/15/96.

Areas classified as Extreme nonattainment for ozone must implement all the transportation requirements for Moderate, Serious, and Severe areas. In addition, each SIP revision for Extreme areas may contain provisions applicable during heavy traffic hours, to reduce the use of high polluting or heavy duty vehicles, notwithstanding any other provision of law. Note that the language is permissive, i.e., the use of such measures is discretionary. Currently, only Los Angeles is classified as an Extreme ozone nonattainment area.

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specifically required to consider TCMs. However, many such areas are likely to utilize TCMs as emissions reduction strategies because the RFP requirements will be difficult to meet without TCMs, because TCMs are required under state law, because TCMs are deemed necessary to fairly allocate responsibility for pollution reduction and to efficiently reduce emissions, etc.

2.3.7 Specific Requirements for CO Nonattainment Areas

Two classifications of CO nonattainment areas are defined in the 1990 Amendments: Moderate (design value 9.1 - 16.4 ppm; attainment date 12/31/95); and Serious (design value 16.5 ppm and up: attainment date 12/31/00). Moderate areas are divided into two sub-classes, with those having a design value greater than 12.7 ppm required to undertake more stringent measures.

Inventories of CO emissions from all sources are required at the same time as the VOC and NO_x inventories, 11/15/92. Updates are required every three years thereafter, beginning 9/30/95. By 11/15/92, Moderate CO nonattainment areas must submit a SIP revision showing the specific annual emission reductions necessary for attainment of the CO standard by 12/31/95. However, SIP revisions for all CO nonattainment areas with a design value over 12.7 ppm must contain forecasts of VMT for each year until attainment, and must provide for annual updates of forecasts and annual reports containing estimates of actual VMT and an assessment of VMT forecast accuracy. The 11/15/92 SIP revision also must provide for the automatic implementation of specific measures if “actual” VMT exceeds the VMT forecasted, or if an area misses the attainment deadline. These contingency measures are to take effect without further action by the state or EPA, and thus will require advance planning. (Note, however, that for most areas EPA expects that the Reasonable Further Progress (RFP) requirement to be more of a constraint than the offset requirement.)

Required mobile source controls for CO nonattainment areas are: 1) oxygenated fuels of at least 2.7 percent oxygen content during high CO season (design value of 9.5 ppm or above, SIP revision due 11/15/92); 2) enhanced I/M (design value above 12.7 ppm, SIP revision due 11/15/92); and 3) clean-fuel vehicle fleet programs (design value above 16 ppm, population greater than 250,000, SIP revision due 5/15/94). TCM requirements for Serious CO areas are similar to those for Severe ozone areas. By 11/15/92, areas classified as Serious for CO were to have submitted SIP revisions that identify and adopt transportation control strategies, with implementation of such measures as necessary to demonstrate attainment. These transportation strategies must offset growth in emissions due to growth in VMT and vehicle trips. Additional documentation, not required for Serious ozone areas, is required for Serious CO areas: their November 1992 SIP revisions were also required to 1) explain a failure to adopt any section 108 (f) measure, 2) contain alternative control measures providing comparable emission reductions, or 3) explain why such reduction is not necessary for attainment.

Areas classified as Serious further must submit a demonstration by 3/31/96 showing that the emission reduction specified in the 1992 SIP revision and required by 12/31/95 has been achieved. If the demonstration is not submitted or the milestone is missed, a SIP revision must be submitted within nine months which implements an economic incentive and transportation control program and achieves annual emission reductions needed for attainment by 2000 or sooner. Note that the economic incentive and transportation control program is mandatory when the milestone is missed by a Serious CO nonattainment area, whereas ozone areas that miss a milestone can choose one of three options.

The considerable emphasis put on reducing CO emissions via transportation actions reflects the fact that CO emissions come mostly from mobile sources. However, states and MPOs still will need to determine what mix of strategies will best match its specific CO problems. Since CO concentrations typically are localized rather than region-wide, TCMs which focus on "hot spots" may play a significant role.

CHAPTER 3: CURRENT ANALYSIS PRACTICE

3.1 Introduction

This chapter describes the transportation analysis and travel forecasting methods that are in current use in regional modeling applications across the country. The chapter begins with a general overview, or "prototype", of current practice. It then looks in more detail at each of the key steps in modeling metropolitan travel phenomena. Acceptable approaches in widespread use among MPOs and other agencies with modeling responsibilities are reviewed, and advanced practices used by some MPOs are presented. Practices that are not recommended or that are recommended only, perhaps, as stopgap approaches are noted.

In many instances practice varies with the particular issues facing the region: for example, the importance of transit, the level of congestion prevalent in the highway network, the degree of concern about growth, the complexity of urban and regional development patterns. Such variation is desirable, reflecting a focusing of attention and resources on the key considerations requiring analysis.

On the other hand, some of the variation in practice is simply the result of differential commitments of resources to the development and upkeep of analysis capabilities. In some regions, data sets and models have been evaluated thoroughly, updated regularly, and used innovatively. In other regions, funding and staffing levels have been insufficient to carry out periodic data collection and model updates. As a result, these MPOs have only sparse and aging data bases, and their analysis capabilities have not kept up with advances in the profession. Some have had to resort to ad hoc "fixes" to produce plausible analysis results. In light of Clean Air Act and ISTEA analysis requirements, MPOs are likely to find continued use of old data and outmoded models increasingly untenable. This chapter is intended, in part, to suggest current norms and to encourage all MPOs to modernize their practices.

Throughout the chapter, alternative modeling approaches which can be matched to particular circumstances are noted. Data requirements and data sources also are discussed. Because of the importance of travel surveys in supporting model development as well as more wide-ranging analyses, a final section of the chapter focuses on survey practices and issues.

3.2 A Prototype of Current Practice

This review and discussion reflects upon "conventional modeling practice". Since there is, in fact, a wide range of practice in evidence, it will be helpful to clarify what is considered prototypical for the purposes of this report. A brief overview of this prototypical modeling approach is depicted in Figure 3.1 and is discussed below.

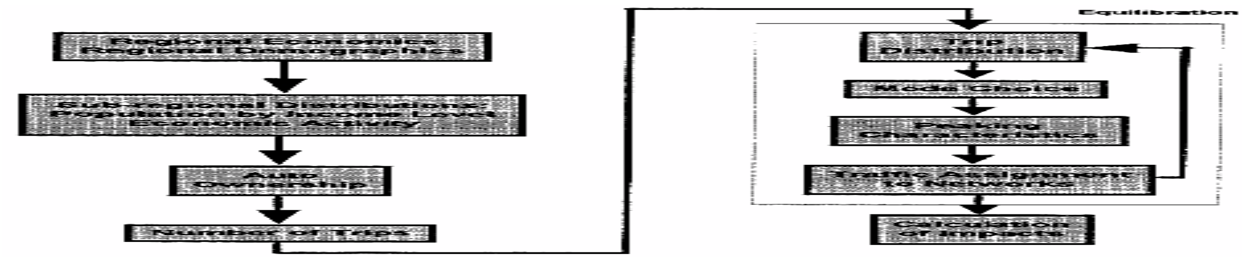
Conventional travel demand analysis follows a straightforward behavioral paradigm based on knowledge and experience accumulated over the past four decades. In this paradigm, travel demand is derived from the daily activities of individuals and businesses. The goal of analysis is to infer from the spatial distribution of activities the amount, type, and location of travel that a population will undertake. Regional travel forecasting requires: 1) gathering a very large number of data inputs at the lowest practical level of aggregation; 2) obtaining plausible forecasts of data inputs such as population, income, and fuel price; 3) developing models to accurately represent travel behavior; 4) and applying the models to the forecasted data inputs to produce useful forecasts of future travel patterns. Good modeling results can be achieved only if both the input assumptions and the technical methods used are adequate.

Travel demand analysis relies on knowledge of where individuals, businesses, and other places of activity are located (or will be located). In the case of forecasts, this is typically done in several steps: economic growth (basic employment) is estimated, then population growth stimulated by those jobs is estimated, then population-serving employment and attendant population increases are estimated. The resulting jobs and population (or households) are then allocated to small areas, or zones, of the region (typically, based on aggregations of census blocks, or in some cases, tracts.) Information on household income, business characteristics, and existing and planned land uses may be used to guide this effort.

Travel demand analysis also requires knowledge of the resources available to households and individuals in making their daily activity and travel decisions. Of particular importance are household auto ownership and household or worker income (projected into the future, in the case of forecasts). Here, estimates are developed from survey data or federal and state records and projections.

A third requirement is knowledge of the performance of the transportation infrastructure available to each traveler. This infrastructure is described as networks of facilities through which transportation service is provided: networks are built to represent peak and off-peak conditions on key highways, transit, and (in some cases) HOV facilities; rarely, bicycle and pedestrian facilities are represented in additional networks. Highway networks typically include limited access facilities, arterials, and (sometimes) collectors, but few if any local access streets. The network is described as a system of links and nodes. So-called “dummy links” are used to represent the average travel times from the centroid of the zone to the network, and hence account in aggregate terms for the portion of the network not specifically modeled.

Figure 3-1: Conventional Regional Travel Models



The population and employment forecasts, allocations to zones, and transportation networks become the inputs or "givens" in the demand modeling process. They are used in conjunction with a set of models of travel behavior which, together with the abstracted demographic, economic, and infrastructure data, produce predictions of travel demand.

In nearly every application, the travel demand models are built using data from surveys of a sample of households. The surveys typically gather demographic and economic information for each household, plus a travel diary recording all the trips each household member made during the survey period (generally one day.) The survey data are used to estimate the coefficients of a hierarchy of models that mirrors a supposed hierarchy of behavior by travelers. Trips are separated into several purposes (such as home-work/work-home and home-shop/shop-home), and each purpose receives separate modeling treatment.

The elements of this hierarchy of travel demand models are commonly called "steps." In the first step, the trips likely to originate and terminate in each zone are calculated ("trip generation"). For example, in the case of home-work/work-home, the number of work trips attracted to a zone is given by the predicted number of employees in that zone (as determined by the economic/demographic forecasts mentioned earlier). The number of work trips produced in a zone is determined by the adult population of the zone and the propensity of adults to be employed. The most common form of trip production model is a cross-classification table which provides average work trip rates for, say, different ranges of household income and different household sizes (exact variable definitions vary greatly). Some trip production models employ regression equations fit to the local survey data. Some, moreover, consider only vehicle trips (not person trips), while others separate vehicle trips from person trips through additional steps.

In the second model step, trip productions and trip attractions are matched to yield a full spatial pattern of trip-making ("trip distribution"). This can be thought of either in collective terms (e.g., job opportunities are matched with residential locations) or in household terms (households choose work places based, in part, on proximity to home, choose residential locations based, in part, on proximity to work, or consider both simultaneously). The typical trip distribution model represents interzonal travel volume as a function of trips produced in the origin zone, trips attracted to the destination zone, an approximate measure of the "cost" of travel between zones (usually the highway travel time), and the comparative attractiveness of competing zones. Because the relationships underlying trip distribution are quite complex and the models used are rudimentary, modelers usually find it necessary to introduce a number of adjustment factors (called “K factors”) to achieve acceptable model fit. These factors are retained when the model is used in forecasting.

In the third model step, interzonal travel volumes (differentiated by trip purpose) are split among the available modes of travel (“mode split”). In the typical case, trips made by vehicles have been separated from the total flow of person-trips in one of the earlier steps, and the mode split model focuses on major vehicular modes only. The mode split usually is depicted as a choice (“mode choice”) based on the traveler's personal characteristics, dollar costs of travel, and various components of travel time, with different weights depending on the qualitative character of each time component. Mode choice models are without question the most econometrically sophisticated elements of conventional travel demand analysis, with the vast majority employing at least a multinomial logit form, and with some venturing into more elaborate nested logit or probit forms.

At this stage, the analysis has produced an interzonal trip table for each mode and trip purpose. These tables now are rearranged to create new trip tables to represent each time period for which the analyst wishes to study the traffic performance of the infrastructure: Mode- and purpose-specific peaking factors based on calculations from the home-interview survey, or occasionally factors developed through a peaking model, are applied to estimate the number of trips of each type that will be made during the peaks and off-peak. Typical time periods are am peak, p.m. peak, and mid-day. Additional adjustments may be made to capture the unique conditions of particularly congested corridors (e.g., flatter peaks under highly-congested conditions).

In the fourth (and usually final) travel demand modeling step, trips in the mode- and time-specific trip tables are assigned to paths in their respective infrastructure networks (“traffic assignment.”) The implied network performance (i.e., interzonal time characteristics) is calculated based on the volume expected on each link. The assignment algorithm typically assumes that each traveling party will attempt to minimize its individual cost (“generalized cost”) for each trip. Some approaches iterate over a number of partial assignments to capture the way that congestion can build at different rates in different parts of the system; the resulting assignment is unlikely to be a true “equilibrium,” but is considered adequate when the iteration steps are small enough. Other approaches calculate equilibrium directly.

There is an obvious tautological character to the conventional four-step travel demand modeling process: the trip distribution and mode split stages depend on estimates of interzonal travel time, yet definitive estimates of travel time are not available until the end of the calculation process (after completion of traffic assignment). Analysts handle this recursive relationship in different ways. All begin with an estimate of the travel time matrices, for instance by loading a factored version of the most closely comparable trip table onto the highway network. Trip distribution and mode split then are performed with the approximate travel times. The resulting trip tables are loaded onto the networks, and new travel time matrices are computed. The initial and final travel time matrices are compared, and the presence of only minor differences is taken to indicate that equilibrium conditions have been satisfied.

It is in the event of a significant difference that practice tends to vary. Some analysts iterate through trip distribution, mode split, and traffic assignment several times until trip tables and travel time matrices stabilize, under the assumption that consistency of travel times throughout the model system is a logical expectation. Others iterate only through mode split and traffic assignment. The latter approach often has its basis in resource constraints and outmoded software rather than in any compelling theoretical justification, although some analysts argue that current trip distribution models are so approximate in their representation of spatial relationships that they can hardly support an analysis of marginal travel time effects.

The entire analysis procedure is dependent on a supportive ensemble of software. Some analysts still use mainframe programs such as the Urban Transportation Planning System (UTPS), which can require a high degree of hardware familiarity and programming skill.

Others have switched to one of the workstation or PC versions that replicate and, to some degree, augment the functionality of the old mainframe software (MinUTP, Tranplan). Still others have chosen from among the software packages that attempt to fully exploit the features of the workstation environment (EMME/2, TransCAD, System 2). The graphical capabilities of the workstation environment have simplified the problem of network and database maintenance, but it remains true that the mechanics of carrying out all of the steps of a conventional modeling exercise require substantial analysis time.

Characteristics of the conventional modeling approach that have generated particular criticism include the following:

- networks are often too sparse, or are described in too little detail, to accurately represent transportation supply
- mode split and traffic assignment are often treated in a recursive framework with feedback and approximate equilibration, but the feedback loops only sometimes extend to trip distribution
- similar feedback loops do not extend to trip generation, to auto ownership, or to the pattern of activity location in the region, although theory would suggest that each would be affected
- time of travel and peaking are treated in highly approximate ways
- route choice and accessibility are often defined in terms of travel time rather than a broader measure encompassing cost or other indicators of quality of service.

In addition, in many conventional modeling approaches, analyses focus on vehicular trips while ignoring or downplaying trips made on foot or by bicycle, and focus on home-based travel while treating non-home based travel in highly approximate ways.

To put this critique into perspective, it is important recall the origin and predominant use of existing urban travel models. By and large, these models were developed to help size capital facilities, especially highways. In effect, the standard analysis question of the past might be framed as:

Given the anticipated level and pattern of travel for the region, how much additional capacity is needed, and where should it be located?

In recent years, versions of conventional models have been used for single mode corridor planning. For example, suppose a decision has been made to implement transit in a corridor. The primary questions might be: 1) how much capacity is required? 2) what are the effects of alternate technologies (as represented by access, wait, in-vehicle, and transfer travel times and travel costs) on ridership? and 3) what are the effects of alternate operating plans (frequency, number of stops, etc.) on ridership? Most analysts have been comfortable assuming that future demographic and socioeconomic conditions, trip generation levels, trip distributions, and peaking factors will remain relatively constant among alternatives under such tightly-constrained conditions. The primary questions then revolve around intra-corridor modal competition and route choice. For these questions the conventional modeling approach arguably suffices.

Use of the models for certain other planning applications can be problematic, however. When transportation investments' ability to shape growth and spur economic activity are key concerns, models that treat land use and development, destination choice, and vehicle trip generation as unaffected by transportation levels of service are clearly not helpful. When the policy under consideration would differentially price congested facilities and merchants are worried about the potential for driving away shoppers, models which use only travel time and not cost in predicting destination choices will be unconvincing. Transportation-air quality planning raises these questions and others as well - seeking, for example, the ability to analyze policies that favor walking, bicycling, alternative work schedules, and a variety of other transportation demand management strategies, and calling for accurate link-level speeds in order to calculate emissions. Thus, current concerns about conventional urban models stem as much from the changing nature of the problems being posed as from the formulations of the models per se.

3.3 Key Model Elements in Detail

Each of the following subsections covers a key modeling step or model component in greater detail. The objective of the modeling step or component is presented, needed data and assumptions are described, and some typical approaches and more advanced practices are discussed, with brief examples. Particular attention is given to the aspects of the model component having greatest relevance to transportation-air quality planning. A brief summary is presented below.

Economic and population forecasts at the regional level (discussed in Section 3.3.1) are often taken from federal or state sources, although a few areas do their own projections. The most common practice is to use state or federal estimates of the region's growth. Some regional agencies develop their own population and employment forecasts as a check on the federal/state estimates, or as the basis for alternative estimates or scenario testing.

Forecasts of land use and development patterns (Section 3.3.2) often are developed through negotiations over local plans. Some areas use formal land use allocation models either by themselves or linked to transportation forecasting steps.

Network descriptions (Section 3.3.3) are prepared for highways and transit, typically using the responsible operating agencies' current maps or inventories and their plans for the future. The level of detail in which networks are described is a major source of variation among regions, both as to the types of facilities represented (in particular, whether all arterials and major collectors are included) and the treatment of special network features such as high occupancy vehicle lanes, ramp meters, and intersection movements. The representation of link speed and capacity also varies greatly among regions, particularly in the number of capacity classifications and range of speed-volume relationships included.

Vehicle ownership (Section 3.3.4) typically is estimated from survey data using cross-classification or regression techniques, with income and household size two commonly utilized variables. A few areas model the choice of vehicle ownership level as a function of household size, income, number of workers, transit and highway accessibility, etc.

Trip generation (Section 3.3.5) estimates also are commonly based on cross-classification tables or regressions, with auto ownership and household size as typical variables. Advanced practice considers a wider variety of variables affecting trip-making, including specific land uses, socioeconomic characteristics, and demographic and lifestyle factors. In a few cases sophisticated modeling approaches such as travel frequency choice have been applied.

Trip distribution (Section 3.3.6) is typically carried out using a “gravity”-type model of spatial interaction. Some formulations improve the behavioral content of these models by incorporating detailed descriptors of zonal characteristics associated with the production and attraction of trips, as well as by including both time and cost factors in the impedances. Advanced practice represents this modeling step as “destination choice”.

Mode split (Section 3.3.7) is nowadays carried out in most areas using choice models that represent major vehicular modes (drive alone, shared ride, transit). Nested logit models for transit choice have become common in advanced practice, e.g., the rail vs. bus choice is nested within the transit option of a transit vs. auto choice, and/or the various transit access modes (walk, drive and park, drop-off, and sometimes others) are nested within the transit option.

Peaking and time of travel distributions (Section 3.3.8) commonly have been derived from counts at key locations or from travel survey data, an approach which, when used in forecasting, treats these matters as insensitive to congestion levels and invariant over time. Post-processor methods have been used to adjust peaking on specific facilities or corridors in accordance with the congestion levels observed there. More advanced practice is to develop explicit behavioral models of time of travel.

Traffic assignment (Section 3.3.9) frequently utilizes incremental assignment methods, though some regional agencies have adopted advanced algorithms that estimate network equilibrium directly. Considerable variation remains in the specification of link impedances (generalized prices) used in these methods and algorithms, with the more advanced applications utilizing both time and cost variables.

3.3.1 Regional Economic and Population Forecasts

Overview

Conventional travel demand analysis employs a straightforward behavioral paradigm in which travel demand is derived from the daily activities of individuals and businesses. Hence regional economic and population forecasts are fundamental to the forecasting process.

Economic growth, for which employment is the usual indicator, is typically forecasted first. Population then is forecasted as a function of the size of the economy as well as demographic trends. In a common formulation, basic employment is estimated, then population growth stimulated by those jobs is estimated, then population-serving employment and attendant population increases are estimated. Adjustments in these estimates may be made to bring total regional population and employment into balance, or (particularly when the regional agency's jurisdictional boundaries are smaller than the region's economic boundaries) differences may be attributed to commuting.

Forecasts of the regional economy commonly are based upon state control totals for economic activity including employment (which totals often are based, in turn, on federal projections of regional economic activity). Population forecasts similarly are derived, in many cases, from federal/state estimates. However, some areas produce their own independent forecasts. These vary widely in their sophistication, ranging from trends-extended analyses to detailed modeling studies. Some regions' models mirror federal and state forecasting approaches, utilizing data on industrial advantage of the region, e.g., comparative shares and growth rates of industries by SIC code, and/or data on earnings, income, land and housing prices, cost of money, resource prices, construction costs, taxes, etc. Some regions further add a qualitative component to their forecasts as a means of accounting for such factors as quality of life. Regions with independent forecasting capabilities have been known to successfully negotiate changes in the federal/state estimates based on their own more detailed work.

The accuracy of employment and population forecasts has not been entirely satisfactory in some regions, particularly (but not only) those in which a large component of total employment is in emerging industries and those which have experienced high population growth rates due to interregional migration or international immigration. A number of regions produce a range of forecasts to reflect the underlying uncertainties in their estimates.

Immigration (legal and illegal) has been an especially problematic component of population forecasts for a number of regions. Immigration rates are hard to forecast because of the underlying difficulties in predicting relative performance of national economies, and because immigration rates can be strongly affected by such factors as war, political oppression, drought, and trade agreements. The complexities spill over into employment forecasting, e.g., immigrant communities often have high rates of informal employment, and regions with a sizeable informal economy tend to have greater difficulties in relating employment and population growth than do regions where informal employment is minor.

In comparison, natural population growth (births and deaths) has been reasonably easy to predict. The birth rate has been the more difficult to forecast, especially so in light of changing ethnic composition, family structure, and social attitudes. The prediction of the interregional migration component of population growth - in-migration and out-migration also has been problematic for many regions.

Basic Practice

The use of regional economic and population forecasts (regional totals) taken from federal or state sources is not only an acceptable practice but, in some cases, is mandated. On the other hand, many regional agencies produce and use (when permitted) their own estimates. The reliability of regionally produced forecasts is entirely dependent on the quality of the underlying data and models.

Simple trends-extended models of population or employment have been used from time to time in regional studies, but they have not proven particularly reliable. Even less reliable, however, are "bottom-up" estimates, in which local plans and projections are put together to form the regional plan and regional growth estimates. The main problem with this approach is that local jurisdictions often mix normative and positive views of the future, meaning that some forecasts are merely hopeful while others attempt to be realistic. In taking a normative approach, local jurisdictions have tended to overestimate their shares of regional employment growth and underestimate, or in any event not accommodate, their shares of regional residential growth. it is not unusual for employment projections aggregated from local plans to total several times the federal/state growth estimates for the region, and for the implied housing needs to far exceed the expected supply of housing.
Because of the methods' unreliability, neither the trends-extended nor bottom-up approach is recommended as the primary basis for travel forecasting, although both trends projections and "bottom-up" estimates can offer useful points of comparison for checking other, more complex forecasts.

Alternative regional forecasts based on detailed studies can, in contrast, be as reliable as federal/state projections, and in some cases are likely to be more accurate.

Advanced Practice

A number of advanced techniques have been employed in growth forecasting at the regional level, including:

- Demographic models to predict regional control totals of population and households; regional share models to predict employment by category
- Input-output models to trace the effects of industrial growth and decline and changes in production on the regional economy

- Detailed simulation models of regional demographic and economic change, for example, accounting for differential birth rates and life expectancies by ethnic group, forecasting educational attainment by family income level and employment rates by income and ethnic group, etc.
- Special studies carried out to better understand and forecast growth or decline in particular industries, population groups, or lifestyle categories.

Among the regional agencies making use of some of these techniques are the Association of Bay Area Governments, Portland Metro, the Sacramento Area Council of Governments, and the Southern California Association of Governments.

Given all of the potential sources of uncertainty, there is much to be said for a scenario-based treatment of regional population and employment forecasts. Under such an approach, assumptions would be varied within reasonable bounds to produce a range of plausible forecasts. Each transportation policy scenario then would be analyzed for "high" and "low" population and employment scenarios, as well as for some midpoint between the two. To make effective use of such information, a planning process must provide sufficient resources for analysis, and must be capable of supporting a search for robust policies (that are adaptable within the identified range of uncertainty). Individuals and institutions must be tolerant of ambiguous outcomes. Because this combination of features rarely is present, most regions find it simpler to identify a "best estimate" for use in planning, ostensibly in order to avoid having conflicting forecasts or inconsistencies in the forecasts prepared for various purposes.

Advanced practice currently does not include efforts to model a causal link between transportation conditions (expenditures and accessibility) and the regional economy. Nevertheless, such links must exist, or else the magnitude of investments we have made in transportation infrastructure (especially highways) would hardly make sense (see, e.g., Garrison, Berry, et al. [1959] and Mohring and Harwitz [1962]). In fact, transportation project documents often make reference to the economic stimulus and growth enabling characteristics of specific investments. However, in practice it has been difficult to separate intra-metropolitan locational effects of infrastructure investment (i.e., competition within a region for fixed totals of jobs and population, as discussed in Subsection 3.3.2) from the true acceleration of regional economic growth.

It is possible to approach the question of economic stimulus through application of an advanced input-output methodology. As this is being written, FHWA plans to fund a study to demonstrate such an approach. However, it will be some time (if ever) before the analysis of regional economic effects can become a routine step in travel impact analysis.

3.3.2 Employment and Population Allocation

Overview

Once regional totals have been estimated, the next analysis step addresses the number of jobs and the population (or number of households) that will be located in each subarea, or zone, of the region (typically, based on census tracts or aggregations or disaggregations of census tracts). Information on existing and planned land uses, business characteristics, household employment and income, and zonal transportation access may be used to guide this effort, which is typically (if somewhat inaccurately) referred to as land use forecasting.

Growth and development are often politically sensitive topics, and regional agencies' forecasts of how population and employment will be distributed in the future are sometimes seen as affecting who gets what. One result has been that land use forecasts are of great concern to, and often must be approved by, localities and their political leadership.

Three broad approaches are commonly used to produce population and employment allocations. Negotiated estimates and scenarios typically are based on their preparers' judgment and normative desires, whereas formal mathematical models typically assume strong market forces are at work and often ignore or downplay political and institutional constraints.

1. Negotiated estimates (currently used in one form or another in nearly all U.S. metropolitan areas) draw upon local plans and projections as the basis for subarea and zonal growth forecasts. Overall population and employment forecasts may be apportioned to specific locations using a simple ratio approach: total growth is assumed to locate in various jurisdictions as a proportion of their estimated growth (e.g., everyone gets 67% of their projections.) Alternatively, growth allocations may be determined through negotiations among local jurisdictions; in one approach, regional agency staff facilitate meetings in which each local jurisdiction's anticipated growth rate is compared to historic performance and market potential, and compromises are struck. Some areas develop both population and employment estimates in this manner and bring them into agreement in a regional plan through negotiations over the planned balance of houses and jobs. Depending on the nature of the agreement, market realism may or may not result.

2. Scenario approaches involve the construction of two or more land use and development alternatives for a future year (scenarios), each of which is then modeled in combination with various transportation options. Two distinct approaches to the development of scenarios are in use:
   - Visionary plans focus on how the region "should" look in the future, i.e., they are highly normative. The visionary plan may be the creation of a limited number of actors - usually urban planners or designers - but it can be developed through a wide-ranging participatory process as well, if ample time is allowed. Typically the visionary plan is compared to a trends-extended plan (i.e., one that continues current policies and patterns of investment) to provide a framework for discussing broader questions about transportation and land use directions. The approach has been used in several metropolitan areas recently.
   - Policy options focus on the choices actually available to decision-makers (or which could become available with identified legislative changes, e.g. regional requirements for compact growth) to develop feasible directions for land use and development. These options are generally constructed in relation to alternative transportation packages which are under consideration. In contrast to the visionary plan approach, which as typically carried out is unconstrained by funding or other implementation considerations, the policy options approach

emphasizes the specification and testing of land use options which are financially feasible and reflect market realities. Specification of the options may be done by regional agency staff, or may be carried out through a cooperative effort which draws upon a wide range of expertise and interests, including economists, real estate specialists, environmentalists, business leaders, and community groups as well as regional agency planners and analysts.

3. Formal mathematical models for land use allocation forecasting also have been developed, but currently are in use is in a minority of regions in the US. In large part this reflects the political and policy sensitivities involved in land use allocations. However, it also is the case that many regional agencies and localities are skeptical about land use models, both because the models themselves are relatively limited in their policy sensitivity and because to date, the forecasts they have produced have not been highly accurate.

From the mid-1970s until relatively recently, the trend in the U.S. was for regional agencies to disregard or downplay the importance of land use modeling; a number of agencies actually replaced formal models with simpler trend-based projections and allocations. Interest in land use models remained strong overseas, however, and modeling advances were made both there and in a few instances in the US. Recently, the resurgence of interest in the linkages among transportation, urban form, and the environment have helped renew interest in formal land use allocation models.

Theoretical work has shown that accessibility is an important determinant of the worth of land for different uses at different locations, and that transportation investments tend to support housing decentralization and business clustering. This is not to say that land use is a simple function of transportation; other factors including the cost and suitability of land and buildings, labor market conditions, the quality and availability of local government services, and such considerations as social class, race, and lifestyle have been shown to have significant impact on location decisions. Nevertheless, approaches which simply treat land use as exogenous to transportation forecasting are known to be deficient from a theoretical point of view, and are increasingly challenged in areas where major transportation infrastructure investments are proposed, where growth and development are rapid, or where land use policy is of key interest for other reasons.

A number of analysts have attempted to develop practical forecasting tools for use in urban land use and transportation planning (see Hamburg, Kaiser and Lathrop (1983), Berechman and Small (1987), Webster et al. (1988), and Bajpai (1990) for detailed reviews of such models.) In general terms, these models allocate jobs and housing within a region as functions of accessibility, land availability, population and employment by category, income (for households), and other factors. Such models are often complicated and expensive to run but nevertheless make several simplifying assumptions not wholly in accord with theory.

First, the behavioral content of many land use allocation models is quite low. For the most part the models do not attempt to represent the location decision-making of either firms or households; instead they rely, with varying levels of sophistication, on extrapolation of past trends subject to a set of constraints. Representation of such factors as economies of urbanization and agglomeration is at best implicit in the models. Furthermore, household allocation models are work-trip driven; but other travel undoubtedly is a factor in household location decisions (this is especially likely for households without a worker, but applies to working households as well). While discrete choice models of household location seem to have promise (see, e.g., Legman, 1975; McFadden, 1978; Weisbrod et al., 1980; Anas, 1982, 1985; Boyce and Kim, 1987; Harvey, 1990), these models remain research tools (they have yet to be implemented in practice), and equivalent models of business location choice have not yet emerged.

Current allocation models contain several specific limitations which may restrict their utility. One limitation has to do with the range of variables considered in modeling location and land use. Currently, most allocation models describe transportation access in terms of highways only, yet in many cases the impact of transit access on land use is a key policy issue. Land availability by zone is generally described in terms of amount, current use, and general zoning category. Yet it is well understood that the availability of sewer, water, and other infrastructure and services, tax rates, crime rates, and a variety of other factors also have strong influence over location decisions, in addition to land availability per se. (Several of the discrete choice models cited earlier include these variables, which are often highly significant.)

Another limitation is that the models do not account for, or only weakly account for, market responses such as shifts in land values and rents and their impact on the intensity of uses of both existing and new development. Finally, the time leads and lags which occur in transportation-land use interactions are poorly represented. (Here, too models have been developed which address these concerns but have not found their way into US practice.)

In view of these limitations it is not entirely surprising that in many applications land use allocation models have had only moderate predictive capability. At the same time, they are increasingly viewed as preferable to approaches which simply ignore transportation-land use interactions.

Basic Practice

While an increasing number of metropolitan areas now have formal growth allocation modeling capabilities, the use of these models is not yet sufficiently widespread for them to be considered a requirement of basic practice at this time. Instead, the basic approach draws upon less formal allocation methodologies.

In general, population and employment allocations which are firmly grounded upon data analysis, with or without models, are preferable to approaches based primarily on the aspirations of localities or individuals, untamed by market or political realities. Both negotiated allocations and scenario-based allocations can be acceptable if they are supported by evidence and defensible forecasts. Negotiated estimates can be acceptable if the negotiations are disciplined by data and forecasts of growth and development trends, including expected transportation investments and levels of service, as well as by local jurisdictions' policies and desires for growth and development.

Acceptable negotiated approaches typically will be based on employment data and employment trends, population data and trends, information on land availability and price, land use occupancy and rent data, information about zoning and other land regulations, local and regional economic development plans and market assessments, data on building permits and construction starts, measures of current and anticipated transportation accessibility, and so on. Approaches which use simple fair share allocations or allocations based solely on local aspirations are not recommended except perhaps for scenario testing (for example, to investigate what would happen if cities' plans came true.)

Allocations developed as part of a scenario testing exercise similarly are acceptable to the extent that they are based on data and data-based forecasts. Scenarios that are based more on normative concepts of good development patterns than on past trends and feasible policy directions can provide useful information for policy makers. However, such scenarios should not be confused with forecasts; a particular scenario cannot be assumed to describe an expected or even a likely future unless the necessary commitments have been made to move toward implementation. This is particularly a consideration for the visionary plan approach, since as noted above, the visions are not necessarily constrained by assessments of feasibility; however it remains a concern with regard to the more feasibility-driven policy options approach, unless the policy options have actually been adopted. Analysts should take care to ascertain that any land use assumptions derived from such scenario tests are in fact reasonably feasible and implementable, since unrealistic assumptions might subject later analyses (including conformity assessments) to challenge.

Advanced Practice

Advanced practice draws upon formal mathematical models to allocate regional growth. These models typically use zone-level time series data on population, employment, land availability, and accessibility to allocate regional population and employment forecasts to subareas.

The main allocation modeling approach now in use in the US is DRAM/EMPAL, components of the software package ITLUP (Putman, 1983, 1991), which was developed as an addition to the standard four-step transportation model (and was in fact distributed at one time as a supplement to UTPS). DRAM/EMPAL can be used alone or as part of an integrated transportation and land use package.

The employment allocation sub-model, EMPAL, allocates employment to zones using exogenous forecasts of total employment by type (basic and non-basic), together with zone specific employment levels and growth trends and zone-specific measures of accessibility to the work force. The residential allocation sub-model, DRAM, then forecasts the future location of households given this distribution of employment and the attractiveness (including accessibility) of the zones. Future year land consumption also is forecasted using base year information and exogenous forecasts.

DRAM and EMPAL are based on singly-constrained spatial-interaction model formulations incorporating multivariate attractiveness functions. Potential employment in zone j occupying workers from zone i is calculated on the basis of the previous population of zone i, the previous attractiveness of zone j (as indicated by jobs and land area), and the current disutility of travel between the zones. Future employment at zone j then is calculated as a function of previous employment and the total potential in j from all worker-generating zones, i=1, N. Similarly, the number of households living in zone i is treated as a function of the attractiveness of zone i (in terms of developable land) and the accessibility of zone i to employment zones. An additional factor in the attractiveness equation has the effect of ensuring that households of similar types will tend to cluster together.

ITLUP's data requirements include, on a zonal level: employment for each distinct employment “sector” (3 to 5 are usual); population by category (four income groups are usual); land allocation by activity; and transportation descriptors (links, speeds, capacities). Data on employment by sector for the period subsequent to the base year are used for calibration. Forecasts require estimates of regional employment by sector, regional population by category, and trips per person by trip purpose, as well as future networks (links, speeds, capacities). Forecasts are done on a zonal level and in five-year increments, with output from one forecast year becoming the input for the next.

Land use outputs include employment by sector, population by income group and working/non working category, land allocation by activity, and vacant land. Travel outputs include trips by origin/destination and purpose; trips by purpose, income group and mode; average travel time by origin/destination and mode; and energy consumption by trip purpose, social/car ownership group, and mode. Air pollution estimates are an additional option.

While DRAM/EMPAL is by far the most commonly used land use model in the U.S., a variety of other models have been developed which are worthy of note. One group of models is based on optimization techniques; in this group are POLIS (Prastacos, 1985a, 1985b), which is currently used in the San Francisco Bay Area; the Herbert-Stevens model, formerly used in the Penn-Jersey Transportation Study and now being revisited by researchers (Herbert and Stevens, 1960); and TOPAZ (Brotchie et al., 1981), originally developed in Australia and used widely there as well as in a few U.S. applications (see, e.g., Dickey and Leiner, 1983).

A particularly interesting approach is incorporated in the various versions of MEPLAN (Echinique, 1987), a land use allocation model used in a number of overseas applications but not yet implemented in the US. In MEPLAN, the location of economic activities and the interactions between them are predicted by an input/output model. The input/output model represents movements of labor, plus the demand from industry and households for services, floor space and land. Households are differentiated by socioeconomic group, having different qualifications for labor and differing consumption demands. Supply and demand (for both activities and space) respond to 'prices' which may be expressed in money terms or as disutilities. An interzonal matrix of 'trade flows' between production and demand zones is produced, subject to specified constraints on production in particular zones, and a distribution matrix is developed based on elasticities of travel conditions and prices. Interzonal flows are then converted to trips by purpose and by socioeconomic group. For example, households' consumption of goods gives rise to shopping trips. In some regional applications of MEPLAN, freight flows are generated directly from commodity movements. Not surprisingly, the added detail and sophistication of the MEPLAN model comes at a cost: the model is highly data hungry and its specific applications are time-consuming.

Advanced practice still falls short on several fronts, undoubtedly reflecting the theoretical and practical limitations described earlier. Despite such weaknesses, thoughtfully applied allocation models are usually improvements over simpler methods for distributing population and employment to subareas. The development and refinement of such models are recommended especially for those regions where the pattern of growth is a major issue.

3.3.3 Network Descriptions

Overview

Network descriptions are prepared for highways and transit and are used as the basis for calculating travel times, estimating levels of service, and producing a variety of other performance indicators. The level of detail in which networks are described is a major source of variation among regions, both as to the types of facilities represented (in particular, whether all arterials and major collectors are included) and the treatment of special network features such as high occupancy vehicle lanes, ramp meters, and intersection movements. The representation of link speed and capacity also varies greatly among regions, particularly in the number of capacity classifications and range of speed-volume relationships included.

The introduction of microcomputers and workstation computer technologies has greatly facilitated transportation network development and modeling. In particular, visual interactive editing capabilities and vastly improved data checking capabilities have speeded up network coding and editing tasks and have considerably reduced the risk of errors.

Basic Practice

Usually regional agency staff draw upon responsible operating agencies' current maps or inventories and their plans for the future in describing networks. The typical network description for highways covers major facilities (usually freeways, expressways, and major arterials), while the typical transit network covers all rail and bus routes. Although buses almost always operate on certain of the links coded in the highway network, in many applications, there is no connection between the highway and transit networks. The practical implication of this artificial separation is that in modeling applications, congestion that appears on the highway network is not automatically reflected in the transit travel times.

Currently many MPOs do not provide separate descriptions of HOV facilities, ramp meters, etc. HOV treatments sometimes are dealt with by hand-adjustments to travel times for affected O-D pairs; similarly ramp metering may be handled via travel time adjustments. Many MPOs, however, simply do not consider these measures in the modeling process and resort to supplementary methods (off-line calculations) to account for their effects.

Some MPOs have not included all the major arterials in their networks, largely because of resource constraints. While in some limited cases a sparse network may be sufficient, there is a growing consensus that networks should include all facilities to the minor arterial or major collector level. A useful rule of thumb in assessing the adequacy of network coverage is whether at least 85 percent of all interzonal travel would occur on the facilities represented in the network.

Advanced Practice

Advanced practice involves the inclusion of a greater number of facilities in the highway network (e.g., minor arterials and significant collectors); explicit coding of special network features such as high occupancy vehicle lanes, ramp meters, and intersection details; and use of a larger number of capacity classifications and a wider range of speed-volume relationships. In addition, separate rail transit and bus transit networks are being coded, each with considerable detail describing access modes (and in some cases extending to separate networks specifically depicting the transit access options.) Such network detail may be needed to support nested logit mode choice models (described below.)

Some regions have adopted software packages which permit network nodes to be given explicit characteristics (e.g., transfer time at a transit terminal). Software also may feature subarea focusing - the ability to represent a network in different levels of detail. The latter feature is particularly useful in ensuring consistency between regional-level analyses and more detailed project-level analyses. In addition, some regions are beginning to experiment with the use of traffic operations simulation models for highly detailed analyses of particular links, corridors, and subareas. The results of these focused analyses may be fed back into the demand modeling system, or may be used to produce more accurate speeds and other measures of effectiveness. This approach is currently being demonstrated in a major California project.

GIS systems are beginning to be implemented as a framework for transportation modeling and are proving to be particularly supportive of network coding applications, although the lead time to become a skilled GIS user can be substantial. Use of a GIS system facilitates the integration and graphical network-oriented representation of a variety of data bases, including HPMS data and the data from pavement management systems, bridge management systems, safety evaluations, and congestion management efforts.

3.3.4 Vehicle Ownership

Overview

Vehicle ownership models predict the number of passenger vehicles owned by (or available to) households in a particular travel analysis zone, or in a specific market segment within a zone. The use of vehicle ownership models reflects the fact that households' travel decisions are strongly related to the availability of vehicles; individuals in households without vehicles must make their trips as passengers in other households' vehicles, by walking or bicycling, or must use public transit. Households with fewer vehicles than licensed drivers must work out vehicle sharing arrangements or priorities of access to the available vehicles. Finally, households with one or more vehicles per licensed driver are free to make single-occupant drive trips to meet all of their travel needs, if they wish. In each of these cases, the average trip length, the fraction of trips made by private vehicle, the average vehicle occupancy level, and, possibly, the number of person trips, are all likely to be directly related to the number of vehicles owned. The net effect is that vehicle-miles of travel and other measures of vehicular travel consumption per household vary significantly as vehicle ownership changes.

In metropolitan areas which do not use vehicle ownership models, other modeling steps often exhibit strong relationships between the households' propensity to travel and household income levels. The accuracy of these model systems can be quite good when income is well specified as an explanatory variable, because of the strong correlation between income and vehicle ownership. However, where residential densities and levels of transit service are high enough to affect vehicle ownership levels, increased forecasting accuracy can be obtained by the explicit prediction of vehicle ownership.

All vehicle ownership models can be used to obtain forecasts of the total number of vehicles owned per travel analysis zone, but many are formulated to predict intermediate variables rather than zonal totals. These intermediate variables include the average number of vehicles per household, or the fractions of households owning or having available zero, one, two....vehicles. In the latter case, the last ownership category is typically either the fraction owning 2+ vehicles or the fraction owning 3+ vehicles. Usually, the upper category is evaluated at an average ownership value taken from survey data, which has the effect of treating it as constant. This has been a source of inaccuracy, since the actual values have tended to rise over time.

While vehicle ownership models are generally applied at an aggregate (zonal) level, they invariably are developed on individual household data. Income is a primary determinant of vehicle ownership. Other variables include:

- Household size (number of persons per household);
- Licensed drivers (number of adults with license);
- Gender (number of licensed adults who are female);
- Labor force participation (number of workers per household);
- Housing type (single family detached or multi-family, for example);
- Employment density in the residence zone;
- Area type and density of the residence zone (CBD, urban, suburban or rural, for example);
- Measures of accessibility by auto and transit between home and work trip destinations by transit and/or auto;
- Measures of accessibility to potential non-work destinations by transit and/or auto.

Many of these variables are correlated with income, which necessitates care in model estimation.

Basic Practice

Typically, MPO models of vehicle ownership or vehicle availability incorporate only socioeconomic variables as factors affecting the predicted levels; no transportation or accessibility variables are used. Elimination of transportation and accessibility variables greatly simplifies the task of developing and applying a model. For example, a simple vehicle ownership forecasting tool can be developed in the form of cross-classification tables from household-level Census or travel survey data, without any upward linkage from the transportation models. The advantages of this simplicity are offset, however, by the resulting models' insensitivity to changes in levels of service by auto and/or transit.

EXAMPLE: DETROIT

The Southeast Michigan Council of Governments (SEMCOG) estimates vehicle availability using sets of empirical curves for the fraction of households owning zero, one, two, and three or more vehicles as a function of household income level (11 categories). The curves are stratified by household size (one, two, and three or more persons) and by residence zone area type (City of Detroit or other). The present curves were derived from 1977 Annual Housing Census data for the Detroit metropolitan region.

As might be expected, vehicle ownership in the SEMCOG model tends to increase with income, with household size, and with suburban location. The highest zero-vehicle fraction occurs for one-person households in the lowest income group living in urban zones. Even in suburban zones, however, the lowest four income groups had fractions of households with zero vehicle ownership of more than six percent.

SEMCOG uses its vehicle availability curves to predict the number of households per zone (given zonal household totals) at each vehicle availability level in each of 25 household categories defined by household size (one, two, three, four, and five or more) and income range (income quintiles). The results are recombined into twenty categories, defined with respect to household size and vehicle availability (i.e., the income dimension is collapsed).

Table 3.1 MTC Worker Household Auto Ownership Model

	Coefficient Variable	Variables in the Utility			Explanation
		0 Vehicles	1 Vehicle	2 or More	
1	4.989		const		One vehicle ownership constant
2	5.689			const	2+ vehicle ownership constant
3	.3935		sinfam		Constant for single family detached unit
4	1.342			sinfam	Constant for single family detached unit
5	-.05419		eden	eden	Workers per acre in the home zone

6	-2.689		autos/hhsize	autos/hhsize	Autos per person in household. The variable "autos" has the value 1 for v-1 and 2.25 for v-2+.
7	.5608	tshop			A measure of the quality of transit service from the home zone for non-work trips, defined as the sum of transit utilities divided by the sum of auto utilities for the shopping destination/mode choice model.
8	.06814	$twork_0$	$twork_1$	$twork_{2+}$	A measure of the quality of transit service from the home zone for work trips. Defined as the household head's work trip transit utility divided by the sum of work trip drive and work trip shared ride utilities.
9	.7919	$\ln(rinc_0)$	$\ln(rinc_1)$	$\ln(rinc_{2+})$	Natural log of the remaining income after housing, auto ownership, and commuting expenses are taken into account.

These twenty categories are then available as input to trip generation (person trips by purpose) using home-based trip production rates per household cross-classified by household size and vehicle availability.

The curves presently in use were derived from 1977 Census Annual Housing Survey data for the Detroit metropolitan region. Updated curves could be developed from more recent census or travel survey data, such as the Public Use Micro Sample (PUMS) from the 1990 Census of Population and Housing.

The SEMCOG vehicle availability model illustrates both the strengths and the weaknesses of basic practice. On the positive side, the model is straightforward and parsimonious, it derives from data that should be readily available for most metropolitan areas (perhaps from multiple sources), and it captures the long-recognized primary relationship between household income and household vehicle ownership. On the negative side, the model ignores gender, workforce participation, and age distribution, which have contributed significantly to the recent growth in vehicle ownership, and it relies on the city-suburb distinction as a crude proxy for the combined effects of factors as diverse as socioeconomic status, land use patterns, and quality of transit service. Considering the magnitude of ongoing changes in urban social and economic structure, it is likely that such a model would be prone to drift farther from reality as the base year of analysis (or the forecast year) became more removed from the calibration year.

Among other things, this implies that frequent recalibration of the model on up-to-date data would be highly desirable.[8]

Advanced Practice

Advanced vehicle ownership models use socioeconomic and accessibility-type variables in their specifications. The resulting models provide greater policy sensitivity and usually are more accurate, although they also increase the costs of model development and application. Advanced auto ownership models have typically, but not necessarily, been structured as multinomial logit choice models which predict the fractions of households owning various numbers of autos (zero, one, two.....).

EXAMPLE: PORTLAND (OR)

[8] The above critique implies that vehicle ownership models can achieve greater explanatory power by including more detail about household structure, land use, and transportation accessibility. Indeed, models incorporating such variables do tend to provide a stronger fit to the data. However, some practitioners would argue that such detail is not necessarily helpful in a planning tool if it requires highly speculative forecasts of additional independent variables (such as trends in female workforce participation). Others would counter that greater detail in the model is always better (as long as it meets appropriate statistical criteria), because one gains a clearer understanding of potential sources of forecast inaccuracy even if meaningful forecasts of complex social indicators prove impossible to obtain. In the latter case, it is always possible to ignore the additional variables (by substituting current average values) or to use a range of hypothetical values as the basis for future scenarios.

The Portland Metro vehicle ownership model is a multinomial logit household-based model with four alternatives: zero, one, two, and three or more vehicles per household. The independent variables are household size (one, two, three, and four or more), household income class (four categories: less than $15,000 per year in 1985 dollars, $15,000-24,999, $25,000-34,999, and $35,000 or higher), workers per household (zero, one, two, and three or more), and the number of employment opportunities within thirty minutes of transit time from the residence zone. The first three independent variables are socioeconomic factors typical of those used in many vehicle ownership models. The final variable, however, is related to the land use pattern in the study area and the level of transit service available or proposed in the study area. Because this variable has a coefficient which decreases as the vehicle ownership level increases, it results in predictions of reduced vehicle ownership levels in residence zones from which many employment opportunities can be reached by transit. In the Portland case, the result is lower predicted levels of vehicle ownership mainly in zones within thirty minutes of transit travel time from the Central Business District. These results appear to be consistent with the Portland survey data, which show that the fractions of households owning zero vehicles are 10 and 52 percent, respectively, in the City of Portland and in the Portland CBD, and less than four percent in the remainder of the study area. Tests of the Portland model indicate that its sensitivities to household income and workers per household are comparable, and substantially higher than the sensitivity to household size.

Metro uses its vehicle ownership model to predict the number of households per zone at each vehicle ownership level in each of 64 household categories defined for a specific household size, income range, and number of workers. Each of these categories has four possible values, as discussed above. The variable “jobs within 30 minutes of transit time” is derived from the distribution of employment data as specified in the land use plan for the alternative being analyzed, and from transit network skim tree travel times, which depend on the transit network and service levels as specified in the transportation plan. Since in Metro's models highway congestion levels affect transit travel times, transit travel times are only available via a feedback loop after highway and transit assignments are completed. Metro thus must iterate its model system, including its vehicle ownership model, until the transit travel times used as input to the auto ownership model are consistent with those predicted in the assignment phase.

Recent work testing a “pedestrian amenities” variable has found it to be important, with higher amenities related to lower auto ownership.

EXAMPLE: SAN FRANCISCO BAY AREA

The Metropolitan Transportation Commission (MTC), the MPO for the San Francisco Bay Area, uses two auto ownership models, one for households with workers and one for households without workers. Both are multinomial logit models with three alternatives: zero, one, and two or more autos per household. The worker-household model takes the form:

$$P_v = \frac{\exp(U_v)}{\sum_{k=0}^{2+} \exp(U_k)}$$

where:

P_v is the probability of choosing vehicle ownership level v;
U_v is the household's utility for vehicle ownership level v;
k represents the set of vehicle ownership levels:
k=0 zero autos in household;
1 one auto in household;
2+ two or more autos in household.

The utility definitions are shown in Table 3.1. For example the utility of owning one auto is:

$$U_1 - 4.989 - .3935xsinfam - .05419xeden - \frac{2.689}{hhsize} + .06814\ xtwork_1 + .7919xln(rinc_1)$$

In general, the MTC model captures a relationship between vehicle ownership and:

- Fraction of households in the residence zone which are single-family detached.
- Employment density (workers per acre) in the residence zone.
- Household size.
- Remaining annual income after deducting housing, auto ownership, and commuting costs from annual household income.
- The quality of transit service for shopping trips, relative to that for auto travel, from the residence zone. This variable is defined as the zone's shopping accessibility by transit divided by the shopping accessibility by auto. Mode-specific accessibilities are obtained as sums of exponentiated utilities from a combined destination/mode choice logit model for shopping trips.
- The quality of transit service for the household head's work trip, relative to that for auto travel. This variable is defined as the zone's work trip accessibility by transit divided by the work trip accessibility by auto. Mode-specific accessibilities are obtained as sums of exponentiated utilities from the logit mode choice model for work trips.

The first two of these variables are zonal or socioeconomic factors typical of those used in many auto ownership models. The remaining variables are all composites which include elements specific to the household's socioeconomic characteristics, housing type, work trip destination, land uses in potential destination zones, levels of service by both auto and transit, and the auto ownership level of the alternative for which the utility is being computed. In the MTC forecasting system, each is computed separately by household category (based on the number of workers in the household) and by the mode of travel to work of the head of household. Taken together, these variables result in predictions of lower levels of auto ownership in zones with good transit service, and inhibit auto ownership levels which are inconsistent with income levels. Conversely, auto ownership levels are increased in zones without transit service.

For a number of reasons, these examples of advanced practice are not entirely satisfactory. For instance, both the Portland and the Bay Area models will assign non-trivial probabilities to options that imply more than one vehicle per licensed driver (e.g., in single person households, which now constitute about 20 percent of all urban households). While it is true that many households do acquire large vehicle fleets exhibiting specialization (e.g., commute vs. weekend travel), the results of this "extra" vehicle acquisition in terms of travel patterns are very different from the results of vehicle acquisition that provides basic access to another licensed driver. At a minimum, this suggests either that auto ownership choice sets should be conditioned on the number of licensed drivers in the household, or that ownership options above the number of licensed drivers should be assigned a much smaller utility increment. Alternatively, the most advanced practice might dictate that two auto ownership predictions should be made: one to capture the total number of vehicles in the region (for fleet related purposes such as diurnal emissions calculations) and one to capture the substantive effects on trip-making.

Despite these caveats, it is true that both of the examples shown here include representation of the key influences on auto ownership - household structure and transportation accessibility - and in so doing provide useful prototypes for advanced practice.

3.3.5 Trip Generation

Overview

Trip generation models are used to predict the trips produced by a household or originating in a zone, usually on a daily basis and for several trip purposes. Purposes vary from region to region, primarily based on the sophistication and complexity of the model system. In the simplest cases, home-based work, home-based non-work, and non- home-based trips have trip generation models. More complex model systems may split home-based non-work trips into shop, school, and other, and non home-based trips into work-related and other.

Home-based trips in most urban areas are about 70 percent of total person trip making and have received the greatest attention. Non-home-based trips sometimes are calculated as a percentage of home-based trips of various types, although many MPOs have attempted to formally model this growing component of travel. Commercial vehicle trips also need to be estimated. Most regional agencies have based their estimates of commercial trips on infrequent surveys which are updated using traffic count data and simple growth-factor methods.

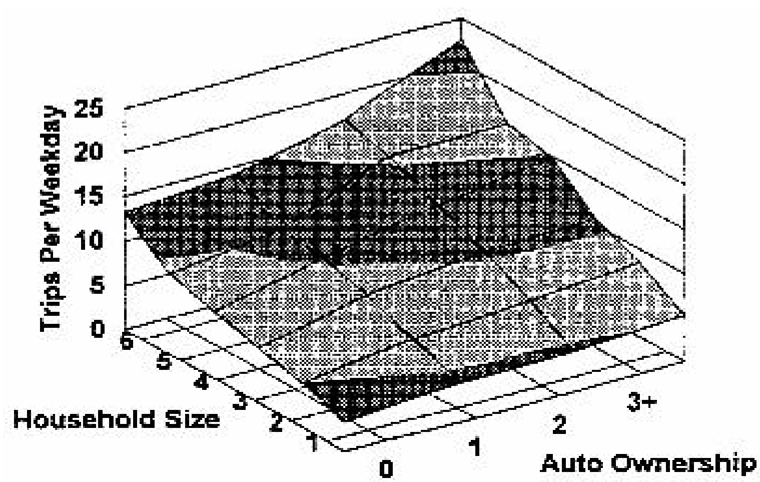
Trip ends are considered to be either a production (typically defined as home or as the origin of a non-home-based trip) or an attraction (the destination where an out-of-home activity will be undertaken). Separate models are used to predict productions and attractions. Since trip productions and attractions are calculated separately, total productions will not necessarily equal total attractions, either for the region as a whole or for a particular zone. This is usually handled mechanically, by multiplying each zone's trip attraction by the ratio of total productions to total attractions. More elaborate balancing algorithms are sometimes used.

Variables commonly used to estimate trip productions include household size, number of workers, income, and auto ownership; land use factors such as residential density and distance of the zone from the central business district (CBD) are less frequently included. Trip attraction variables include employment levels disaggregated by occupation type and floor space disaggregated by business type; accessibility to the work force, represented by travel times, is rare in US applications but found fairly frequently in applications overseas.

Most trip generation models have considered only trips made by vehicle (often called "vehicle trips", but more accurately called "person trips by vehicle"), although some MPOs have developed models which estimate total trips regardless of mode ("total person trips"). In the most common approach to producing vehicle trip estimates, trips on foot or by bicycle are excluded from the data sets used to estimate trip generation rates. An alternate approach, mostly used by smaller MPOs and local jurisdictions, directly estimates auto trips, i.e., transit trips also are excluded from the estimation data sets. The latter models are typically used in highway capacity and level of service studies, or where transit is virtually nonexistent.

The distinction between modeling person trips by vehicle and modeling total person trips, rather than being purely semantic, is a fundamental issue in model development. Modelers have preferred to exclude walk trips as early in the modeling sequence as possible, because doing so avoids complexity in mode choice (i.e., the need to introduce walk as an explicit mode, and to develop metrics for variables that determine the propensity to walk) and in trip distribution (i.e., the need to develop an accessibility measure that covers both walk trips and trips by vehicle). However, recent work has shown that accessibility and land use conditions are powerful determinants of the decision to walk (and to link trips into complex chains), and thus strongly influence the number of person trips by vehicle. Such strong correlations are not apparent in the total number of person trips. Hence, there is a clear tradeoff between introducing complexity in trip generation and introducing complexity in later model stages.

Total Weekday Person Trip Generation
All Modes Including Walk
Figure 3.2: Bay Area 1981 Trip Generation Rates



Given the desirability of accounting for pricing and land use options, and of properly representing the effects of congestion, some model developers are opting for greater complexity in later model steps, in return for a simplification of trip generation.

Basic Practice

Two general approaches to trip generation are in common use: cross-classification analysis and regression models.

Cross-Classification Analysis

Cross-classification analysis groups individual households together according to common socioeconomic characteristics (auto ownership level, income, household size, etc.) to create relatively homogeneous groups. Average trip production rates are then computed for each group from observed data. Cross-classification analysis similarly can be performed for trip attraction calculations. Classification is generally by land use or employment (e.g., manufacturing, retail, office; number of employees per acre).

Among the advantages of cross-classification are that it is simple to apply and captures correlations among the independent variables well. But the method also has a number of drawbacks: 1) in typical applications within-category variances are ignored, even though the vast majority of variation arises within rather than between cells; 2) cell sizes may differ substantially and estimates of trip rates are dependent for their accuracy on the number of households or zones in each cell; 3) the method is sensitive to the grouping applied to each parameter, and for some variables may be sensitive to the zone system used; and 4) it is particularly difficult to account for land use and accessibility factors in a cross classification methodology, both because the number of cells quickly becomes too large and because these variables are particularly difficult to divide into meaningful ranges.

Nevertheless, cross-classification is the most common method in practice, and is a reliable method when a small number of variables is thought to be sufficient for a good trip generation model.

Regression Models

Regression was once a common technique for trip generation, though today it is used less frequently than cross-classification. Linear regression models are the most common; they are simple and inexpensive to estimate from data typically available to MPOs. However, the imposition of linearity introduces a number of problems in modeling. For example, most surveys have shown that trip-making is not linearly related to auto ownership, but increases dramatically with the first car and to a declining extent as the number of cars increases. The use of a linear form in such circumstances reduces the goodness of model fit (see Figure 3.2, which provides an example of person trips by vehicle from the 1981 Bay Area travel survey). Instability in model parameters over time also may result when a linear form is assumed but the underlying variable exhibits nonlinear properties. Transforms of variables (e.g., exponential forms, Box-COx transforms, Box-Tukey transforms) provide a way of overcoming some of these difficulties while retaining the use of linear regression estimation software.

Nonlinear regression techniques allow more modeling flexibility but are less frequently available in basic statistical software packages and hence are less commonly applied. Nevertheless, these techniques are finding their way into use in some regional agencies' practice, primarily because non-linear models allow both a high degree of flexibility in functional form (much like cross-classification) and a large number of explanatory variables.

Home-Based Trip Generation

Home-based trip generation models represent the propensity of a household to make trips as a function of its socioeconomic and, sometimes, locational characteristics. Models have been estimated based on zonal averages or household-level data using variables such as:

- Household size
- Number of workers
- Household income
- Auto ownership
- Number of licensed drivers
- Number of household members under five years old
- Number of household members over five but under 16
- Age of head of household
- Occupation of head of household
- Occupations of other workers
- Marital status
- Housing type
- Own or rent
- Length of residence
- Distance from the central business district (CBD)

Note that characteristics of the transportation system are not included on the list of variables in common use. This amounts to an implicit assumption that transportation level of service is not an important factor affecting trip rates. As discussed above, this assumption is much more likely to be warranted in the case of total person trips, where the choice between motorized and non-motorized modes is not subsumed in the trip generation model.

There is an extensive literature on both cross-classification and regression approaches to trip generation. The following are two examples of simple cross-classification models representing total household person trips,[9] for Madison (WI) in 1962:

	Cars Owned		
Family Size	**0**	**1**	**2+**
1	1.0	2.7	4.4
2	1.5	5.1	7.0
3	3.1	7.2	9.4
4	3.2	8.0	11.7
5	5.2	9.2	13.4

and for Miami (FL) in 1973:

	Cars Owned		
Family Size	**0**	**1**	**2+**
1	1.0	2.9	5.6
2	1.9	4.5	5.9
3	2.9	6.2	7.7
4	4.1	8.5	10.7
5	5.8	10.2	13.7

It is notable that the two tables show strong similarities, despite the differences in data sources, treatments, and interpretations. Such stability has led many to argue that cross-classification is a robust, perhaps transferable technique, and has led to its widespread acceptance in the field. However, as the generally higher 1981 Bay Area data in Figure 3.2 suggest, other factors of the sort discussed earlier are present as well, particularly when the future is expected to bring fundamental differences in highway accessibility and/or land use patterns.

[9] Source: FHWA, 1975.

Regression models are less and less used in basic practice, primarily because in their simple functional forms they are more likely than cross-classification to introduce errors into forecasts. It also is true that the development of more credible regression equations (e.g., with polynomial terms to capture non-linearities and cross terms to capture correlations) requires a substantially higher knowledge of statistics than is the case for a cross-classification model that implicitly reflects the same features. Nevertheless, many regression models remain in use for basic practice, and for this reason it is worth discussing their general characteristics.

Two basic types of equations have been used: one estimated on zonal averages for independent and dependent variables, and one estimated on the values of variables for a sample of individual households. When data are averaged at the zonal level, as much as 80 percent of the sample variability (in, say, trips per household) is removed in the averaging process. The resulting regression equations give the superficial appearance of fitting the data much better, simply because the regression goodness-of-fit statistics seem higher. Two models estimated on the same data, drawn from McCarthy [1969], illustrate this well:

A zonal average model for home-based trips per household:

$$T_i = -1.09 + 1.66\, HHS_i - 1.83\, CH5_i + 1.44\, A_i + 0.64\, I_i \quad R^2 = .61$$

where:

- T_i = the average number of person trips per household in zone i
- HHS_i = the average household size in zone i
- $CH5_i$ = the average number of children under 5 in zone i
- A_i = the average number of cars per household in zone i
- I_i = the average number of workers per household in zone i

and a household model for home-based trips:

$$T_h = -1.42 + 1.46\, HHS_h - 1.65\, CH5_h + 1.69\, A_h + 0.75\, I_h \quad R^2 = .38$$

where:

- T_h = the number of person trips for household h
- HHS_h = the size of household h
- $CH5_h$ = the number of children under 5 in household h
- A_h = the number of cars available to household h
- I_h = the number of workers in household h

Even though equation 3.3 appears to provide a better fit, there is no doubt from a theoretical viewpoint that the coefficients of equation 3.4 are more likely to be "correct". If one employs a regression equation, then, the estimation methodology always should use disaggregated data even though the forecasting procedure likely will use zonal averages.

The cross-classification trip generation tables and graph shown previously reveal clear nonlinearities for each variable (as values of the other variable are held constant). While some of these non-linearities could be accounted for by the additional variables in equations 3.3 and 3.4, there is no real reason to expect the effects of any of the variables to be linear throughout the range of interest. Recognizing this, practitioners have developed a strong preference for cross-classification methods in basic applications. As later subsections will make clear, however, it is not so easy to apply cross-classification in advanced practice, because of the geometric increase in the number of cells as variables are added.

Non-Residential Trip Generation

Non-residential trip generation models serve two purposes: to estimate the number of attractions of home-based trips; and to estimate the number of attractions and productions of trips which are non-home-based. (Commercial trips are again estimated separately.) Non- residential trip generation rates also are widely used to determine the traffic consequences of development proposals for specific sites. In general, this latter application requires the estimation of an average trip generation rate, per unit area, for uses of different types.

Non-residential person trips may be further categorized as employee work trips, other employee trips, and visitor (or "other") trips. Work trip rates are closely related to the number of employees per unit area for a particular use; visitor trip rates (including customers, clients, etc.) vary considerably with the land use. Non-home-based trips from nonresidential land uses will largely be trips made by workers traveling to other nonresidential locations (especially work-related business, but also including lunch hour trips to restaurants and shopping). Other non-home-based trips are the result of trip chaining (e.g., stopping at a gas station and then proceeding to work produces a home-based trip followed by a non-home based trip; a shopping excursion to several stores may produce a lengthy chain of non-home based trips.) Hence these trips tend to be related in part to the number of employees, and in part to the type of land use.

Non-residential trip generation has received considerably less attention than has home-based trip generation, and the techniques that have been used are generally less sophisticated. Typically, simple cross-classification schemes are used, although a few attempts have been made to use regression techniques to relate nonresidential trip making to various attributes of the land uses from which those trips are produced, or to which they are attracted.

In cross-classification applications, the most commonly used classifications are land use types (offices of various types, industrial, retail, medical, education, etc.). Trip generation rates are expressed per unit area or size (acres, square footage, employees, etc.). The rates are typically derived from data aggregated over the entire region, although in some cases separate rates are calculated for a typology of areas, e.g., CBD, inner suburb, outer suburb, rural. A further breakdown into peak and off-peak periods is commonly used for site studies.

Regression equations also have been developed but many have been extremely simple - one or two variables are common. These equations are not necessarily more rigorous than the simple cross-classification schemes, in large part because the variables used as descriptors of the number of trips made are highly correlated with each other.

Freight trips are sometimes handled as part of the non-residential trip generation analysis, but few transportation modeling efforts have included much analysis of freight trips. A typical approach is to express truck trips as a percentage of person trips or vehicle trips based on counts. A few areas have occasionally developed freight O-D matrices which they update using VMT, employment, or population growth factors. While it is recognized that such methods impose strong assumptions to the effect that truck travel will maintain a constant relationship to overall travel (or to population or employment growth) over the forecast period, this simplification has been accepted on the grounds that truck traffic is only 5-10 percent of overall trip-making. Obviously, local variations exist and may be significant.

Advanced Practice

Advanced practice in trip generation begins with the inclusion of a wider range of socioeconomic variables in trip generation models and extends to the estimation of separate models for a wider range of trip purposes, e.g., home-work, home-school, home-shop, home-other, non- home-based work-related, non-home-based other. In addition, greater attention is given to time of travel in some cases, e.g., peak, off-peak, midday.

While many elementary trip generation models estimate vehicle trips only, more advanced approaches estimate person trips by all modes (including walking and biking.) However, a focus on person trip generation implies greater complexity in trip distribution and mode choice (in order to distinguish vehicle trips from person trips in a spatial context). For this reason, many modelers continue to work with vehicle trip generation models, even though vehicle trips may be harder to estimate effectively (because they are sensitive to a far wider range of factors such as land use densities).

Even in the more advanced applications few trip generation models include transportation variables. However, the current interest in whether accessibility affects trip making (either person trips or vehicle trips) may alter this. Whether improved accessibility will lead to more trips being made, or merely longer trips, is part of the issue. If the latter, then this is properly a matter for the trip distribution model rather than trip generation. It is reasonable to suppose that trip rates will be affected more for discretionary trip purposes than for obligatory trips such as the journey to work, and if changes occur at the margin, i.e., for the most infrequent trips, the net result on trip rates could be almost negligible (and hard to detect via standard data collection approaches.)

EXAMPLE: PORTLAND (OR) TRIP GENERATION

Portland's trip generation models predict trip origins and destinations by each of six trip purposes:

- Home-based work
- Home-based school
- Home-based college
- Home-based other
- Non-home-based work-related
- Non-home-based non-work-related

In general, two models exist for each trip purpose: one to predict trip ends at home (for home-based trips) or at work (for non- home-based work-related trips), and one to predict the other end of these trips. The models depend on a set of demographic characteristics that are projected for each zone:

- Household size (4 categories)
- Household income (4 categories)
- Age of the "head" of household (4 categories)
- Workers per household (4 categories)
- Vehicles per household (4 categories)
- Children per household (4 categories)

and on a set of attraction factors characterizing non-home locations:

- Total employment
- Retail employment
- Total households
- Students and employees at colleges

While the trip generation procedures make extensive use of household characteristics, they do not reflect land use indicators such as housing type (single family vs. multiple family), residential density, mix of uses, or density of trip attractions. Empirical evidence suggests that these factors strongly influence the number of person trips by vehicle, but have an important effect on total person trips only in the extreme. Since Portland retains all trips - including walk - through trip distribution, the omission of land use factors from trip generation should not be problematic. However, in other regions where walk and bike trips have been excluded from the analysis, the omission of land use characteristics from trip generation could be a serious deficiency, at least in terms of capturing the effects of land use alternatives.

Portland's trip generation procedures also ignore the accessibility of a zone to various desired activities. Conceptually, one might expect an individual to participate in more out-of-home activities as a larger number of suitable opportunities come within easy travel range of the home (or work) zone. Thus, some measure of accessibility is a logical element of trip generation. In practice, analysts have considered this effect secondary, which, coupled with the complexity of constructing a good accessibility measure, has led virtually all MPOs to ignore accessibility as a trip generation variable (the MTC model shown below is a conspicuous exception). Empirical work suggests that accessibility effects are identifiable but not major, so this is not likely to be a serious problem for most analysis purposes (more research is needed to verify this assertion, however).

Curiously, accessibility has an indirect effect on trip generation that may be just as important. Auto ownership is sensitive to accessibility (especially transit accessibility) at the home zone, and trip generation is sensitive to auto ownership. Thus, a model system in which some measure of level-of-service has an effect on auto ownership also will show an implicit trip generation effect. The Portland model fits this criterion, due to a transit access variable that appears earlier in the model sequence.

EXAMPLE: BAY AREA HOME-BASED SHOPPING TRIP FREQUENCY

The MTC shopping trip frequency model is a non-linear regression yielding an inverse function of household characteristics, home zone characteristics, and aggregate destination attractiveness (as embodied in the expected utility for shopping destination/mode choice). The exact model specification is:

$$hbshop_i = \frac{.8194}{.07766 + \exp(-.34174\, x hhsize_i - .051512 x (inc_i + 100) - .052681 x E[U_{idm}] + .1146x}$$

where:

hbshop$_i$ is the number of daily home-based shopping trips by household i (person trips by vehicle);
hhsize$_i$ is the number of persons in household i;
inc$_i$ is the income of household i;
E[U$_{idm}$] is the expected utility from the shopping destination/mode choice model for household i, defined as the natural log of the denominator of that model's logit equation;
eden is the service and retail employment density in household i's home zone, expressed in workers per gross acre.

The inverse exponential form of this function makes it somewhat difficult to interpret. Basically, household shopping trips increase with household size, income, and accessibility to shopping opportunities, and decrease with rising local density of retail opportunities. The latter relation emerges because this is a vehicle trip generation model, and residents are less likely to make a shopping trip by vehicle if there are plentiful shopping opportunities within walking distance. In a fully person trip model (including walk), the density variable would have a negligible or slightly positive effect on shopping trip generation.

Summary

Overall, the factors affecting trip generation are reasonably well understood. However, while existing models account for key income and demographic factors, additional factors could be included. In particular, factors reflecting the influence of accessibility would be useful in many areas, even though the effect on trip rates is likely to be small.

Simple methods for estimating relationships are acceptable, although regressions should be nonlinear; simple linear regressions are often inferior to cross classification approaches. Advanced practice should consider a wider variety of variables affecting trip-making, including land use, socioeconomic and demographic/lifestyle factors. Trip generation models are distinguished by whether they predict total person trips or only person trips in vehicles. Person trips are the much more basic unit, in the sense that a small number of economic and life-cycle factors appear to account for the bulk of variation in total person trip generation; a person trip approach does lead to more complex models in later steps, however.

3.3.6 Trip Distribution/Destination Choice

Overview

Trip distribution represents the spatial interactions among zones in the metropolitan region. Trip distribution models allocate the total number of trips originating in each zone among the available destination zones: the set of zonal trip productions P_i and attractions A_j, both estimated in the trip generation step, are linked. There is a direct analog in individual behavior: given a person's location (e.g., a home or workplace zone) and a decision to make a trip of a certain kind, a destination choice model computes the probability of selecting each location where the purpose of the trip could be fulfilled. The discussion in this section considers the aggregate concept of trip distribution for basic practice, then turns to destination choice in the discussion of advanced approaches.

In either modeling approach, the variables considered include the time, distance, and/or costs of travel between the zonal centroids for all origin zones i and destination zones j, as well as characteristics of the zones themselves (population, employment, etc.) and sometimes, characteristics of the travelers. Data on origin-destination (OD) pairs are used to calibrate the matching of productions and attractions. These OD data are most often taken from a travel survey, although occasionally OD matrices are estimated from traffic counts.

The terms “production - attraction” and “origin - destination” are used somewhat interchangeably in this text, and it is not really necessary to distinguish among them in communicating the basic concepts of trip distribution. However, the reader should be aware that these terms denote two quite different ways of expressing the spatial trip pattern. Each row in an origin - destination table literally represents the zone of origin and each column literally represents the zone of destination, so that, e.g., a home-work trip would appear in a different cell than the corresponding work-home trip. In contrast, each row in a production attraction table represents the zone responsible for “producing” a trip, while each column represents the zone responsible for “attracting” a trip. Hence, because the home is said to produce work trips and the workplace is said to attract work trips, both the home-work trip and its corresponding work-home trip would appear in the same cell of a production attraction table.

The difference is more than semantic. Trip distribution models generally work in terms of productions and attractions, while traffic assignment requires origins and destinations. At some point a trip table must be converted from one format to the other. The conversion is trivial only if one assumes perfect symmetry. Unfortunately, even in the relatively simple case of home-based work travel, symmetry is a dubious assumption (because workers are much more likely to stop at an intermediate point on the way home from work than on the way there). For this and other reasons, managing the distinction between production attraction and origin - destination can be one of the hidden pitfalls of travel demand analysis.

Basic Practice

Trip distribution is most often accomplished through the use of a growth-factor method or a gravity model, although other approaches are sometimes applied, including so-called intervening opportunities and destination choice formulations.

Growth-Factor Methods

Growth-factor methods use zonal growth rates together with pre-existing data on trip interchanges and total trip ends to forecast future interzonal trips. The methods assume that future trips between each pair of zones will be proportional to the present number of such trips, and to some function of the growth factors for each of the two zones. The formulation results in certain peculiarities; for example, any zone which has no trips in the base case will have no trips in the future. Furthermore, since only one growth factor can be applied to a particular zone, either the zone must be homogeneous with respect to growth rate or the error potential will be high.

Growth factors may be derived from earlier steps of the modeling process, in which case they may reflect the variables used in land use allocation, auto ownership, and trip generation models; or they may be taken from exogenous sources. In the latter case care must be taken to assure that the growth rates are consistent with the assumptions made elsewhere in the model system, or this could be a source of substantial error. Probably more of a concern is the fact that travel times and travel costs are not directly taken into consideration in most growth factor methods, except as they may be reflected in the growth rates and in the initial trip table. Unless no significant changes in the transportation networks will occur over the forecast period, this omission of travel time and cost variables amounts to assuming that trip distribution is not affected by changes in the network - an untenable assumption in most cases.

Several types of growth factor methods, reflecting different levels of complexity, have been employed over the years. However, the simpler methods (e.g., uniform growth factor, average growth factor) are known to be seriously flawed, and today only the Fratar method is commonly applied.

The Fratar method assumes that the number of trips from zone i to zone j is proportional to the present number of trips from zone i, modified by growth factors for the production and attraction zones, and the change in relative attractiveness of all zones. The basic Fratar equation is given by:

$$T^*_{ij} = T^0_{ij} \ x \ G^*_i \ x \ G^*_j \ x \ \frac{\sum_{t=1}^{N} T^0_{iz}}{\sum_{t=1}^{N} G^*_2 \ X \ T^0_{iz}}$$

where:

T^*_{ij} is the forecast year number of trips from i to j

T^o_{ij} is the base year number of trips from i to j

G^*_I is the growth ratio (base to forecast year) for productions at zone i

G^*_j is the growth ratio for attractions at zone j

The ratio of sums is the inverse of the average growth rate among all zones attracting trips from i.

After Fratar computations are made, the total trips attracted to each zone will not necessarily agree with the totals implied by the attraction zone growth factors, simply because of the mathematical form of equation 3.6. Therefore, an iterative process is necessary to balance trips.

The Fratar method is properly described as a projection technique given an existing trip distribution, rather than as a trip distribution model per se. The method is included here because, under a restricted set of circumstances, it can be part of an acceptable analysis approach. For example, if one is forecasting non-work, off-peak trips, and there is neither significant off-peak congestion nor major new infrastructure, any changes in the trip distribution likely would be proportional to zonal growth. Fratar (or a similar factoring technique) should be capable of capturing these changes.

Gravity Models[10]

The gravity model is the most common form of trip distribution model currently in use. Its name derives from a loose analogy to Newton's Law of Gravitation. The basic structure of the gravity model is as follows:

$$T_{ij} = P_{ix} \ A_{jx} \ B_{ix} \ D_{jx} \ f(C_{ij})$$

where:

T_{ij} is the number of trips between zones i and j;

P_i is the total trips produced in zone i;

A_j is the total trips attracted to zone j;

C_{ij} is some measure of the “cost” of travel from i to j, that may include price, travel time (perhaps disaggregated in various ways), and/or distance;

[10] The following derivation and discussion is based in part on Stopher and Meyburg (1975).

$f(C_{ij})$, sometimes called a "friction factor" in the literature, is a function that converts C ij into a "disutility" of travel (or, conceptually, into a measure of spatial separation) between i and j;
B_i, D_j are constants associated with the production and attraction zones (explained below).

Values for the constants B and D are based on simple logic, i.e., the number of trips from zone i to all destinations j, j = 1 to N, must equal the number of trips produced in that zone:

$$P_1 = \sum_{j=1}^{N} T_{ij} = P_i \; B_i \sum_{j=1}^{N} A_j \; D_j \; f(C_{ij})$$

Similarly, the number of trips to zone j from all origins i, i=1 to N, must equal the number of trips attracted to that zone:

$$A_j = \sum_{r=1}^{N} T_{ij} = A_j \; D_j \sum_{r=1}^{N} P_i \; B_i \; f(C_{ij})$$

Rearranging the terms in each equation yields:

$$B_i = \frac{1}{\sum_{j-1}^{N} A_i \; D_i \; f(C_{ij})}$$

and:

$$D_j = \frac{1}{\sum_{i-1}^{N} P_i \; B_i \; f(C_{ij})}$$

The system of equations defined by 3.7, 3.10, and 3.11 constitutes a complete, doubly-constrained gravity model of trip distribution. The unknowns in this system include the values of the B_i and D_j and the parameters of the function $f(C_{ij})$. It is possible to estimate this system of equations in a number of ways, including the aggregate approach proposed by Sen and Soot (1981) or the disaggregate estimation method developed by Daly (1982). However, either approach requires a fairly high level of sophistication in statistics and econometrics.

Because estimation of the doubly-constrained form of the gravity model has been viewed as difficult, practitioners have felt a need to simplify the gravity model form in some way. The conventional approach is to relax the second trip conservation rule, by setting $D_i = 1$ for all j. The result is the singly-constrained gravity model:

$$T_{ij} = P_i \frac{A_j \, f(C_{ij})}{\sum_{j=1}^{N} A_j \; f(C_{ij})}$$

in which the trips produced at i (P_i) are apportioned among destinations according to the attractiveness of each destination (A_j) and the disutility of travel for each trip interchange ($f(C_{ij})$).

Two alternative approaches have been used to solve for $f(C_{ij})$. In the first, the function is assumed to have a single unknown parameter (say, an exponent). The analyst assigns a trial value to the parameter, calculates the T_{ij}s for each zone-to-zone movement on the base-year data using this trial exponent, and computes the P is and A_js. The A_js obtained from this first approximation are then compared to the original A_js (the P_js are constrained to their original values by the form of the gravity model). The analyst then recomputes the T_{ij}s using a new approximation of the parameter. The process is repeated until the estimates of the A_js are acceptably close to the observed A_js. The analyst also compares the trip length distribution from the survey with the length distribution predicted by the model at each iteration, seeking the closest possible correspondence between predicted and observed values.

In general, attempts to calibrate a gravity model in this way have not produced particularly satisfactory results. Typically, the generalized cost function C_{ij} has been represented in highly simplified terms (e.g., as highway travel time - t_{ij}), and only the simplest functional forms (e.g., t_{ij}^{b}) have been specified. The resulting single parameter friction factor equation rarely has been adequate to replicate the complex travel patterns constitution trip distribution over the entire region.
A second approach, followed in many regions, is to use more flexibly-defined travel time factors, $f(t_{ij})$. These factors resemble the generalized cost function $f(C_{ij})$ discussed above, but with a less formal treatment of the friction factor parameter. For example, the friction factor might vary by geographic area, by zonal attributes, by time-of-day, or by length of trip. Alternatively, a set of friction factors may be set forth in a lookup table developed from empirical data, rather than described by an equation.

An example of a lookup table of friction factors, developed for the Los Angeles area, is shown in Table 3.2.[11] Travel times are represented as a set of time intervals. A separate value of $F(t_{ij})$ is determined for each time interval via an iterative process, and is applied to trips for which the travel time is in that interval.

[11] The data in this table are for the Los Angeles 1967 weekday person trip distribution models, which remain in use at this time [Caltrans, 1973]. Only a subset of the factors are shown here. The actual intervals are one minute in length. Numbers in the table are for the one minute intervals centered on the time shown.

To obtain values for the $F(t_{ij})$s, initial values are chosen, either arbitrarily (i.e., all 1.0) or based on an earlier parameter estimation (i.e., following the first approach described above). These initial values are plugged into the gravity model, and the trip total for each ij pair, T_{ij}, is estimated. An aggregate goodness-of- fit statistic is calculated (e.g., the sum of squared differences between observed and estimated T_{ij}s), along with the observed and estimated trip length distributions. Based on a review of these statistics, the values of the $F(t_{ij})$s are adjusted judgmentally, interval-by-interval, to provide a closer fit to the observed data. This process is repeated until a specified criterion for closure is met, e.g., when no friction factor changes from the previous iteration by more than a predetermined amount. While friction factors produced in this ad hoc fashion may result in a gravity model which matches observed data reasonably well, the use of the model in forecasting requires an assumption that a set of unspecified processes and relationships for which the friction factors are proxies will not undergo change.

Another serious difficulty with the conventional, iterative methods of calibrating friction factors for a singly constrained gravity model is that there is no guarantee that the resulting model will replicate the observed attractions A_j in the base year data. It is common to use a procedure based on repeated cycles of row and column factoring to "balance", or force a match between, the calculated and observed attractions. This process yields a revised matrix of T_{ij}s, which must be rechecked according to the goodness of fit criteria.

Table 3.2 Representative Trip Distribution Friction Factors

Time Interval Midpoint	Trip Type				
	Home-Other	Other-Other	Work-Other	Home-Work	Home-Shop
5.5	22500	22800	27000	24200	14300
10.5	5300	5300	11100	10650	1900
15.5	1100	1150	4100	4800	310
20.5	350	360	1775	2300	74
25.5	138	140	930	1230	22
30.5	70	69	530	700	9
35.5	40	40	315	440	5
40.5	26	25	200	280	3
45.5	18	17	130	180	2
50.5	13	12	95	118	2
55.5	10	9	69	80	2

60.5	8	7	51	55	1
65.5	7	6	38	40	1
70.5	6	5	28	28	1

It also is common to apply adjustments to specific trip interchanges to improve the fit of the model. These adjustments are denoted k_{ij} (hence "k" factors), and are simply the ration between observed and estimated values for the interchanges in question. Because the small sample sizes of most home interview surveys result in too few observations to assure the statistical significance of estimated trip interchanges at the zonal level, k factors typically are computed only for more aggregate district interchanges, or to match screenline counts.

The need for k factors arises because nothing about the calibration procedure ensures accuracy for specific interchanges. In fact, typical aggregate goodness of fit criteria tend to favor accuracy for short trips (because the vast majority of trips are short), and adding the trip length distribution as a secondary goodness-of-fit criterion does not fully eliminate this problem.

Link flow estimates are highly sensitive to trip distribution errors, and as a result k factors are a practical necessity when the gravity model otherwise fails to produce accurate T_{ij}s. Arguably, the k factors can be viewed as stand-ins for variables omitted from the typical gravity model. However, may analysts interpret the need for extensive k factors as a sign that something is wrong with the data, with the modeling procedure, or with the gravity model itself. As Stopher and Meyburg say:

> *The need for constants k_{ij} has been a particular source of concern about the gravity model. the k_{ij} have been justified as representing socioeconomic factors that affect trip making but are not otherwise represented in the gravity model. However, such socio-economic factors must be assumed to remain constant throughout the forecast period - a questionable assumption which may be a significant source of error in predicting future trip distributions.*

All in all, gravity model calibration is a subtle art as much as it is a science. Because the process developing a credible gravity model can be arduous and open-ended, there has been a tendency in some regions to stick with an acceptable specification for a very long time.

Advanced Practice

Advanced practice represents this step of the modeling process as destination choice. Here, a traveler originating at a specific place is assumed to choose among destinations,[12] e.g.,:

[12] While each zone may be treated as a "destination", travelers are presumed to choose particular activities or places (shopping areas, workplaces, etc.) - "elementary alternatives" - as their destinations. Zones hence represent "bundles" or aggregations of discrete destination choice alternatives. It

$$P_{ij} = \frac{\exp(V_{ij})}{\sum_{k=1}^{N} \exp(V_{ij})}$$

where:

P_{ij} is the probability a traveler originating in place i will choose place j.
V_{ij} is the utility, or attractiveness, of place j to a traveler originating in place i.

The model is specified to represent the destination choices of individual travelers as a function of destination attractiveness, origin-destination travel conditions, and personal characteristics which influence the response to the attractiveness and travel conditions (factors which together constitute the utility of an alternative). The attractiveness of each destination j is described in terms of such variables as total employment, employment by job category, square footage by land use category, number of establishments by type, and similar indicators. Travel conditions between i and j are represented by travel time(s) and cost(s) for one or more modes available to the traveler. Personal characteristics which influence the choices made typically include household or personal income, traveler age and sex, household structure, and auto availability.

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nevertheless is possible to treat zones as the alternatives in a destination choice model, as long as variables are introduced to scale the utility to reflect the number of elementary alternatives in each zone.

Formulating the trip distribution model as multinomial logit,[13] as shown here, has several advantages. First, a high-quality data set of several thousand observations should be adequate to support a very strong model estimation. Second, the logit formulation allows unbiased parameter estimation even if the estimation database includes only a subset of the possible trip destinations. Thus, the data and computational aspects of setting up the destination choice model are relatively simple.

Probably more importantly, the utility function formulation facilitates the inclusion of a wide variety of variables which are thought to influence destination choice. The formulation can accommodate the differences in taste and circumstance which are known to influence destination choice but which are accounted for in a gravity model only clumsily, though the extensive use of k factors and other adjustments.

While the formula looks quite different, the logit destination choice model has much in common with the gravity model. For example, the logit form will, by definition, conserve origin flows like the singly constrained gravity model. In fact, if the utility takes a form such as:

$$V_{ij} = \ln(B_j) + \quad * t_{ij}$$

where:

B_j is an attraction factor for zone j
t_{ij} is the travel time between zones i and
á is a coefficient with a negative value
then P_{ij}, is a form of the gravity formulation shown earlier, with the friction factor as an exponential function of travel time.

The singly-constrained logit destination choice model still requires attraction balancing, although the amount of adjustment needed is reduced when the basis for zonal attractiveness is more fully described. Similarly, k factors usually are needed to produce accurate traffic assignments, although once again the more complete the utility function is in describing the determinants of attractiveness and the characteristics of travel impedance the less the need for ad hoc intervention. Viewed in this light, the logit destination choice model is simply an efficient vehicle for estimating trip distribution parameters.

Nevertheless, only a few regional agencies have adopted disaggregate destination choice modeling over aggregate trip distribution approaches; the aggregate gravity-type model remains deeply ingrained in practice despite its apparent disadvantages.

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[13] The multinomial logit model formulation is discussed in more detail in the section on mode split/mode choice, the modeling step for which logit's its use is most developed and widespread.

EXAMPLE: PORTLAND (OR) METRO DISAGGREGATE TRIP DISTRIBUTION MODELS

The Portland MPO uses disaggregate logit estimation to develop a quadratic friction factor for its gravity model formulation. The basic equation is the standard logit form shown in 3.13.

Each destination alternative is simply a traffic analysis zone in the Portland METRO geography. The utility of each destination alternative is a function of the highway travel time from the origin zone and the trip attractions for the destination zone (computed in trip generation). A different utility formulation is estimated for each of Portland's trip purposes [Portland METRO 1991]:

Home-Based Work: $V_{ij}=\ln(A_j)-.175t_{ij}/pk+.0009(t_{ij}/pk)_2$

Home-Based School: $V_{ij}=\ln(A_j)-.600t_{ij}/op+.0120(t_{ij}/op)_2$

Home-Based College: $V_{ij}=\ln(A_j)-.450t_{ij}/op+.0020(t_{ij}/op)_2$

Home-Based Other: $V_{ij}=\ln(A_j)-.390t_{ij}/op+.0030(t_{ij}/op)_2$

NHB Work-Related: $V_{ij}=\ln(A_j)-.270t_{ij}/op+.0020(t_{ij}/op)_2$

where:

V_{ij} is the destination choice "utility" of a trip from origin zone i to destination zone j
A_j is the computed trip attractions at destination j, specific to each purpose
t_{ij}/pk is the highway travel time from origin zone i to destination zone j, under off-peak conditions
t_{ij}/op is the highway travel time from origin zone i to destination zone j, under off-peak conditions

These parameters were produced with standard logit estimation software, using samples of trips drawn from a 1985 home interview survey.

The equivalence of the Portland models to a conventional gravity formulation is easily shown. In the case of home-based work trips, when the utility (V_{ij}) is substituted in equation 3.13, an analog to the gravity model results:

$$P_{ij} = \frac{\exp(\ln(A_i) - .175\, t_{ij/pk} + .0009\, t^2_{ij/pk})}{\sum_{k=1}^{N} \exp(\ln(A_k) - .175\, t_{ik/pk} + .0009\, t^2_{ik/pk})}$$

or:

$$P_{ij} = \frac{A_j \exp(-.175\, t_{ij/pk} + .0009\, t^2_{ij/pk})}{\sum_{k=1}^{N} A_k \exp(-.175\, t_{ik/pk} + .0009\, t^2_{ik/pk})}$$

When this probability (P_{ij}) is evaluated for a specific zone pair ij, the resulting value is effectively an estimate of the share of trips produced at i (P_{ij}) that will travel to j (T_{ij}). Thus:

$$T_{ij} = P_i\, P_{ij} = P_i \frac{A_j \exp(-.175\, t_{ij/pk} + .0009\, t^2_{ij/pk})}{\sum_{k=1}^{N} A_k \exp(-.175\, t_{ik/pk} + .0009\, t^2_{ik/pk})}$$

A comparison with 3.12 shows that 3.17 is exactly a gravity model with an exponentiated, quadratic friction factor. In effect, METRO analysts are using an individual choice framework to estimate the parameters of a conventional gravity model. However, in carrying out parameter estimation this way, they have been able to develop a more sophisticated friction factor specification.

It is possible to carry this approach even farther, i.e., to add detail about destination attractiveness (such as a density variable to complement the size variable A_j, or a destination parking cost variable), to include more characteristics of zone-to-zone level of service (such as parking costs and tolls), or to vary the utility specification according to social or economic factors (such as income). The effect is to improve the representation of factors that influence destination choice, within the basic framework of the gravity model. It is even possible to build in a multi-modal representation of impedance, either by entering travel time variables for multiple modes directly in the utility equations, or by using the log of the denominator of a mode choice model to capture impedance in a comprehensive way.

EXAMPLE: BAY AREA DESTINATION/MODE CHOICE MODEL

The MTC shopping destination/mode choice model reflects an attempt to incorporate multimodal travel impedance. The model is a logit probability equation with a set of choice alternatives encompassing the auto and transit modes, and with the full set of zones accessible to a household for the shopping trip purpose. Each specific mode and destination combination is a separate alternative. Thus, if ten destinations are available, each with two modes, there are twenty choice alternatives recognized by this model.

The basic model form is:

$$P_{ijm} = \frac{\exp(V_{ijm})}{\sum_{k=1}^{N} \sum_{l=a,t} \exp(V_{ijm})}$$

where:

P_{ijm} is the probability of taking a shopping trip to destination j by mode m;
V_{ijm} is the traveler's utility for the destination i, mode m combination;
k represents the set of available destinations (defined as zones or districts);
l represents the set of available modes (a=auto or t=transit).

The utility equations for each origin-destination pair are defined in Table 3.3 [Cambridge Systematics, 1980]. Each column in the table translates into a utility equation, one for auto between any origin and destination, and one for transit between any origin and destination. For example, the utility of the auto mode to a specific destination k is:

$$U_{da} = -.8631/.2563\, xcbd_d + 5.053x(autos/hhsize)$$
$$-.000202x(time_{da}\, xinc) - .02447\, xcost_{da} + .0005995\, xrden_d + \ln(rjobs_d)$$

This type of logit model is known as a joint or simultaneous choice formulation, because it treats two choices - mode and destination, in this case - as if they were part of a single decision process. In the period since MTC's models were developed, there have been significant advances in the theory of logit analysis, especially concerning the treatment of choices that may be related but are not necessarily "simultaneous". It is now thought preferable to estimate a nested rather than simultaneous structure, and to judge from the parameters associated with the nested terms whether the choices truly are simultaneous.

Table 3.3 MTC Shopping Destination/Mode Choice Model

	Coefficient Value	Variables in the Utility		Explanation
		Auto	Transit	
1	-.8631	const		Auto constant
2	.2563	cbd		Constant for central business district
3	.8912		cbd	Constant for central business district
4	5.053	autos/hhsize		Autos per person in household
5	-.000202	time(a)*inc	time(t)*inc	Door-to-door travel time (minutes) weighted by income

6	-.02447	cost(a)		Cost (cents)
7	-.02299		fare*hhsize	Transit fare (cents) weighted by household size
8	.0005995	rden	rden	Retail density (employees per population serving acre
9	1.0	ln(rjobs)	ln(rjobs)	Natural log of retail workers in zone

3.3.7 Mode Split/Mode Choice

Overview

Mode choice models are used to estimate the share of trips made using each means, or mode, of travel of interest in the analysis. Mode choice models typically address major vehicular modes (at minimum, autos and transit, with shared ride treated as a separate mode from drive-alone in an increasing number of approaches) and represent traveler decisions about which mode to use as a function of modal characteristics, traveler and household characteristics, and sometimes, characteristics of the urban environment. More advanced models also include non-motorized modes (walk, bike).

Mode choice has long been considered a key step in the conventional modeling framework, and a large body of research on the topic has accumulated since the late 1950s. This work has strengthened the theoretical and empirical underpinnings of mode choice and has developed and refined econometric and statistical methods for model estimation. Today mode choice models are probably the best understood and most sophisticated step in the travel demand forecasting process.

While in past years a variety of methods, from diversion curves to regression models, have been used to estimate mode "split", today discrete choice models have largely replaced these earlier approaches. These models could be estimated on aggregate (zone-level) data, but generally treat each household separately in the estimation process and aggregate to the zone level afterwards. Separate models are developed for different trip purposes.

In particular, a multinomial logit model formulation is widely used:

$$P_m = \frac{\exp(V_m)}{\sum_{i=1}^{N} \exp(V_i)}$$

where:

P_m is the probability of choosing mode m;
V_m is the traveler's utility for choosing mode m;
N represents the set of available modes.

The most common mode choice variables are travel time, travel cost, household or individual income, number of workers in the household, and household auto ownership level. Indeed, some models have only these variables plus mode-specific constants. In such simple models, however, mode-specific constants often "explain" a considerable amount of the observed pattern of choice. Hence many analyses have expanded the list of variables to include greater detail: transit travel time is separated into access time, in-vehicle time, wait time, and transfer time; auto costs reflect parking charges as well as vehicle operating expenses, and so on. Other variables also have been incorporated into mode choice models; among them are socioeconomic characteristics of the traveler such as gender, age, household size, and presence of children, and land use characteristics of the travel environment such as development density or whether the trip occurs or ends in a CBD.

Certain problems arise in the application of multinomial logit models when alternatives are closely related, because the logit formulation assumes independence (i.e., no correlation) of alternatives. The use of a probit formulation is one way to address this issue, as probit models estimate covariances among the utilities. However, estimation of probit models has proven to be highly complex and software for the estimation of models including more than two modes has not been widely available. Consequently an alternative method, nested logit, has become the preferred approach for practical applications. (See Daganzo (1979) and Ben Akiva & Lerman (1985) for more detailed discussions of the limitations of logit models and the issues involved in probit modeling; Sobel (1981), Ben Akiva & Lerman (1985), Hensher (1986c), and Daly (1987) provide detailed discussions of nested logit.)

In their most common and simplest applications, nested logit models have two levels (e.g., rail vs. bus; transit vs. auto). However, additional levels are sometimes used, for example to model alternative transit access modes such as walk vs. transit vs. auto; auto drop-off vs. park. Such additional detail can be particularly important in situations where multi-modal trips are common and their classification by "main mode" would omit critical information, e.g., in evaluating the emissions implications of policies involving park and ride. Airport access applications have utilized particularly complicated nested logit structures to represent the range of auto, parking, transit, and paratransit options available to air travelers.

While the treatment of auto and transit modes has tended toward greater complexity and sophistication, bicycling and walking modes continue to be omitted from the mode choice models of all but a few metropolitan areas. Such an omission is problematic, not only because these trips are an important component of personal mobility, but because cross-elasticities are quite high between walk trips and short bus and auto trips, depending on fares, parking charges, travel times, etc. The inclusion of bike and walk modes in models may be problematic, however, because many such trips occur entirely within zone (for which trips of all sorts are rather poorly represented in conventional practice) and because in many data collection efforts little attention was given to accurately gathering, coding, and checking walk and bike trips. (On the latter point, one MPO reported a doubling of reported walk trips in a recent survey, where great pains were taken to collect this information, in comparison to a mid-1970s survey which emphasized vehicle trips.)

It also remains the case that a considerable number of variables found through research to be important to mode choice are commonly omitted from the models used in practice. In particular, research has shown that the comfort, convenience, and reliability of the various modes are critical variables in travelers' mode choices, and that the inclusion of measures or indicators of these variables improves model fit (Abkowitz, 1981 b). Nevertheless, they are only occasionally incorporated into models used in practice, partly because data on these matters are not readily available and forecasts of future conditions would be hard to develop. Other factors such as the match of transit schedules to preferred times of travel are captured only partially through access and wait time estimates, but methods for addressing this concern (such as submodels of choice of time of day of travel or activity analyses of time constraints and their effects on mode choice) remain research tools.

Another area where additional work remains to be done involves the use of attitudinal variables in determining what options are included in a traveler's choice set. Standard mode choice models assume that, apart from questions of vehicle availability, for the same O-D pair all travelers have the same set of modes available. However, there is substantial evidence that certain people do not consider certain modes, whether for lack of information, out of habit, or for reasons such as image or status. Attitudinal surveys may offer a way to address these issues.

EXAMPLE: BAY AREA WORK MODE CHOICE

The Bay Area work mode choice model is a straightforward logit formulation (eq. 3.20) with three alternatives:

- drive alone (a)
- shared ride (s)
- transit (t)

The utility equations are defined in Table 3.4. For example, the utility for drive alone is:

$$V_a = -2.512 - .00000714xdinc - 1.067xcbd - .0244\,xivtt_a$$
$$-.077\,xwalk_a - 21.43x(cost_a/inc) + 1.958xautos + .677xhead$$

EXAMPLE: PORTLAND (OR) WORK MODE CHOICE

The Portland work mode choice model is two-tiered logit formulation, with an upper-level choice between motorized and non-motorized modes, and a lower-level choice among four motorized alternatives:

- drive alone (a)
- shared ride (s)
- transit walk access (tw)

- transit auto access (ta)

The upper-level choice is a simple binary logit model:

$$P_{w/b} = \frac{1}{1 + \exp(1.299 + .718\, dist_a - 1.347 valcar)}$$

where:

$P_{w/b}$ is the probability that a worker will choose the walk/bike mode;
$dist_a$ is the trip distance by auto;
valcar is a dummy variable with a value 1.0 if the worker's household has fewer vehicles than workers.

Walk/bike probability is assumed to be zero for distances greater than 2.56 miles.

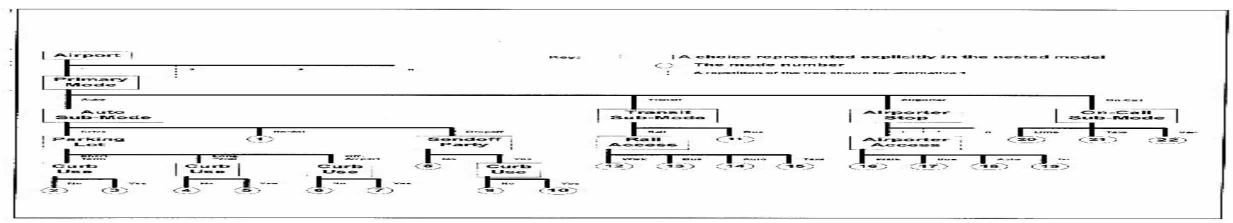
Table 3.4 Variables in the Bay Area Work Mode Choice Model

	Coefficient Value	Variables in the Utility			Explanation
		a	s	t	
1	-.00000714	dinc	dinc		Household disposable income
2	-1.067	cbd			Constant for central business district
3	-.347		cbd		Constant for central business district
4	.327		nwork		Number of workers in household
5	-.0244	ivtt(a)	ivtt(s)	ivtt(t)	In-vehicle travel time (minutes)
6	-.077	walk(a)	walk(s)	walk(t)	Walk time (minutes)
7	-.045			wait(t)	Transit initiated wait (minutes)
8	-.0428			xferwait	Transit transfer wait (minutes)
9	-21.43	cost(a)+inc	cost(s)+inc	cost(t)-inc	Cost (cents)/household income ($)
10	1.958	autos			Number of autos in household
11	1.763		autos		Number of autos in household

12	1.389			autos|acc	Number of autos for auto access
13	-1.237			aac	Constant for auto access to transit
14	.677	head			Constant for head of household
15	-2.512	const			Drive a one constant
16	-3.473		const		Shared ride constant

The utility equations for the lower-level choice are similar in form to the Bay Area model shown above.

Figure 3.3 Nested Model Structure for Bay Area Airport Access and Airport Choice



EXAMPLE: BAY AREA AIRPORT ACCESS

The potential of nested logit for mode choice analysis is only beginning to be realized in practice. Nevertheless, several hierarchical models of mode choice have been developed for specialized applications. The structure of one such model - for airport access in the San Francisco Bay Area - is shown in Figure 3.3 [Harvey, 1989].

Efforts are now underway in a number of cities to implement this type of model structure for work mode choice analysis.

3.3.8 Peaking Factors/Time of Travel

Overview

Peaking intensity and duration and, more generally, the time at which travel occurs, are critical to the estimation of a number of important travel metrics, including speeds, congestion, and emissions. Yet peaking and time of travel are included in the typical travel model in highly approximate ways, commonly by developing peaking or time-of-day factors from observed data and assuming the same patterns will persist in the future. More robust, behavioral representations of the time-of-day of travel are still primarily research tools; their introduction into practice is only now beginning, at least in U.S. applications.

Ideally, travel models would include separate assignments for at least three time periods during the day: am peak, off-peak, and p.m. peak. In the past, however, many MPOs have not been able to justify the expense of the additional forecasting accuracy this would provide; most have used a single weekday peak period for forecasting purposes, with all networks, travel cost information, and calibrations oriented toward this one peak period. With the expanded funds for planning provided by ISTEA, a larger number of MPOs are now able to develop models for multiple time periods, as well as a more robust treatment of peaking. Hence the treatment of peaking factors and the time at which travel occurs will receive increased attention.

The choice of which peak period(s) to model must be made taking in account such considerations as the availability of count data, previous modeling efforts, local conditions, and the applications for which the model is intended. Air quality problems may point to a need for information about a particular peak period. For example, the am peak is most critical for ozone purposes, since morning emissions of VOCs and NO_x have a longer time to react to light than do pollutants emitted in the p.m. peak. As a result, 0_3 concentrations typically peak during the late-morning or early-afternoon hours (Horowitz, 1982b, p. 71). On the other hand, areawide traffic volumes and congestion are typically higher during the afternoon peak than at other times of day; CO concentrations are also typically higher in the afternoon and evening hours. Hence an area with a CO problem may need to devote modeling resources to the p.m. peak.

The length of peak periods to be represented in the models also must be decided. While it is common to specify a one-hour peak period, many metropolitan areas have some facilities experiencing congestion for 3-6 hours a day (or more), and so have defined peak periods that are at least 2 or 3 hours long.[14] Network capacities are defined for the entire peak period, effectively allowing for "peak spreading" within the peak period.

Figure 3.3 A Comparison of Regional and Localized Peaking Characteristics

[14] An implicit modeling assumption is that all trips can be completed within the peak period. if the peak period being modeled is too short (e.g., under an hour), this will not be true.

Basic Practice

Peaking factors are most commonly specified as exogenous values that are fixed and independent of congestion levels. These time-of-day factors (TODFs) are usually determined from travel survey data, with a separate TODF for each trip purpose. In some cases the peaks' timing and duration are estimated from traffic data (e.g., 24-hour machine counts on streets and highways), perhaps interpreted and adjusted based on data from special studies (e.g., travel surveys of workplaces and customer-serving businesses in a particular area, driveway counts at major activity centers.) Occasionally, time-of-day factors are borrowed from other areas and adjusted during the model calibration process, but this is not recommended except, perhaps, as a stopgap measure, because TODFs are highly dependent on each area's characteristics such as facility design and capacity, types of employment, and local custom and business practices.

Very simple applications apply peaking factors to 24 hour link-level volumes, after traffic assignment to the network has been accomplished and without regard to trip purposes. The peak percentages may be link-specific or facility classification-specific, but most commonly a single factor, typically 8-12 percent of ADT, is applied to all the links in the region to obtain a crude estimate of total bi-directional peak hour travel. A directional split percentage (e.g., 60/40), derived from observed traffic conditions, then is applied to obtain link-level peak volumes. This procedure yields only a rough approximation of link- or corridor-level peaking, though it may suffice for smaller MPOs where the duration and intensity of congestion are limited.

Figure 3.4, taken from Bay Area data, illustrates that peaking on particular facilities may vary substantially from peaking region-wide. In the figure, the actual hourly traffic volumes on I-880, in Oakland, CA, are expressed as a percent of total AADT (here about 225,000); also shown are the hourly volumes that would be predicted using time-of-day factors from the Metropolitan Transportation Commission's 1981 home interview survey. The MTC peaking factors would predict higher, sharper peaks in the am and p.m. (although the MTC factors also predict higher midday travel as a percent of total). In general, there is little reason to expect specific facilities to exhibit the same peaking patterns or characteristics as “regional averages”, and application of a fixed TODF may be a significant source of error.

Peaking also has been estimated by extrapolation from work trip data, in applications that are exercising only work trip models. In these cases, the peak period work trip table is expanded to represent trips for all purposes during the peak period (or for the entire day), with the expansion factors derived from full runs of the regional model system, from survey data, or even from national sources. Although this approach is fairly common in subregional planning and design applications, it is not a substitute for having and using a complete set of work and non-work travel models, and is not recommended as the primary means of conducting major transportation analyses, especially when air quality analyses are to be carried out.

Many regional planning agencies estimate peaking factors before assignment of traffic to the networks. Common approaches to estimating peak trip tables are:

1. Time-of-day factors applied before trip distribution. Peak/off-peak factors may be developed as an integral part of the trip generation phase (as suggested by Stopher and Meyburg, 1975), e.g., models may directly include a measure of congestion (or more generally, a measure of accessibility) in estimating trip generation rates at particular locations and times of day. This approach has the advantage of allowing for a correlation between the number of trips made and the qualities of transportation services available at specific times and locations. However, if overly simple measures of accessibility, e.g., regional averages, are used, much of the potential of the approach will be lost.

   Alternatively, time of day factors may be estimated as an intermediate step between trip generation and trip distribution. In this approach, a separate TODF should be applied for the attraction-to-production versus the production-to-attraction daily volume in order to determine the peak period volumes.

2. Time-of-day factors (TODFs) applied before mode choice. In the typical application of this approach, peak network characteristics (e.g., travel times) are used for work mode choice, and off-peak characteristics are used for non-work mode choice. In other applications, each trip table (by purpose) is split among time periods, so that mode choice and assignment can apply to the range of conditions experienced by travelers. Both approaches impose strong assumptions about travel behavior. FTA (UMTA, 1986) has indicated its preference for the first approach, primarily out of concern about the stability of the unspecified factors leading to the time splits in the latter: "[The first] approach is preferred because the time-of-day factoring is done (by purpose) for trips on all modes together, reflecting only the influence of activity patterns throughout the day. These factors... are likely to be reasonably stable over time and across alternatives."

3. TODFs applied after mode choice. In this approach, TODFs are developed by both trip purpose and mode. Two versions of this approach are common. The first, sometimes used in areas that have developed a mode choice model based on 24-hour supply characteristics, applies TODFs to create a prototypical peak hour trip table for assignment. Because this approach results in trip distribution and mode split being done without accounting for congested times, it is highly undesirable in all but the least congested areas.

The second approach is to apply a crude peak or off-peak designation to each trip purpose before trip distribution, as in #2, and then apply more refined TODFs to each trip table after mode choice in order to create more plausible tables for assignment. In most cases, the peaking factors are derived from the most recent travel survey, but specific adjustments are made with a heavy dose of judgment. UMTA (1986) cautions against this approach, noting that "the factors may not be stable over major changes in the ... [transportation] system that affect the quality of service for work trips differently from the quality for non-work travel" (p. 5-18).

Many of the adjustments being made to trip tables are intended to better cope with modal, facility, corridor, and subregional variations in peaking. Recently, some agencies have developed ad hoc procedures which draw upon on empirical studies to estimate the probable impact of congestion on peaking levels and duration. While it can be argued that these adjustments serve to improve the realism of assigned traffic volumes, they generally fall short of being formal models (e.g., relating the peak hour percent to the ratio of actual daily volume to theoretical daily capacity in a corridor). Moreover, adjustments are almost always applied to reduce unrealistically high volumes in excess of capacity; peak loads rarely are adjusted upward in forecasting applications to reflect higher future flows.

Modest advances have been made in a few regions in the representation of peak spreading. Experience with urban traffic suggests that peaking is sensitive to congestion;[15] peak spreading has been observed from both time-series and cross-sectional data.

One approach to making TODFs sensitive was developed recently for Phoenix (Loudon, Ruiter, and Schlappi, 1988). The method is based on data from 49 corridors in Arizona, California, and Texas. It assumes that the 3-hour peak is a fixed percentage of daily trips, but allows the peak hour (as a percentage of the 3-hour volume) to vary according to congestion levels (measured by V/C ratios).

The method is an iterative one, with the following steps:

1. Compute the ratio of the current assigned (3-hour) volume to the 3-hour link capacity (V/C).
2. Apply a peak spreading model to provide a peaking factor: the ratio of 1-hour volume to three-hour volume.
3. Determine the revised peak-hour volume as the product of the peaking factor and the assigned volume.
4. Compute the ratio of peak-hour volume to hourly link capacity.
5. Apply a peak-hour speed model to estimate revised the link speed.

This link volume updating process continues throughout the iterative equilibrium procedure.

When applied in the Phoenix area, this technique was found to improve the estimates of average speed and VMT. The root mean squared error (RMSE) of speeds on links was reduced by 35% (from 56, to 36.6%), and the percent VMT error declined from 16.4% to 2.2%.

As its authors note, there are some limitations to the procedure:

> "First, there is no guarantee of continuity of flow in the peak-hour prediction. Differences in the three-hour V/C ratio predicted for two adjacent links could result in a different amount of peak-spreading predicted for each. While this could and does occur, the impact of it is likely to be small because of the calibration of the peaking model on a facility type (rather than link-specific) basis, thereby averaging the effects over a facility. A second limitation is that the peak-

[15] In fact, it has been argued that the Interstate highway program's principal benefit in urban areas was not so much the elimination of congestion, as the shortening of the duration of congestion.

> spreading model is applied at the link level while the peak-spreading on a specific link may occur as a result of a single congestion point on some other link in the network or as a result of the perception of travelers of the average level of congestion in the corridor... A final limitation of the recommended procedures for peak-spreading is that they do not reflect spreading of the peak outside of a three-hour period."

These advances, while improving model fit, still fall short of providing basic insight into the duration and magnitude of peaks or, more fundamentally, into the behavioral processes that underlie peaking.

Advanced Practice

Peaking and time of travel are critical determinants of level of service, congestion, and emissions and concentrations of emissions. For example, the success of strategies to reduce the intensity of highway congestion depends critically on a low elasticity of trip departure time with respect to trip duration, yet common experience on congested facilities suggests otherwise, i.e., peaks narrow but do not decline in intensity very much. Recognizing this, academicians interested in congestion relief and highway pricing have been working on a more realistic behavioral representation of peaking. The results of this research are not yet implemented in practice, but may well be in at least a few areas over the next 3-5 years.

Thinking in terms of the am peak work trip (for simplicity), peak spreading is seen to result from two related phenomena:

1. The adjustment of departure times in response to a perception of increased (or less predictable) door-to-door travel times.[16] There is no effect on the timing of activities (work).
2. The rescheduling of activities to allow for a more satisfactory (or affordable) travel experience. Both trip departure and activity start times may vary.

The first phenomenon, while hardly desirable from a social or environmental viewpoint, is simpler to address analytically. It implies a straightforward relationship between decreasing speeds and a broadening peak (albeit a relationship that may still necessitate a resourceful extrapolation to project future values on the basis of current survey and count data).

The second phenomenon has been the focus of much research over the past decade. This research falls roughly into four categories:

1. Empirical studies of highly-congested corridors.
2. Thought experiments with bottleneck queuing models.
3. Econometric analyses of stated time-of-travel preference.
4. Econometric analyses of revealed time-of-travel preference.

[16] Or increased travel costs, in the hypothetical case of congestion pricing.

The revealed preference studies, in particular, have been quite promising. They indicate substantial activity scheduling (hence, travel time) elasticities with respect to travel conditions, and suggest a close relationship among activity timing, trip generation, and trip chaining.

While models of the choice of the time of travel are probably not ready to move into the mainstream of regional modeling, research has come far enough and the models sufficiently well-behaved that their introduction into advanced modeling practice would be desirable.

Several MPOs, including METRO (Portland, OR) and SACOG (Sacramento), have proposed explicit time choice components for pending model system updates, and MTC will be developing such a model in 1994.

It is no small irony, and perhaps no coincidence, that the explicit time-of-day component of trip generation discussed by Stopher and Meyburg in 1975 (and evident in the literature as early as 1960) has reached the threshold of practicality in the changed policy environment of the 1990s.

3.3.9 Traffic Assignment/Route Choice

Overview

Traffic assignment[17] is the step in which traffic volumes are estimated for each link in the network and each time period under analysis. Traffic assignment is based on (or determined by) the simultaneous interaction of link travel time (or speed); the capacity of the link; and the volume assigned to the link, considering other paths through the network. Assignment plays an important role in the determination of link speeds, VMT, and VHT - all of which affect emissions estimates as well as transportation system performance.

The traffic assignment step of the modeling sequence has been dealt with in great mathematical detail; most approaches are highly complex and computer-dependent. Yet there are both theoretical and practical questions about the validity of current practice. From a theoretical perspective, as noted in Bates & Dasgupta (1990), the evidence is weak that the assignment techniques reflect actual route choice behavior. From a practical perspective, data limitations, combined with the inherent difficulties of adequately representing link and node characteristics via a few variables, make it extremely difficult to judge the performance of assignment models.

[17] Transit assignment involves a number of particular considerations which are not dealt with in this version of the Manual. See Dial (1967), Roden (1986), and A.J. Horowitz (1987) for expositions of transit assignment issues. In general, significant progress has been made in the area of transit assignment, but sophisticated multi-path transit assignments are critically important only in the very largest metropolitan areas. Furthermore, transit route assignment will have little direct bearing on air quality impacts in a region (though the realism of transit travel times is an important determinant of mode choice model accuracy wherever transit is a significant mode).

Moreover, of all of steps in the four-step travel forecasting process, traffic assignment probably has received the least critical scrutiny from modeling practitioners: default values and procedures typically have been utilized, and validation typically has focused only on link volumes. The use of the software "as is" probably reflects the ease with which software packages facilitate application, at least when the defaults are used. Limited validation probably reflects the fact that loaded (i.e., congested) speeds output by the model historically have been a secondary concern to the transportation planner, so long as traffic volumes are within 10 to 20 percent of the actual values.

For many metropolitan areas, however, the casual application of traffic assignment models may be past. Today, the outputs of network models (including speeds as well as other traffic characteristics) have come to be examined closely, because they are critical to air quality modeling and analysis, because the traffic effects of proposed projects may be controversial, and because traffic forecasts now must be compared for consistency with anticipated growth rates and land use patterns, among other reasons. Hence the details of the specification and performance of this step of modeling are coming under increasing scrutiny.

Basic Practice

The traffic assignment step requires 1) the development of adequately detailed and coded networks, and 2) an algorithm for assigning traffic to links in light of the various alternative routes.

Developing the Network

In typical practice, both highway and transit networks are developed to represent all facilities of the arterial classification or higher (highways) and all public facilities and scheduled services/frequencies (transit). Highway links are coded for initial speeds, capacities, volume-delay relationships, and other key characteristics (e.g., intersection operational features), with the level of detail varying with both the software package and the application. Nodes also may be coded with detailed descriptors, in some cases.

Practitioners are now coding more detail into a more elaborate set of networks than in the past. For example, in order to produce reasonable accuracy on arterial links and to match fine-grained zonal depictions, many MPOs now code all facilities down to the major collector classification. In addition, modelers are finding that it often is important to code intersections and other nodes in some detail, and to explicitly deal with the operations of special purpose links such as HOV lanes and freeway ramp meters (discussed below).

The initial speeds for links are most commonly coded as free-flow speeds, taking into account the effects of traffic control devices, if present. Use of posted speed limits as maximum speeds, e.g. capping freeway speeds at 55 MPH, has been the practice in some agencies, but this should be discontinued, since many studies indicate that median traffic speeds under uncongested conditions are typically higher than the posted speed limits.

Volume-delay relationships are typically handled via an equation of the general form:

$$T_i + 1 = T_i * (1 + a * (V/C\ )_b)$$

where:

V/C is the volume/capacity ratio
T_i is the link time on at time i
a, b are coefficients.

A common form of this model is the BPR formulation discussed earlier. Unfortunately, this widespread formulation does not accurately represent speed-flow conditions when queuing is present, and over-predicts congested travel speeds. As a result, many regional modelers have developed variants of the formulation to match particular facility types or local conditions, or have developed post-processors to produce more realistic speeds.

It is also fairly common in planning models to have estimated volumes in excess of the capacity on individual facilities. However, there are no observed speed/flow curves for volume/capacity ratios in excess of 1.00. Consequently, the BPR curve (or some similar curve) is applied in situations where volumes exceed the facility's capacity.

The BPR curve does not take account for the effects of queuing on travel speeds and demand. Planning models using the BPR curve consequently will significantly overestimate speeds of facilities near capacity, at capacity, or over capacity.

As noted earlier, modelers are finding it important to code special purpose links and nodes into the networks. For example, many metropolitan areas have implemented or are proposing extensive systems of HOV lanes. These HOV lanes are intended to improve air quality and reduce traffic congestion, but in many areas decision-makers and other concerned groups are unwilling to simply assume the impacts will be beneficial. Hence there is a need to explicitly represent HOV lanes' effects in modeling efforts. Many of the widely used transportation planning software packages now permit this, providing for the separate specification of HOV links in the highway network. These links are available only to HOV trips, with access to the HOV lanes represented by a special set of zero-travel time/distance links.[18] The resulting network is like the rungs of a ladder, with the HOV and mixed-flow lanes coded parallel to each other.[19] HOV bypass lanes, which allow HOVs to avoid the delay associated with freeway ramp metering, also can be coded.

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[18] A time penalty could be associated with these links to simulate the time needed for weaving in or out of the HOV lanes. This would tend to discourage short HOV trips (say, from one ramp to the next) from using the HOV facility, as probably occurs in reality.

[19] Although modelers are increasingly coding HOV elements into their networks, there currently appears to be no consensus on what to do next: e.g., whether HOV trips should be loaded before or

after other vehicle trips, or whether a portion of each table should be loaded so that the some degree of route diversion due to congestion is experienced by the HOVs.

Ramp metering is another element which has become increasingly important to represent explicitly in modeling efforts. Ramp metering can play an important role in reducing freeway congestion, but the impact on air quality is less clear. The emissions from queuing vehicles on a ramp, as well the effects of on-ramp accelerations and decelerations and of the different driving cycle of vehicles diverted to parallel arterials, all are topics of ongoing research, and how these phenomena should be modeled has not been fully resolved. Even volume and delay estimates for ramp-metered links can be complicated to produce. Some agencies have applied "penalties" to ramps that are metered to represent average delays; but this approach is problematic, because delay at the ramp is usually a function of ramp (and sometimes mainline) volumes. Moreover a fixed penalty will reduce the traffic estimated to use the ramp. Experience in San Diego indicates that the estimates of delays and volumes can oscillate significantly without reaching convergence. More research needs to be done in this area, but one approach to achieving convergence might be to designate the metered on ramps with a special assignment group/facility type code, and then code a special V/C-travel time curve to represent the delays that occur at the ramp, as a function of the ramp volume. The "capacity" of the ramp would have to be adjusted to reflect the ramp metering rate. This would require an assumption that the metering rate is fixed, but in many applications, this is the actual situation.[20]

Traffic Assignment Algorithms

Once networks are developed, traffic volumes (flows) on each link are estimated using an assignment algorithm. The early assignment techniques were sharply constrained by computer capacity and speed limitations, and consequently were critically dependent on efficient algorithms for tracing paths through a network; certain simplifications and compromises were accepted to obtain workable procedures. With computer advances it has been possible to implement increasingly sophisticated network analysis techniques, although practice sometimes lags behind in its implementation of the improved approaches.

All-or-nothing (AON) assignment - assigning all traffic between an OD pair to the minimum (shortest; fastest) path through the network - was once widely applied, but is now recognized as being unrealistic and is in declining use. AON assignments have little value beyond their application in long-range system-level planning, in which they can be used to predict travel paths ("desires") in an ideal world in which no congestion exists.[21]

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[20] In reality, modeling the metered ramp is somewhat more complicated, because it must include consideration of the period in which the departure rate at the ramp exceeds the arrival rate, at the trailing shoulder of the peak period. Thus, delay will depend on how quickly the arrival rate drops off toward the end of the peak period. Some reasonable assumptions about this "post peak" period might be assumed for all metered ramps based on average or local conditions.

[21] AON assignments could also be used to compare how close to true equilibrium the final iteration of an equilibrium assignment is. This would involve using an AON assignment to load the trip table using the final speeds from an equilibrium assignment. If the VHT from the AON assignment approximates that from the final loaded equilibrium network, then the assignment is close to a true equilibrium. If the VHT decreases with the AON assignment, then shorter paths have been found (i.e., some users could unilaterally decrease their travel time by switching to another path).

Incremental capacity restraint and equilibrium assignments are the two most commonly used assignment techniques. In the "incremental loading" method, the traffic is divided into a number of parts which are successively loaded. After loading each part of the traffic, link costs are re-estimated, then the next traffic increment is loaded using the new link costs. Assignment may be to the current minimum path or, possibly, to a selection of such paths.

The most sophisticated approach, equilibrium assignment, attempts to find a solution according to Wardrop's (1952) user equilibrium principle that no traveler can improve his or her travel time by unilaterally changing routes. There are a number of variants on the specification of the objective function to allow for different criteria of optimality.

These latest techniques have gone a long way toward providing realistic representations of declining level of service as traffic loads increase.[22] Moreover, at least in principle, they are capable of estimating the generalized cost of highway travel between each pair of zones, which can then be used in the earlier steps of the model system.

Advanced Practice

Advanced practice in traffic assignment heavily depends on the application of software with advanced capabilities, e.g., capable of representing specialized links and nodes and incorporating advanced equilibrium algorithms. Regardless of the modeling technology, however, practitioners can make progress toward better network representation and modeling. Common features of advanced practice in this regard are the following:

- an explicit effort to include all of the facilities known or likely to carry interzonal traffic, regardless of functional category;
- a large number of functional categories, to better match actual roadway categories;
- incorporation of the effects of treatments at intersections and interchanges;
- local calibration of volume-delay curves.

In addition, post-processors may be applied to provide more realistic speed estimates for congested flow situations, and/or queuing analysis techniques may be applied to estimate travel speeds and other performance measures in situations where volumes are predicted to exceed capacity. The queuing analyses could be relatively simple ones (e.g., estimate queues by dividing the peak period into hour-long intervals and performing a queuing analysis for each one hour time slice; calculate the average speed for the peak period over all one hour time slices); alternatively, detailed traffic operations microsimulations could be carried out with the results fed back to the model system.

[22] Note, however, that the various programs available to estimate equilibrium assignment do not necessarily lead to the same solution, an indication that the current methods require further assessment.

Traffic assignment is “route choice” when viewed from the traveler's perspective. Research indicates that the processes through which route choices are made are not necessarily as straightforward as the optimization algorithms incorporated into most model systems, and may reflect such factors as willingness (or unwillingness) to “go the wrong direction” to get to a superior route, willingness to make left turns, etc. Some modelers treat route choice probabilistically and allow for a certain amount of uncertainty in route selection. Researchers also have developed models which attempt to incorporate additional variables in a formal representation of the route choice process.

3.4 Model Interrelationships

3.4.1 Overview

The material in Section 3.3 largely deals with individual model steps in isolation. However, the model system is actually a tightly-linked hierarchy, especially in advanced practice. Thus it is important to pay attention not only to the individual model steps, but to their interrelationships as well.

In conventional practice, the outputs of trip generation are used in trip distribution; the outputs of trip distribution are used in mode choice, and so on. However, linkages with other modeling steps, notably auto ownership, time-of-travel, and the location of housing and jobs, are often dealt with exogenously or are linked to the other models in an ad hoc manner.

Moreover available software does not require that the times and costs used in the various model steps are consistent with one another, and indeed many applications produce network travel times and costs that are far different from the ones used in earlier trip distribution and mode choice steps. Most practitioners compare the initial travel times and costs and iterate through the models as necessary to achieve a specified level of consistency. A more theoretically satisfactory approach is to assure consistency in the specification of the submodels' structure and linkages. In concept, linkages should be accomplished through the use of a generalized cost and/or accessibility measure, fed upward through the model hierarchy.

This section elaborates on the key concepts involved in model linkages, then describes how such linkages might be accomplished by varying the level of detail with which demand and supply components are handled.

3.4.2 Key Concepts

Generalized Costs and Utility

The concept of generalized cost is a central one in travel demand theory and is increasingly important in modeling applications, not only in mode choice (where the use of various costs of travel is well developed), but in trip distribution, trip generation, and other models as well.

Early travel models incorporated only a rough measure of cost, generally measured by distance (or travel time) for the auto modes. However, it was quickly recognized that mode choice models also had to include dollar costs, to reflect the impact of transit fares. Research on the demand for transit soon revealed that different elements of travel time - access time, wait time, transfer time, in-vehicle time - were given different weight in travelers' decisions, and further examination of costs indicated that overall out-of-pocket expenses (including tolls and parking charges, where they exist) better reflected the costs considered in travel decisions than travel distances (times) alone. The tradeoffs travelers made between travel times and travel costs led to considerable research on the “value of time.” By the late 1960s the concept of cost came to be recognized as including both monetary expenses and time expenditures, and economists began referring to the combined time and money elements of a travel mode as its “generalized cost”.
During the 1970s, work on discrete choice/random utility models made it clear that there was a direct relation between generalized cost $f(C_{ij})$ and the utility function V:

$$V = - l \; f(C_{ij})$$

However, utility functions often include a variety of variables in addition to the time and cost variables traditionally considered part of the generalized cost. For example, alternative-specific variables such as comfort, seating availability, safety, and reliability (among others) could be included in a utility function. Such alternative-specific variables can be thought of as additional kinds of “costs” (or “benefits”) of the alternatives.

Utility functions used in transportation models also include household- or individual-specific variables such as age, sex, income, disability,..., because it is clear that the importance of many costs is a function of the individual or household's characteristics. For example, parking charges may affect everyone's willingness to use auto modes or travel to a particular destination, but the effect probably will be larger on those with lower incomes. Comfort may be more important to the elderly than to young travelers.

Overall, then, a well-specified utility function can be thought of as a broader conception of generalized cost, and one which is capable of representing the considerable level of variation in behavior known to exist among different socioeconomic and demographic classifications.

The inclusion of generalized cost of the transportation alternatives is standard practice in mode choice and trip distribution models, although especially in the latter the variables included are usually few and may be too broadly defined. Modeling exercises that have adequately tested generalized cost as a factor in trip generation have found it to be significant, and such models are finding their way into advanced practice. Similarly, generalized cost has been found to be significant in auto ownership and in location choice models, though only a few applications have proceeded to date. This is an area where future model development should be able to make important advances. Nested logit, discussed below, is one way to proceed, but other approaches also deserve further development.

Work done in the 1970s and early 1980s demonstrated that the log of the denominator of the multinomial logit model (often referred to as the logsum) is an exact measure of the expected utility (i.e., a direct measure of the overall benefit) of the alternatives under consideration. That recognition has led to the use of the logsum of the mode choices between a particular OD pair as a variable in the estimation of destination choice, where it represents the accessibility of the destination. Similarly, the logsum of the destination choice model can be used as a measure of accessibility (travel choices and activity options) in the trip generation model, and so on. This approach, called nested logit (or tree logit in European applications), also provides a formal test of the order of the model steps: a coefficient greater than one for the logsum variable indicates that the choice hierarchy is probably improperly ordered.[23] (See Ben Akiva and Lerman (1985) for the derivation of this property.)

Nested model structures are somewhat more complicated to estimate than conventional models, and commercial software for model estimation currently is available from only one source. However, nested structures are capable of efficiently representing theoretically and empirically supported relationships: the times and costs of the transportation system should affect mode choice, the available transportation modes and their characteristics should affect destination choice, the accessibility of various destinations should affect trip generation rates, and so on. Hence, the theoretical rigor and internal consistency available through this modeling approach make it highly desirable in spite of the greater difficulties in estimation and application it entails.

Feedback and Recursion

It is widely recognized that some recursion is needed in the modeling process in order to provide internal consistency, i.e., to assure that the travel times and costs at network equilibrium are compatible with the times and costs used in earlier model steps. As time and cost variables are incorporated into more of the model steps and as the number of linkages is increased, a considerably larger level of effort is likely to be needed to attain an acceptable degree of consistency. For example, it may be necessary to recalculate several earlier model steps, mode choice, destination choice, and perhaps others,[24] in

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[23] Note that it is possible that the hierarchical structure would vary by trip purpose, or even by socioeconomic/demographic category.

[24] As noted earlier, generalized cost has been found to be significant in trip generation, auto ownership, and household location models, as well as in mode choice and destination choice (trip

order to incorporate reasonable time and cost values (appropriate logsums, in the case of formally nested models). Several passes through the model system may be needed in cases where capacity constraints lead to substantially reduced volumes and speeds at numerous locations throughout the network.[25]

Convergence criteria also may become an issue as models become more complex and interconnected. In the past, practitioners often have established simple convergence criteria, e.g., iterate until the differences in travel times in a particular model step are no larger than 1%, or stop after eight iterations. In a model system with several linkages, not all components will converge at the same rate, raising questions about when to quit. Convergence may be especially complex when there are linkages to location choice models and land use allocation models, i.e., when both short term and long term responses must be considered. In addition, when analyzing transportation alternatives the model system may converge faster for some alternatives than for others. Recent findings have suggested that, at minimum, the alternatives should reach the same level of convergence for a number of indicators in order for the comparison of the alternatives to be valid (Bates and Dasgupta, 1991). A procedure which is potentially more complicated but which may be more direct is to define convergence criteria on the assessment indicators themselves (for example, the measure of benefits) rather than for the models per se (Williams et al. (1989)).

3.4.3 Level of Detail

The desire for greater detail and inter-connectivity in modeling has to be considered, in most areas, in light of funding constraints. To keep costs within limits, some agencies have developed models that treat demand in great detail but handle supply in a simplified fashion. One way to do this is to use large zones and reduce network representation, either by simplifying the treatment of capacity or by limiting the network to key links only. This approach may lose too much detail and accuracy for some applications but may suffice for others. Another strategy, discussed in Section 3.4, is to use travel time and cost matrices in conjunction with detailed demand models, feeding the outputs into and running the detailed network models only when significant changes are anticipated.

Regardless of the level at which the network is represented, however, the network models used in demand forecasting are likely to lack sufficient detail for certain analyses. In these cases the network

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distribution). However, the number of studies and applications including generalized cost in these other models is still quite small, and this inclusion cannot be deemed part of conventional practice at this time.

[25] Boyce (1993) argues that an alternate, and preferable, approach is to develop a single system of consistent equations for which equilibrium can be calculated in one analytical step.

simulation models used by traffic engineers (also discussed in Section 3.4) may be called upon to provide greater resolution, with the results used to adjust the demand models or model outputs. Over the longer run, as computer advances proceed, it may be possible to combine detailed network simulation models with detailed demand models and still obtain fast turnaround at reasonable cost. (The costs of collecting and coding the detailed network data would still be a consideration, although GIS coding of street networks combined with remote sensing, electronic traffic counting and coding, and other technological advances could reduce these expenses as well.)

Other refinements in modeling level of detail and interconnections probably should be implemented in many regions in relatively short order. Bates and Dasgupta (1991) suggest the following:

- Bus in-vehicle times should be consistent with the travel times and delays in the highway networks.
- Parking capacity constraints should be accounted for in auto travel times, in the form of added access time (search time and, potentially, walking time).
- Enforcement effort and the perceived cost of illegal parking should be considered in estimating actual (or perceived) parking costs in a district.
- Transit load factors should be reflected in transit travel times (e.g., via longer wait times for routes with heavy loads).

The importance of such refinements will depend on the nature of the alternatives available or under consideration in each region, as well as the level of effort required to develop the improvements.

3.5 Supplemental Methods

In a number of cases the available four-step model system is not capable of representing particular policy options. This may be because key variables are omitted from the models, because there are no local data on the factors in question, or because much greater level of detail is needed than can reasonably be introduced into a regional model system. This section discusses how special purpose models and special study results can be used to supplement the analyses produced using the four-step model system, with a focus on the analyses needed to evaluate TCMs.

3.5.1 Sketch-Planning Methods

Sketch planning methods are useful both to supplement the full model system and as quick response or screening approaches which can be applied as more easily, faster and cheaper than the full model system. A variety of methods, from simple transfer of experience to elaborate microsimulation of demand, fall under this rubric.

Transfer of Experience

Many urban areas assess travel and emissions impacts of TCMs using empirical information on observed performance from previous implementations. A number of reference documents support this approach, providing discussions of the objectives of each measure, likely markets, and previous experiences. Some of these reference documents also provide guidance on simple impact analysis procedures.[26]

A very simple way to transfer experience from other applications of a TCM is to apply the observed percentage change(s) in travel metrics to the case at hand. The analyst must separately estimate the size of the market to which the change applies, e.g., if a program at firms with 100 or more employees has produced a 3 percent average reduction in the number who drive to work, the analyst must take care to apply the 3 percent average only to the share of employment that is in firms of that size.

[26] See, e.g., COMSIS Corporation and Harold Katz and Associates, "Evaluation of Travel Demand Management Measures to Relieve Congestion", Report prepared for the Federal Highway Administration, Washington, D.C., 1990; D. Eisinger, E. Deakin et al., "Transportation Control Measures: State Implementation Plan Guidance", report prepared for the U.S. Environmental Protection Agency, 1990; Robert Dunphy and Ben C. Lin, "Transportation Management through Partnerships", Urban Land Institute, Washington, DC, 1990; Michael Meyer (ed.), "A Toolbox for Alleviating Traffic Congestion", Institute of Transportation Engineers, Washington, DC, 1989.

Estimating TCM impacts based on inference from empirical evidence must be done with caution, as the particular circumstances at the case study sites may or may not be replicated at the site being analyzed. While research has confirmed consistencies in travel behavior across US urban areas for a given set of conditions, those conditions can vary from place to place in ways that are not immediately obvious to the casual observer. For example, income differences between two places could lead to different results from application of a measure. Or employer-based programs of a certain type may work much more effectively at suburban back-office locations than in headquarters or research installations. Similarly, traffic signal timing may produce estimated emissions reductions averaging five percent in older, three-dial signal systems, but only half as much in newer signal systems which have been periodically retimed from the central computer.[27]

Worksheet, Spreadsheet, and Pivot Point Methods

A second, more formal, approach to TCM analysis involves the use of simple manual and computerized methods for estimating travel demand and traffic operations impacts. These procedures can be used as an alternate set of analysis tools for the transportation agency which lacks full-scale travel forecasting capabilities, but the more common use of the methods has been as an inexpensive quick-response supplement to such models.

One of the earliest reports on these methods was commissioned by EPA in the late 1970s.[28] (The Department of Energy sponsored even earlier work on these methods for use in transportation energy conservation analysis.) The manual leads the analyst through the steps necessary to estimate the size of the target market and properly estimate the changes in travel indicators (mode shares, emissions, etc.) likely to result from the application of various demand management measures. Methods for analyzing various traffic operations improvements are also discussed, including greenband and computerized traffic signal timing methods. Worksheets, calculator-based methods, and simple computer applications are explained step-by-step, and examples are provided.

More recently, microcomputer-based spreadsheet models have been developed to carry out similar analysis approaches. One such spreadsheet model, originally developed for the San Diego Association of Governments, calculates baseline travel characteristics, estimates TCM effects, prepares emissions inventory estimates, and estimates costs of control measures to the public and private sectors and to vehicle owners.[29] The travel estimation module is a spreadsheet which contains equations for quantifying

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[27] Readers should be aware that debate has arisen over whether signal timing improvements will reduce emissions in the long run, i.e., whether the improved travel conditions for autos will lead to more vehicular use.

[28] Cambridge Systematics, Inc., "Transportation Air Quality Analysis - Sketch Planning Methods' (two vols.), report prepared for the US Environmental Protection Agency, Washington, DC, December 1979.

[29] Sierra Research and JHK, "Methodologies for Quantifying the Emissions Reductions of Transportation Control Measures", prepared for the San Diego Association of Governments, San

TCM impacts on travel, largely using elasticities identified through a literature review. (The user can substitute locally-based equations or parameters.) A large amount of descriptive information also is provided about each TCM, along with caveats about applying the default parameters and elasticities.

Diego, 1990.

A more complex approach is represented by the TDM Evaluation Model, which estimates the travel impacts of a variety of demand management measures including transit service improvements, ridesharing programs, preferential parking for HOVs, parking charges, and variable work hours programs.[30] A combination of techniques is used, including a "generic" mode choice model exercised in a "pivot point" fashion and empirical data from research studies (used for institutionally-oriented TCMs). Default coefficients for the variables are provided but other coefficients can be substituted. Personal and vehicle trip tables taken from existing forecasts, along with estimates of base case mode shares, are used to estimate impacts of the TCM in question for each OD pair. Output can be in a form which can be passed back to the regional travel models, through which traffic assignments, emissions estimates, etc. would be performed. Detailed analyses of market segments to which the various measures are applied also are assisted by the model; for example, variations in the characteristics of the employment base (professional, clerical, etc.) are taken into account.

Microsimulation of Demand

A third approach makes direct use of the travel demand models developed for a region, but substantially reduces the time and cost of analyses by using travel time matrices instead of running the regional network models. In two applications of this approach,[31] an additional feature - sample enumeration - is used together with models of individual and household choice (disaggregate demand models) to create a microsimulation approach which permits highly detailed and disaggregate investigations of demand response.

In sample enumeration, the models are applied to a sample of individuals or households drawn from travel surveys. The choice behavior of each individual or household is predicted by the model(s), and the responses are added together to form an estimate of the population behavior. If individuals are sampled randomly from the population, the average prediction for the sample group will converge on the true value for the population at large for a comparatively small sample size relative to population size. This principle permits sample enumeration to provide an unbiased prediction of population behavior without requiring information on multivariate probability distributions or market segmentation.

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[30] COMSIS, TDM Evaluation Model, prepared for the Federal Highway Administration, Washington, DC, 1990.

[31] These are the SRGP - Short Range Generalized Policy - Program (Cambridge Systematics, Inc., Cambridge, MA), and STEP - Short-Range Transportation Evaluation Program (G. Harvey, Berkeley, CA.) The two programs share common parentage and overlapping authorship.

The use of individuals or households in forecasting allows the model predictions to represent the full distribution of population attributes, which would not be the case if, for example, zonal or interzonal averages were used instead. The approach's household/individual orientation also affords an extremely high degree of flexibility in policy representation. For example, a parking charge at certain destination zones can be shown as an increase in auto parking cost for each work trip ending in those zones. For many models, such a policy would have to be shown as a change in average auto trip cost for some segment of the population, with an attendant loss of accuracy and realism.

Outputs also can be tabulated flexibly. For the basic outputs of the model, each household result is multiplied by a weighting, or "expansion," factor which depends on the sampling rate for that household, and the factored values for the different households are added together to give the total travel pattern and transportation impacts for the study area. However, since the computations are performed for each household, the results also can be classified according to household type (e.g., low income vs. high income), trip purpose, or geographic area (e.g., by county, city, or zone of residence). This enables the analyst to assess equity issues and explore the market segmentation and geographic distribution of transportation policy impacts, in addition to providing travel data covering the entire study area.

The sample enumeration microsimulation program STEP has been used extensively in the San Francisco Bay Area to analyze TCMs, as well as in analyses of pricing and equity in the South Coast (greater Los Angeles) area. STEP currently is being extended to Sacramento and San Diego, as well as to California statewide for use in air quality and energy conservation analyses.

STEP is based on a set of eight models of individual and household behavior: auto ownership level, work trip mode choice, work trip destination choice, carpool size, shopping trip frequency, shopping destination/mode choice, social/recreational trip frequency, and social/recreational destination/mode choice. The models were estimated with a full range of policy variables including fuel cost, other auto operating costs, tolls, parking charges, transit fares, household incomes, number of workers per households, autos per household, and a detailed breakdown of travel times (access, wait, in-vehicle, etc.); thus the models are sensitive to a full range of demand management, pricing and operational policies. The STEP program applies the models to the sample of households or individuals, along with time and cost data for the travel options which are open to each household, to predict the trip-making pattern and transportation-related impacts for the households in the sample. Among other things, the forecasts for each household include number of trips per day by trip purpose; the number of trips per day by mode; carpool size; auto ownership level; and expected distribution of trips. Many of these outputs are computed for each trip which the household is predicted to make, in addition to daily household totals. The STEP program also includes subroutines which directly compute auto emissions, fuel consumption, and gas tax, toll, and parking revenues, as well as such travel indicators as VMT, total travel time, etc.

3.5.2 Traffic Engineering Methods (Arterials, Freeways)

While considerable emphasis has been given in recent years to sketch planning methods for demand analysis, a number of important TCMs focus on improving traffic operations rather than controlling demand. These traffic engineering approaches include intersection design improvements (installation of turn lanes, e.g.); traffic signal timing; freeway ramp metering; bottleneck removal; and flow metering, among other items.[32] A wide range of methods for analyzing these strategies has been developed, but few have been integrated with demand models, either at the regional model level or in sketch planning approaches. Consequently analyses of traffic operations TCMs will need to be done largely off-system, with results fed back into the regional model system (when of sufficient scale) to explore implications for demand. (Some measures, e.g., individual intersection improvements and signal timing on local streets not represented in the network, are typically too fine-grained to be fed back into the regional models.)

Many of the techniques for traffic operations analyses are documented in the Highway Capacity Manual (HCM). For example, the Manual includes both a simple ("planning") method and a more detailed ("operations") method for individual signalized intersections; methods for analyzing weaving sections; unsignalized intersection analysis methods, etc. The HCM as a whole is updated from time to time and specific chapters and methods are continually being reviewed and improved. Several states supplement the HCM with their own manuals on analysis methods for traffic operations and control, which also may be valuable sources for MPOs.

For a number of common traffic operations strategies computerized analysis techniques are in widespread use. For example, programs for timing traffic signals as a system include PASSER (for arterials) and TRANSYT (for arterials or grid systems); these programs also produce outputs on travel time and delay which can be used to calculate performance, emissions, etc. (Some versions directly output emissions). NETSIM, a much more complex program, can be used to analyze complex signal equipment, detailed intersection design, etc., and provide detailed information on the impacts of these changes. On the other extreme, hand calculation methods (e.g., bandwidth analyses) can provide useful results for simple applications.

Freeway operations including bottleneck analyses and ramp metering can be analyzed using FREQ, TRAFLO, or INTRAS, all complex mainframe models. Shock wave analyses also can be done by hand for simple applications, but hand calculations are overly cumbersome for most realistic situations.

One complication for TCM analysis is that the traffic operations analysis methods all are extremely data intensive. As a result, MPOs will frequently have to estimate impacts of traffic operations projects by inference from the results of previous experiences. For example, in California most MPOs have estimated the impact of signal timing by using the results of the state's Fuel-Efficient Traffic Signal Management (FETSIM) program, which has produced evaluations based on hundreds of signal timing projects throughout the state. Special studies, e.g., of the effects of ramp metering along I-80, also may be used.

[32] Readers should be aware of the ongoing debate about the long term impacts of speed improvements.

3.5.3 Speed Estimation

Travel speed models provide predictions of highway or transit speeds over a range of volume levels. A single model typically applies to a specific facility type or classification, providing speed (or travel time)[33] as a function of vehicle or passenger flow per unit of time. Model parameters differ among facility types according to physical and operational characteristics.

Travel speed ("speed-flow") models are used in analyzing link performance, both to predict average daily speeds as a function of total daily volume and, more appropriately, to predict average speeds for peak hours or peak periods as functions of volumes for those same periods. Although the concept of a speed-flow relation applies to highway, transit, pedestrian, and bicycle facilities, explicit models are used only for highway facilities in all but the most advanced applications. For example, while bus travel time depends both on the speed of links traversed by the route and on the volume of boarding and alighting passengers, it is customary to estimate bus time simply by taking some fraction of private vehicle speeds on the shared links. Similarly, it is customary to estimate walk time by measuring distance and assuming an average walk speed.

Accurate travel speeds on transportation facilities are important in the travel forecasting process for several reasons. First, credible demand forecasts require travel time estimates that are consistent with plausible facility performance. Second, travel speeds or travel times must be known for all facilities and links used in highway and transit assignments. Typically, these performance measures are expressed as functions which predict slower speeds as facility volumes increase. The role of this function is to ensure that capacity constraint or network equilibrium assignment methods predict realistic facility volumes throughout the highway and transit networks. Third, highway link-level speeds are required to obtain emissions rates, which in turn are used in estimating total mobile source emissions in an area. Because emissions rates are related to vehicle speeds, the accuracy of emissions estimates depends on the accuracy of link-level speeds.

Many analysts have developed procedures to assure that models predict realistic link-level volumes for current and future years, but in some cases this has been accomplished by adjusting link speeds, with

[33] Travel speed and travel time can be used interchangeably here, since, if time is expressed per unit of distance, the one is simply the inverse of the other. While the literature on travel speed modeling refers to both metrics, the term "speed-flow relation" generally denotes a function depicting speed as dependent on flow, and the term "volume-delay function" suggests either a speed-flow relation or a time-flow relation. When the term "volume-delay" is used in this document, it means a time-flow relation.

the result that speeds coming out of assignment are not always meaningful. Because analysts may find it necessary in future analyses to utilize the assignment speeds in trip distribution, it is becoming increasingly important for the speeds produced in assignment to be as accurate as possible. For some organizations, this will require model refinements (e.g., more accurate representation of volume-delay relationships), as well as more complex model runs (e.g., equilibrium assignment and linkages to trip distribution or above).

Travel speed models are typically specified with just two independent variables: the ratio of link volume to link capacity, and free-flow travel speed. Link capacity and free-flow travel speed, in turn, are typically values which vary by link type (freeway, arterial, collector, etc.), speed limit, number of lanes, area type (CBD, urban, suburban, or rural), and possibly other link characteristics. These characteristics fall short of capturing the entire range of facility features which have been found by traffic engineers to affect travel speeds. For example, variables related to such features as traffic signal operations, fractions of heavy vehicle volumes, and crossing vehicular and pedestrian volumes are only considered, if at all, in terms of their average or typical impact on speeds and capacities by facility class. There have been some efforts to incorporate these factors by expanding the number of link types to reflect variations within each major class.

$$S = \frac{S_0}{1 + a(V/C\ )_k}$$

One speed-flow relationship in common usage has the following general mathematical form:

where:

S = travel speed at volume V

S_0 = free-flow travel speed, a value defined for each facility category or specified for each facility as a link descriptor

C = facility capacity, a value defined for each facility category or specified for each facility as a link descriptor. Capacity typically represents maximum hourly flows under Level of Service C, D, or E conditions

a, k = function parameters, possibly defined for each facility category. Both parameters must be greater than 0.

Such a function typically is used for volume/capacity ratios that yield speeds down to some arbitrarily low number, say 2 mph. For higher volume/capacity ratios, speed is held constant at this value. Although volume/capacity ratios greater than 1.5 (with capacity defined for LOS C) are technically impossible to observe in the field,[34] they sometimes do arise in future-year traffic assignments where the

[34] It should be recognized that capacity is not a precise term, in the following sense. While a fixed point on a highway link does have a unique and measurable capacity (instantaneous volume per unit time), the link as a whole will accommodate greater peak-hour volume than the minimum fixed point capacity along its length. This is because a queue may form during the peak hour and dissipate in a

level of infrastructure expansion is inconsistent with projected increases in demand and the demand functions are not flexible enough to show the full range of behavioral change. Without a simplification of the speed-flow relation in these situations, the optimization procedure in traffic assignment may become unstable for very high volume/capacity ratios, and diagnosis may be quite difficult.

Basic Practice

Speed-Flow Relationships

In the most common version of the general relationship described above, termed the BPR function (after the Bureau of Public Roads, FHWA's predecessor), the capacity C represents "LOS C" conditions, and the values of a and b are 0.15 and 4, respectively, for all facility types. Capacity values and free-flow travel speeds are typically taken from look-up tables which have three dimensions: facility type, number of lanes, and area type. The values used in the look-up tables are either specified locally based on a combination of observed values and values determined using the Highway Capacity Manual (TRB, 1985), or are taken from the default values included in the highway assignment program.

In many areas, the basic BPR speed-flow equation has been revised or replaced, most often when peak hour or peak period assignments rather than daily assignments are performed. Sometimes, these revisions have been made to correct differences between the BPR function and locally observed speed-flow relationships (or the relationships provided in graphical form in the HCM). According to Small's [1992] review of this literature, efforts to fit the BPR equation to real-world data generally yield higher values of a and values of k that range between 2.5 and 5.

Others have made revisions primarily to ensure more plausible or reliable outputs from traffic assignment. While the chosen strategy differs in each case, there is a tendency for these fix-ups to use lower values of a and higher values of k (to make the deterioration in speed more rapid as the volume/capacity ratio goes above 1.0), and to cut the speed deterioration off at some point (to avoid computational problems in the assignment routine when the volume/capacity ratio becomes very high).

When functional forms are chosen to replicate observed speed-flow data, there is a tendency not to modify them in order to correct for volume (or speed) discrepancies at links and screenlines, but to

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subsequent time period. The difference between apparent volume at the entrance to the link and actual link capacity is held in a queue behind the bottleneck and experiences resulting delay. Despite this, it remains true that in the real world traffic volumes over minimum link capacities cannot be sustained for very long periods. For example, at a V/C ratio of 2.0 (with capacity defined for LOS C), the queue on a freeway lane would effectively lengthen by about a mile every 15 minutes, leading to exponential growth in link travel times. Such unrealistically high V/C ratios can be avoided through careful review of analysis assumptions, accurate representation of volume-delay relationships (as discussed here and in subsection 3.3.9), use of equilibrium assignment, and reliance on a model structure that fully captures the effect of travel time on demand (including peak spreading).

search for errors in link descriptions, expand the coverage of the network where appropriate, and otherwise address the root causes.

EXAMPLE: DETROIT

For its daily assignments, the Southeast Michigan Council of Governments uses the BPR equation as specified above, but only for volume/capacity ratios in the range from 0 to 1.85. Above 1.85, speed is held constant at a value determined by substituting 1.85 into the BPR equation:

$$S = \frac{S_0}{1 + .15(1.85)^4} = \frac{S_0}{2.757}$$

EXAMPLE: BOSTON

For peak hour assignments, the Central Transportation Planning Staff, responsible for planning analyses in support of the regional MPO, modifies the BPR function by specifying a and k values of 0.075 and 7, respectively.

EXAMPLE: PHOENIX

For peak period assignments, the Maricopa Association of Governments Transportation and Planning Office uses different functions depending on facility type (freeway or arterial) and volume/capacity ratio. Based on local data for volume/capacity ratios less than 1.33, the BPR functional form was retained for both facility types, but with the following facility type-specific coefficients:

Facility Type	**a**	**k**
Freeways	0.1225	8
Arterials	0.1513	7

For volume/capacity ratios greater than 1.33, MAG staff uses the following functions for peak period assignments:

$$Freeways: S = s_0 * (.25 + .4374 * (V/C)^{-3})$$

$$Arterials: S = s_0 * (.25 + .5184 * (V/C)^{-3})$$

These functions ensure that the minimum speeds on all facilities, regardless of the levels of traffic assigned, are one-quarter of the free-flow speeds. This is intended to compensate for travel demand models that are not fully-sensitive to the effects of travel time.

Travel speeds produced by traffic assignment programs are often used by MPOs and other planning agencies to inventory present emissions and to predict future emissions. This approach ensures consistency between travel model output speeds and input speeds for emissions calculations. However, if the travel model output speeds are inaccurate, the approach is likely to introduce large errors into emissions predictions. To assure reasonable link-level speeds and emissions estimates, post-processing procedures frequently have been applied.

Post-processing procedures typically estimate existing or future travel volumes by hour of the day; refine the travel speeds provided by traffic assignments; accumulate vehicle-miles by link, hour, and vehicle type; apply the appropriate emissions rates to each vehicle-mile component; and sum up the resulting emissions by analysis grid cell. Several methods can be used, including the Highway Performance Monitoring System Analytic Process (HPMS-AP) and HCM-based post-processors.

HPMS-AP computes average travel speed for various vehicle types, classes of road, and geographic areas (FHWA, 1987). Its input variables include initial running speed (analogous to the free-flow and/or volume/capacity-related speeds discussed above), estimated volumes, facility capacity, pavement condition, roadway curves and gradients, speed change cycles and their minimum speeds, stop cycles, acceleration and deceleration rates, and the fraction of time spent idling. A number of these variables, if necessary, can be approximated based on facility characteristics such as functional class, facility location (urban or rural), design speed, and speed limit; or the variables can be estimated using default procedures incorporated into HPMS itself - speed change cycles, minimum speeds during these cycles, and stop cycles are examples. The HPMS-AP can be used as the travel speed estimation component of an emissions inventory post-processor to provide greater accuracy and detail in travel speeds than those provided by many traffic assignment procedures.

Material distributed by the EPA discusses how emissions inventory post-processors can be developed to incorporate travel speed estimation methods consistent with those included in the HCM (Cambridge Systematics, Inc., 1991c). It outlines a basic method which makes maximum use of the facility-specific information normally obtained as part of the highway network development and traffic assignment processes used by MPOs, plus the speed-volume relationships included in the HCM. It focuses on procedures which can be used to generalize the detailed speed estimation methods in the HCM to allow them to be applied to network development and traffic assignment outputs. For the basic method, these procedures call for determining average or typical values of the missing characteristics for selected link categories from secondary data sources such as existing highway facility inventories, facility design information maintained by public works or equivalent agencies, and facility operations data maintained by traffic and parking departments. The report also discusses a number extensions of the basic method which, with additional analysis time and effort, will provide improved travel speed estimates. The extensions include:

- The use of any additional available types of link-specific information;
- Field collection of information on average link characteristics;
- The use of local capacity and speed data where these differ from the HCM;
- The conduct of special studies for critical links such as freeway weaving sections and approaches to complex signalized intersections; and
- The use of peak spreading analysis methods to provide realistic future-year speeds in highly congested subareas.

This approach, with its emphasis on improving the network representation based on locally collected data, is to be preferred over methods which simply "fix up" speed estimates.

Advanced Practice

The most advanced current practice involves the use of alternate functional forms to represent speed-flow relationships, usually on an ad hoc basis. Portland METRO is one of several MPOs which are pursuing this course.

There also has been renewed interest in empirical research on speed-flow relationships in recent years, following a number of studies revealing more complex, path-dependent behavior than is captured in a BPR-type equation. This work can be expected to yield more accurate formulations, both for detailed operations analyses and for approximate planning studies.

In general, the development of improved network models which produce reasonable volumes and speeds is preferred over long-term reliance on post-processors. Implausible speed or volume outputs should be considered an indication that the model system needs careful review and probably will require improvement. Possible reasons for such problems include: coding errors; too short a peak period; too few facility types coded; too sparse a network; local driver behavior and/or facility characteristics different from the typical; or inadequate modeling of mode choice, destination choice, and/or trip rates, leading to excessive assignments to network links.

3.5.4 Direct VMT Estimation

Travel models produce estimates of vehicle-miles of travel (VMT), but for a variety of reasons regional agencies may find it necessary, on occasion, to directly estimate VMT from traffic counts or other types of empirical data. Off-model VMT estimates may be needed, for example, in cases where the model networks are too sparse to adequately capture total VMT, when networks need updating, or when models omit certain types of travel (e.g., school bus trips, truck traffic, interregional trips.) Depending on the specific deficiencies for which the off-model estimates are intended to compensate, these additional VMT estimates may replace the model estimates, be used to compensate for the model estimates, or added to the model estimates.

As discussed in later sections, estimates of VMT based on traffic counts or other empirical data also can be used to check the validity of model-forecasted VMT.

Several methods have been used to directly estimate total VMT. Probably the most widely used method is to extrapolate from HPMS data, an approach endorsed by FHWA and EPA for meeting Clean Air Act VMT estimation requirements. However, some urban areas will need to improve the existing HPMS sample of links to ensure that the sample is adequately representative.

Even more approximate VMT estimation methods are used in some areas, e.g., some estimates are based on estimated fuel efficiency of the on-road fleet and aggregate fuel sales corrected for off-road fuel use and out-of-state refueling and travel. See Cambridge Systematics (1991a), Fleet and DeCorla-Souza (1991), and U.S. Environmental Protection Agency (1992a) for discussion of these VMT estimation strategies.

Special studies, including license plate surveys, focused counts, and special travel surveys, may be used to estimate VMT for traffic not included in the regional models, such as through trips or truck travel.

3.6 Model Development and Validation

While sound model specifications are critically important, even the best-designed model system can be no better than the data on which it is based. The development of good models depends on the availability of high-quality information on land uses and their locations, transportation facilities and services, levels of activity at the various locations, and travel patterns and choices, in order to be able to estimate sound model coefficients. Moreover the data must be available in sufficient detail to capture the variations present within the region being studied.

Once models have been estimated, they need to be validated, that is, checked to verify that they are performing adequately. Validation can be accomplished for individual models by using a partitioned data set (with one subsample used to estimate the models and the other used to check their performance). Validation for the model system as a whole can be accomplished by producing forecasts for a known year (when the estimation data set is several years old) or by “back-casting” (using the model to estimate travel patterns for a year prior to that for which the model was estimated). Both types of validation require high quality data.

This section provides a brief overview of key data requirements for model development and validation and identifies sources for these data. The section then discusses some of the issues that arise in validation, including approaches for measuring accuracy. The section concludes with an extensive discussion of home interview survey practice, a topic of considerable importance since these surveys are the best source for much of the data needed.

3.6.1 Typical Data Needs

A prototypical list of the kinds of data needed for good modeling practice is presented below. Many regional agencies will require more data than are listed here, or will require the data in different forms; some will require more detail. Hence this list should be considered illustrative and basic, rather than an exhaustive listing of the data required.

Typical data requirements include the following:

- Socio-economic Data
- By Census tract or Traffic Analysis Zone (TAZ):[35]
    - Number of households (typically by dwelling unit type), stratified by:
        - household size
        - income
        - vehicle availability
        - age of "head"
        - number of workers
        - number of children
        - number of autos
    - Employment (at least retail and non-retail; preferably by SIC code) by Census tract.
- Land Use/Activity Data By Census Tract/TAZ:
    - Acres of land in each major use (typically residential, retail, other commercial, manufacturing, governmental; also parks, open space, agricultural, undeveloped)
    - Square footage of each major use
    - Housing characteristics (single family, multi-family)
- Network Characteristics
    - Highway link capacities, distances, and free-flow speeds by functional class (freeway, arterial, etc.)
    - Speed-flow curves by functional class
    - Critical intersection geometry and signal timing
    - Locations, speeds, and distances of HOV facilities
    - Locations and capacities of park and ride lots
    - Cost of parking by census tract/TAZ
    - Perceived auto operating costs per mile
    - Ramp metering locations and rates
    - Transit distances, frequencies, speeds, and fares
    - Level-of-service data for transit access alternatives
    - Terminal characteristics.
- Base Travel Demand
    - Average daily household vehicle trip generation rates (single family and multi-family) by trip purposes (at minimum, HBW, HBO, and NHB)

[35] Census tract data may be split as necessary to match Traffic Analysis Zone (TAZ) definitions.

- Trip generation rates for additional trip purposes (e.g., home-shop, home-social/recreational, home-school, work-other, etc.)
- Trip generation rates by income, age of "head", number of workers, number of children, and/or auto ownership level
- Peaking factors by trip purpose
- Special generators' trip generation characteristics
- Vehicle trip length distribution by trip purpose
- External station traffic counts: trip purpose and identification of production/attraction end of trip at external station.

- Estimation/Calibration/Validation Data
  - Home interview survey travel diaries for at least 1000 households (for trip generation rates, trip length distribution, and mode split)
  - Daily and peak hour traffic counts at 100 to 200 locations or 1-10 percent of all links (generally the smaller the area modeled, the higher the percentage of links with counts there will be)
  - Seasonal and day-of-week adjustment factors for counts
  - Peak period turning movement traffic counts at key locations
  - Daily and peak hour transit boardings system-wide and by transit line
  - Vehicle occupancy counts.

Table 3.5 Data Development and Estimation Alternatives - Vehicle Trip Models

Data Type	Best Source	Back-Up Source	Alternate Estimation Method
Socio-Economic Data			
Households by structure type by zone	Latest U.S. Census. Split tracts as necessary	Aerial photos and field counts	Building permits; utility company records
Employment by zone	Latest Census Transportation Planning Package (CTPP). Split census tract data as necessary.	State employer; office data by zip code. Split zip codes as necessary.	Derive from surveys of floor space and average employee densities (not recommended).
Households stratified by income*	Latest U.S. Census	Derive from median income (less satisfactory)	State income tax records (if available)
Households stratified by auto ownership*	Latest U.S. Census	Use median income to estimate auto ownership	Motor vehicle department records (zip code geography as first)???
Network Characteristics Data			
Highway capacity, distances, free-flow speeds, speed-flow curves	Field survey geometric and speed data; use HCM to calculate capacities	None	None
Speed-flow curves by	Field survey speed-flow	Use 1985 HCM speed-flow	BPR curve with

functional class*	relationships	relationships	modifications
Intersection geometry and signal timing*	Field surveys and aerial photos	None	None
Travel Demand Data			
Vehicle trip generation rates and peaking	Home interview surveys	NCHRP 187 or other area surveys	ITE rates (not recommended)
Special generators	Contact institution and/or contact survey	Use ITE rates	None
Trip length distribution	Home interview survey	U.S. Census CTPP and/or other areas	NCHRP 187 friction factor curves
External station counts	Field survey for model	Agency records	NCHRP 187
Validation Data			
Daily traffic counts	7-day counts conducted specifically for model	24-hour counts obtained from agency records	None
Peak period turning movement counts*	2-hour AM and PM counts for model	Historic data from agency records	None

Table 3.6 Data Development and Estimation Alternatives - Multimodal Models

Data Type	Best Source	Back-Up Source	Alternate Estimation Method
Socio-Economic Data			
Households by structure type by zone	Latest U.S. Census. Split tracts as necessary	Aerial photos and field counts	Building permits; air photos; utility company records
Employment by zone	Latest Census Transportation Planning Package (CTPP). Split census tract data as necessary.	State employment office data by zip code. Split zip codes as necessary.	Derive from surveys of floor space and average employee densities (not recommended). Proprietary sources, e.g., Dun & Bradstreet
Median income or households stratified by income*	Latest U.S. Census	Derive stratification from median income (less satisfactory)	State income tax records (if available)
Average population per household or households stratified by person/house*	Latest U.S. Census	Derive stratification from average population/house (less satisfactory)	None
Network Characteristics Data			
Highway capacities, distances, free-flow speeds, speed-flow curves; Locations, speeds, and length of	Field survey geometric and speed data. Use HCM to calculate capacities. Contact local office of state transportation department for HOV facility, park and ride lots, and ramp metering data.		

HOV facilities; Locations and capacities of park/ride lots; Ramp metering locations and rates			
Service frequencies, distances, fares, and speeds for transit service	Transit agency route maps and route schedules		
Cost of parking by census tract/TAZ	Survey of actual costs paid by parkers	Estimate from average parking fees charged in area discounted for employer/store subsidies	None
Perceived auto operating costs per mile	Local agency estimates	State estimates	U.S. DOT or AAA annual estimates
Speed-flow curves by functional class*	Field survey speed-flow relationships	Use 1985 HCM speed-flow relationships	BPR curve with modifications
Intersection geometry and signal timing*	Field surveys and aerial photos		
Travel Demand Data			
Vehicle trip generation rates and peaking	Home interview survey	NCHRP 187 or other area surveys	ITE rates (not recommended)
Special generators	Contact institution and/or conduct survey	Use ITE rates	None
Time and cost elasticities for mode choice	Home survey and logit model calibration	Elasticities from other areas	NCHRP 187
Walk and auto access links	Local coding conventions	UMTA/FTA Draft Guidelines	None
Trip length distribution	Home interview survey	U.S. Census CTPP and/or other areas	NCHRP 187 friction factor curves
External station counts	Field survey for model	Agency records	NCHRP 187
Validation Data			
Daily and peak period traffic counts	7-day counts conducted specifically for model	24-hour counts obtained from agency records	None
Home interview survey	Home interview survey every 5 to 10 years	Surveys elsewhere	None
Seasonal and day of week adjust factors	Historic data from permanent count stations	Data from other areas	HCM
Vehicle occupancy	Field surveys	NCHRP 187 or other areas (not recommended); census for JTW data	None
Daily/peak transit boardings	Field counts for model	Transit operator records	None
Peak period turning movement counts*	2-hour AM and PM counts for model	Historic data from agency records	None

3.6.2 Data Sources

Tables 3.5 and 3.6 summarize best (preferred) sources for the data typically required for model development and validation. Alternative and back-up sources are also identified, for situations where the preferred data source is unavailable or excessively dated.

Socio-Economic Data

A basic data source for virtually any regional model is the decennial U.S. Census. Basic Census data (i.e., 100% enumeration items) include population, age, and dwelling unit number and type. The 1990 Census Transportation Planning Package (CTPP) provides, in addition to these basic data, journey-to-work (JTW) mode split, mean travel time to work, departure time for work, JTW auto occupancy, location of principal workplace, number of employed residents, income, and household auto ownership.

Other potential sources of socioeconomic data useful for transportation modeling include the following:

- The state employment/unemployment department can usually provide information on existing number of jobs and employed residents, by industry sector and geographic subdivisions (usually city or county).
- County Business Patterns provides estimates of employment by zip code, type of industry, and employer size.
- Jurisdictions with locally administered business licenses may be able to use this information to estimate the number of employers, and possibly the number of employees, by location. Dun & Bradstreet also can provide this information by zip code, including the number of employees and addresses of work locations. Extensive address processing of this information makes it costly for an entire region, however.
- Local agency building or planning departments may have information on building permits, which can help identify commercial and residential square footage and growth rates. Likewise, local utilities are sometimes willing to provide information on new water or electric connections, by type of unit (single family, multi-family, commercial), which can be used to estimate growth rates. Although time consuming to compile, this information can be useful in updating a database (say, from a census year to the current year), or may be used as a validation source.
- Aerial photos have been used in some transportation studies for dwelling unit counts and building coverage estimates. However, compilation of this information is time consuming, and it usually is impossible to tell the function of non-residential buildings.[36]
- County Tax Assessor's property (parcel) records may have some use, particularly if they have been computerized. However, they require considerable aggregation and past use has suggested that these data are not as accurate as one might expect of tax records. Land use codes used by assessors are typically not very descriptive for transportation purposes.

Network Characteristics

Most regional agencies assemble data from the state highway agency or DOT, transit operators, and local governments as major inputs to network development. However, they also carry out primary data gathering activities, including verification of link characteristics, speed measurements, delay studies,

[36] An effective use of aerial photos in transportation analysis is in evaluating traffic density and platooning, both important determinants of level of service on uninterrupted flow facilities.

transit waiting time studies, etc. These verification efforts have proven to be critical to the accuracy of the network models, since link descriptions prepared by other agencies, often for other uses, may reflect different assumptions or may be coded using different protocols from those needed for the regional model.

Speed measurements are particularly important for accurate network modeling. Off-peak (uncongested) speeds should be measured as the basis for free-flow speed estimates used in the networks; in most areas, midday measurements are adequate, but in the largest, most congested regions, late evening measurements may be necessary to avoid congestion. Peak hour travel speeds also should be measured for use in validation, that is, to compare with the congested speeds estimated by the model. These speed measurements can be done with floating car runs.

Regional agencies also must take the lead in defining centroid connectors and other "dummy links" in the highway and transit networks. Centroid locations should reflect population and activity distributions in the zones, and the link time and cost estimates should be checked for reasonableness.

The level of sophistication and complexity with which transit access links are represented can make a significant difference in model performance, and in regions where transit is a major mode, attention given to these details can significantly improve transit forecasts.

Travel Demand Data

Typical sources of travel demand information include:

- Home interview surveys
- Census journey-to-work reports
- Census Public Use Master Sample (PUMS) data
- Roadside interviews
- License plate studies
- Special studies

Other sources of information, primarily used for comparison to other areas or to national averages because regional samples are too small, include the National Personal Transportation Survey, conducted periodically by the U.S. DOT, and Characteristics of Urban Travel Demand [UMTA, 1988].

Home interview surveys are generally considered the best source of information on travel behavior. Typically they are comprised of two parts: a questionnaire on socioeconomic characteristics of the household and its members, and a one- or multiple-day travel diary completed by (or for) all household members. Such surveys are costly: a coded and cleaned one-day travel diary and questionnaire currently costs some $30 - $100 per household, and multi-day diaries cost more. However, they are so valuable a source of information for so many purposes that most MPOs should budget for a complete survey every 10 years, or more frequently if the region is growing or changing very quickly.

Sampling rates are typically one percent or less of all households: very small surveys or surveys focused on particular subareas can be used to develop mode choice models or trip distribution models, but larger region-wide surveys are needed for OD and trip length analyses.

Most areas have relied on purely random sampling strategies. However, when transit or other modes of concern are small shares of the regional total, a purely random sample may produce too few transit (or bike, or walk, or vanpool) trips to support detailed analysis. Rather than greatly increase the size of the overall sample at very high cost, an efficient strategy is to use choice-based sampling. The choice-based sample must be weighted to reflect each alternative's overall population share but otherwise can be used much as any other sample in data analysis and model development.

Because of the importance of home interview surveys they are discussed in detail in Section 3.6.4.

Census journey to work reports have been used for model development in some areas where travel surveys have not been conducted or are excessively dated. However, since only work trips are included, only work trip models can be developed on these data; moreover, since the data are aggregate, only aggregate models can be estimated. A more common use for Census journey to work data is in model validation.

The Census Public Use Master Sample (PUMS) now being made available on CD-ROM offers considerable promise for model development and validation. It consists of a five percent sample of the full Census data for the region, with each household in the sample coded to an MPO-defined geographic area (TAZ or district). While only work trip travel data are included, such variables as household size and demographics, income, employment levels, and auto ownership are in the reports. Hence a possible use is in estimating robust auto ownership models.

Roadside interviews are rarely used for large scale studies: Stopping motorists is difficult and may arouse resentment, especially during peak hours. The method nevertheless is used in some areas, usually outside the peak periods, to carry out brief surveys, check vehicle safety and emissions equipment, and so on.

License plate studies can be useful for OD analyses and often are used to estimate commercial vehicle traffic. In some cases license plate surveys have been used as the basis for identifying a sample, e.g., license plates of multi-occupant vehicles are recorded and the owners are contacted to participate in a retrospective survey. However, some states now restrict access to address information out of concern for vehicle owners' safety and privacy, greatly limiting the utility of this latter application.

Special studies conducted by modal operators or by the regional agency itself also may be a source of travel demand data, to supplement travel demand surveys or as a check on the surveys. Transit operators, in particular, are important sources of information. Most transit operators can supply data on:

- total system ridership

- ridership by period (am peak, mid-day, p.m. peak)
- ridership by line

Some can provide ons and offs by stops or stations. A few can provide socio-economic and OD data from passenger surveys, although this information is not usually updated very frequently. Transit on-board surveys can be used as choice-based samples to supplement home interview survey data for model estimation, although in many cases their design and implementation has not been sufficiently rigorous to support modeling applications; MPOs may find it advantageous to participate in on-board survey design and even to help fund implementation in order to assure that the data produced are sound.

Other special studies that are commonly carried out focus on major activity centers or particular population groups. For example, special trip generation studies may be carried out for such activity centers as hospitals, universities, or unique commercial districts. Special population-based travel studies may be carried out if the demographics of a population or area of concern are quite different from the regional average.

External Stations

External stations are the nodes linking the region or study area to outlying areas. The smaller the study area, the more important the external stations are likely to be. It is possible to assess external station travel volumes using a variety of techniques: manual and machine counts; larger (regional or statewide) travel models; roadside interview surveys; license plate surveys (matching or registered address). Future volumes at external stations can be estimated with simple growth factor techniques, although direct prediction of trip end productions and attractions based on the growth in adjacent areas as preferable. Statewide travel models or the models from other regional agencies may be useful for this purpose.

The number of traffic count locations that should be used in model validation depends on the particulars of the application. Factors that should be included are: what counts are readily available (balancing cost versus accuracy); the density of the study area; prior knowledge of whether abrupt changes occur in volumes on particular links; and whether the counts are being used to validate an entirely new model, versus update a previously validated model. Count locations should be geographically balanced, but weighted towards key facilities (e.g., bridges) and should include all crossings of potential screenlines or cordon lines. While practice varies widely, one would like to have ground counts for the largest number of links possible. As a general guide, perhaps major links should be counted once every 10 years, with opportunistic coverage elsewhere in the system. Such a strategy might produce usable counts for 5 percent or so of the highway network. Multi-day counts are best, geared to the season for which the model is calibrated. Counts should also be from a consistent peak period and should include directional volumes if they are to be used to validate peak volume estimates.

3.6.3 Model Calibration and Validation

The accuracy of the model system requires calibration and validation of both the individual models and the model system as a whole. These activities require the judgment that develops through experience, as well as technical know-how.

Calibration is most often carried out using a separate sample of data from those on which the model was estimated. Preferably this is a random subset of the data from which the estimation data also are drawn. In some cases analysts use a second data set for calibration, but this may introduce uncertainties due to differences in the data sets. For example, Census journey-to-work trip tables are sometimes used to check work trip mode choice and trip distribution model estimates; but because the Census reports usual mode to work, whereas surveys report travel day choices, the comparison is imprecise.

Validation of the overall model system also is carried out using a separate sample of data from the estimation data set, typically for a different year. The model is run on the data set and its performance evaluated. If performance is weak, the analyst must diagnose the problem. Possibilities include: one or more variables in the estimated model whose inclusion or specification should be reconsidered; coding errors in the network; or possibly data problems (errors in coding; unrepresentative sample). Potential sources of error are checked and corrected if found, and the model is re-run and reevaluated.
In most areas, calibration and validation tests have focused on estimated vs. measured volumes, ignoring other model outputs such as vehicle-miles traveled (VMT), vehicle-hours traveled (VHT), congested speeds, travel times, and delay. Moreover, transit patronage projections by transit line have received less attention than highway volumes by link. With a greater scrutiny being given to the full range of model performance, however, it will be increasingly important for analysts to evaluate each model output in some detail.

Basic Practice

Data availability is a major consideration in selecting data sets for model calibration and validation. The calibration year is usually selected for a convenient match to the available socioeconomic data (e.g., a decennial Census year). Moreover, calibration is typically updated at least once every ten years to coincide with new U.S. Census information. Some high growth regions may elect to fund a mid-term Census update or home interview survey and update their model calibration every 5 years.

Most models are calibrated and validated for a supposedly "typical" month and day, rather than for maximum or worst-case conditions. Hence, the design (calibration) month for the model is selected to be an average month for the region. Here, too, the availability of data sets for comparison purposes is a consideration: the month of April is often selected to coincide with the month when Census surveys are distributed. However, regional agencies should consider their planning needs in deciding on the calibration and validation strategy. For example, if travel volumes are significantly different during the worst air quality months (which usually occur in the summer or winter), the agency might consider using these months for model development and calibration, or might develop adjustment factors (based on traffic counts, special surveys, etc.) to capture seasonal differences. Recreational areas may find it necessary and desirable to calibrate to summer (or winter) conditions.

The design day is typically the average of three weekdays: Tuesday, Wednesday, and Thursday. Friday and Monday are excluded because they are influenced by recreational travel. Here, too, however, regional agencies may select a different design day if it would better suit their planning needs. For example, analysts in an area where recreational travel is a key consideration may choose to model a typical Friday or Saturday to better represent critical peak travel conditions in the area.

To test the accuracy of the model system, modelers typically define a set of screenlines (or cut lines) and check model-estimated traffic volumes across these lines against actual counts of the traffic crossing the lines. It is desirable to establish at least two screenlines which extend to the limits of the region (one approximately east-west, the other approximately north-south), although generally, the more screenlines, the better. Additional screenlines can be located along natural or constructed barriers (rivers, lakes, mountain ranges, freeways, canals, etc.) within the region.

Every street that crosses a screenline must be taken into account. Streets which carry a significant traffic volume should be coded into the highway network and included in counts; count data should include vehicle occupancy and transit line patronage as well as vehicles. Minor streets which individually carry very small amounts of traffic may be omitted from the network and formal counts, but their volumes should be estimated and accounted for in the validation analysis.

Due to resource constraints, analysts sometimes define shorter screenlines that cross a few key facilities. They include only those key facilities in their networks and use counts for only those facilities in their validation tests. However, this practice may lead to serious difficulties in comparing the models to the counts. In particular, if streets which carry substantial traffic are omitted from the network, the model loadings may not represent the actual volumes on particular facilities but "corridor" volumes. Hence the model outputs would not be directly comparable to traffic counts on specific facilities. This is another reason for coding all streets down to the collector level, as discussed in an earlier section.

Modelers typically use two measures of accuracy: the "numerical difference" and the "percent error" between the model estimates and the screenline counts. The "numerical difference" is the simple difference in trips between the model estimate and the traffic count. A standard of, say + 500 trips may be established as the test. The difference is typically large for high volume links and low for low volume streets, however, so the size of the numerical difference does not reliably reflect the true significance of error.

The "percent error" is often preferred by modelers since its relative magnitude gives an indication of the relative significance of the error. Errors of 10% or less are typical for the total volumes crossing each screenline. Errors of 10% up to 100% are typical for individual streets crossing the screenlines, with the lower percent errors for high volume links and vice streets crossing the screenlines, with the lower percent errors for high volume links and vice versa. Models are typically considered to be validated if the traffic volume totals for each of the screenlines are within 10% of the counts.

While traffic counts are used to validate models, traffic counts themselves are subject to error. Daily, weekly, and seasonal variations in traffic volumes mean that any single day's count (or any three day average) probably does not represent average annual conditions. Even a full year of counts is not likely to be entirely accurate. Machine counter accuracy is often no better than +/- 10%, and such factors as the proportion of traffic with three or more axles, the angle at which traffic crosses count hoses (especially on curves or near driveways), cars parking across count hoses or blocking electronic counters, and a variety of other problems are known to affect the accuracy of machine counts.

Advanced Practice

Many agencies have sought additional, more rigorous and comprehensive criteria for evaluating the validity of their models. The Sacramento Area Council of Governments (SACOG) and the Contra Costa County Transportation Authority (CCCTA) are two examples of this practice.[37]

A common measure of accuracy is the "Root Mean Square Error" (RMSE), which is simply the sample standard deviation from statistics:

$$RMSE = \sqrt{\frac{\sum_j (Model_j - Count_j)^2}{(Number\ of\ Counts - 1)}}$$

Unlike percent error, RMSE puts a greater weight on large errors. With some assumptions about the distribution of errors, one can use the RMSE to make statements concerning the probability that an error will be some standard deviations from the mean.

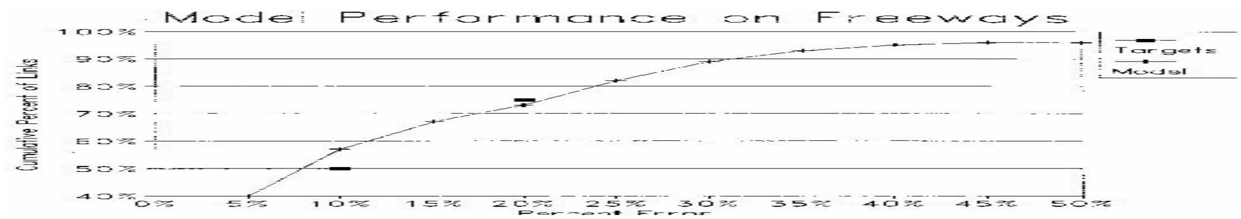
The CCCTA developed a set of validation criteria (in addition to the standard screenlines) that had to be met by consultants developing models for the Authority. Each model's peak hour volume estimates had to meet the following validation targets:

- 75% of all freeway links must be within 20% of the counts,
- 50% of all freeway links must be within 10% of the counts,
- 75% of all major arterial links must be within 30% of the counts,
- 50% of all major arterial links must be within 15% of the counts,
- 50% of all intersection major turn movements (defined below) must be within 20% of the turn counts.

[37] See James (1987) for a discussion of model accuracy.

Model Performance on Freeways

Figure 3.5: Example CCCTA Validation



- 30% of all intersection secondary turn movements must be within 20% of the turn counts.

Each models' validation results were plotted in a cumulative plot against the validation targets to observe how well the models met the validation targets (Figure 3.6).

The CCCTA criteria apply only to those locations where count data are available, but include links both on and off the screenlines used for model validation. Count data were available for over 50% of the freeway ramps and mainline sections. (Freeway mainline volumes were determined from one mainline count by adding and subtracting ramp volumes to obtain mainline volumes for upstream and downstream locations). Peak period turning movement counts were available for approximately 50% of the signalized intersections in the study area. The turning movement counts were used to validate both the arterial links and the intersection turning movements.

It should be noted that, for CCCTA, a major arterial is defined as one that carries over 10,000 vehicles a day, "major turning movement is defined as over 1,000 vehicles per hour, and "secondary turn movement" is defined as 500-1000 vehicles per hour. These criteria and the count information generally restricted the application of the validation criteria to less than 5% of the links in the highway network.

A recent FHWA document has proposed maximum acceptable error guidelines. For individual links, the maximum acceptable error should be equal to half the capacity of a single lane (FHWA, 1991). Using this criterion would reduce the probability that planners will over-estimate (or under-estimate) the number of lanes required.

Considering regional totals, FHWA advises that the total of all counts on all links should be within 5-10% of sum of the model estimates for those links; otherwise the model is biased toward over-estimating or under-estimating total regional travel. FHWA further suggests that counts be obtained for up to 65% of the freeway and primary arterial links in the network, but this may not be feasible in the larger regions. For very large regions, traffic counts for 1-3 percent of the links in the model would be more likely, and probably sufficient.

A correlation coefficient between counts and model estimates of 88% or greater is also suggested; this measure is best used to compare different validation runs and determine if the latest correction to model resulted in a net improvement or loss of accuracy in the model. Failure of the correlation coefficient to increase between model runs indicates that either the modeler is pursuing the wrong course in calibrating the model, or the modeler has reached the point of "diminishing returns," and further refinements to the model result in as many losses in accuracy as gains.

FHWA suggests the following error limit totals by functional class:

Freeways	<	7%
Principal Arterials	<	10%
Minor Arterials	<	15%
Collectors	<	25%
Frontage Roads	<	25%

The percent error in this case is defined as the difference between the total volume assigned to the functional class and the model estimate divided by the sum of the counts for that functional class. The measure indicates whether there is a bias in the model toward one or more of the functional classes. Clearly, these error limits permit relatively poor model performance for roads below the minor arterial classification. Areas that find it necessary to model such facilities accurately will need to establish more stringent acceptability criteria.

3.6.4 Collecting Survey Data

Introduction

It bears repeating that the quality of modeling outputs can never be better than the data that go into the models' estimation and application.

Provisions of both ISTEA and the Clean Air Act, namely VMT tracking and monitoring requirements and the various management systems required by ISTEA, will assure that regional agencies will collect data on many aspects of the transportation system. These data will be useful in model development, calibration, validation, and updates; however, there is no comparable requirement for travel survey data collection. Hence, data that ordinarily have been collected through household surveys could become the weak link in the travel forecasting process, unless substantial improvements in survey procedures are implemented and the surveys are periodically updated or repeated.

In a number of urban areas, there are concerns that household travel survey databases are out of date, and may not represent the current population. Economic and demographic changes have taken place over the last 15-20 years that call into question the validity of using travel models based on old data sets. These changes include:

- Real income has grown for some groups but declined for others during the 1980s, in a pattern that significantly differs from earlier conditions.

- Family size and structure have changed. In particular, the proportion of households with more than one worker has increased sharply in the last 20 years, corresponding to the increase in labor force participation rate for women. Single-person households have also increased in proportion to the general population.
- Changes in travel supply in the past 15-20 years (e.g., increased congestion, implementation of HOV facilities, trip reduction programs) present travelers with conditions and options that in many cases did not exist when previous surveys were conducted.

Given these conditions and the demands being placed on modeling, it is highly likely that many regional agencies will need to collect new travel surveys.

Because travel survey data are expensive to collect, many regional agencies have had difficulty obtaining funding for new travel surveys. Staff analysts will need to make it clear to policy makers both why existing data are problematic, and what benefits can be obtained from a new survey. They should be aware that advances in survey techniques have reduced costs and improved quality, and that new approaches have been developed for better utilizing the data collected. Thus new surveys offer the potential for development of much better travel models, and also can be used in a variety of other ways.

This subsection presents an overview of the collection and use of household travel survey data. It begins with a review of household travel survey data collection experience, focusing on recent surveys in the San Francisco Bay Area; this includes a summary of lessons learned from the survey experience. It then discusses the use of household travel survey data beyond that of estimating traditional travel demand models. Finally, it looks at recent advances in household travel survey data collection, with an emphasis on longitudinal data.

Review of Household Travel Survey Data Collection Experience

Early Surveys

Household travel survey data were initially collected through home interview surveys, as part of the original large-scale regional transportation studies in the 1950s and 1960s (e.g., Chicago Area Transportation Study, Detroit Study, Bay Area Transportation Study). These surveys typically had large sample sizes and high cost; for example, the 1965 survey for the Bay Area Transportation Study covered 30,000 households at a cost of over $217 per household in current dollars.[38]

These home interview surveys set the tone for all household travel surveys since then. The surveys gathered information on characteristics of the household (e.g., number of persons, dwelling unit type, number of vehicles, income), persons in the household (e.g., age, sex, occupation, workplace location), and trips made by each person in the household on a designated “travel day” (e.g., origin and destination times, activities, and locations; travel mode). The survey data were used almost exclusively

[38] Purvis, 1992.

for estimation of large-scale regional travel demand models. As will be discussed later, there was no extensive use of these data for other purposes for which they could have been utilized.

These surveys were the first of their kind, and provided the formative experience with collecting household travel data. But they suffered from a number of disadvantages, chief of which was their large cost. Another disadvantage was their susceptibility to interviewer bias. Because interviewers were reluctant to go into "rough" areas, minorities and low-income persons were under-represented in home interview surveys.

The high cost of the home interview survey method made regional agencies reluctant to undertake further data collection to update the data sets. As a result, in many regions, these original data sets have remained the only source of household travel data for the past 15-25 years.

Recent Surveys

As the original household travel survey data sets grew older, regional planning agencies became increasingly concerned that the data were becoming out of date. The high cost of conducting a home interview survey led some regional planning agencies to consider to gathering household travel data by means of telephone surveys. Telephone surveys were viewed as having a significant cost advantage over home interview surveys, furthermore, because interviewers would not have to personally visit households, interviewer bias resulting from reluctance to visit "rough" areas was not a factor. However, some potential drawbacks also were apparent:

- The sampling frame excludes without recourse those households without telephones.
- Unless precautions are taken, the sample may be biased against households with unlisted numbers.
- If the sample is not carefully drawn to reduce the chance of geographic bias, the geographic distribution of the sample may not match that of the population as a whole.
- A mechanism must be established for collecting trip data from persons in the household. Simply asking persons to recollect their travel on a specified day will result in missing trips, especially non-work trips.

These potential drawbacks (except the first) have been overcome by the following:

- Use of a valid technique for drawing a random sample of residential telephone numbers, e.g. random-digit dialing, use of a reverse telephone directory with randomization of the last digits, etc.
- Use of a two-stage interview with diaries for recording travel. During the initial contact, information is secured from the household on characteristics of the household and persons in the household; at this time the travel day is established and a follow-up interview to collect travel information is scheduled. The household is then mailed a set of diaries for recording trips. In the second interview, each person in the household is interviewed about his trips on the travel day; alternatively the diaries can simply be mailed in.

In 1980, Caltrans conducted a travel survey in the San Francisco Bay Area of 2,000 households using a two-stage telephone survey. The survey sample was randomly drawn from a reverse-address telephone book, with controls on the sample to avoid geographic bias. The survey was successfully carried out, demonstrating the validity of a telephone survey for gathering household travel data.

At the same time, the Metropolitan Transportation Commission (MTC) was planning a new household survey to update its 1965 database. The survey design and questionnaire format were based on those of the 1980 Caltrans survey. The survey collected data from 7,200 households at a cost of about $70 per completed interview.[39]

[39] See Crain & Associates (1981) and Reynolds, Flynn, and Reinke (1982).

The main difference between the MTC and the Caltrans surveys was that the MTC survey used directory-based random-digit dialing to obtain the sample; at the end of the survey, approximately 10 numbers were drawn from the reverse telephone directory to improve the geographic coverage of the sample.[40] As will be discussed below, this difference had important implications for the validity of the sample. A two-stage interview process was used as follows:

- The initial contact with the household was used to explain the purpose of the survey, obtain the cooperation of the household, and gather information about the household and its occupants. At this time a specific travel day was designated for the household. Household occupants were then sent a set of travel diaries on which to record their trips and instructions for filling the diaries.
- The second contact was scheduled for one or two days after the travel day. Each household member of about 10 years of age and over was interviewed to get information on his or her trips for the travel day; travel information was gathered by as many follow-up call back as necessary to contact every household member. In some instances, households were contacted during the coding process if trip origin or destination locations could not be coded as originally given to the interviewers.

The survey was carried out over a three-month period in the Spring 1981. Interviews were completed at 7,200 households at a cost of about $70 per household. The overall response rate (number of completed interviews divided by number of households contacted) was 70 percent.

The success of this survey led MTC to plan a new survey coincident with the 1990 Census. As carried out, this survey had three subsamples:

- Single-day trip data were collected from 9,000 households.
- Multi-day trip data were collected from 1,200 households.
- As part of this survey, the San Francisco Bay Area Rapid Transit District (BART) funded a special sample of 1,100 households, divided roughly evenly between BART users and

[40] In directory-based random dialing used for the 1981 Bay Area Travel Survey, the following procedure was followed:

1. Select residential telephone numbers at random from the telephone book.
2. For each number selected, add one to the number.
3. If the number is a working residential telephone number, attempt to contact the household at least 8 times at different times of the day, different days of the week, and weekdays and weekends.
4. If the household is contacted, attempt to recruit the household for the interview. If the household agrees to participate, conduct the interview.
5. If a successful interview cannot be conducted at the number (nonworking number, nonresidential number, cannot establish contact, household refuses to participate, etc.), add one to the number and go back to Step 3.

households considered as part of BART's "latent" market (households who could potentially use BART, but didn't).[41]

As an incentive to participate, households who were asked to maintain multi-day trip diaries were given a payment of $10.

The questionnaire for this survey was based on those used in the earlier Bay Area surveys, but questions were added to gain additional information on household and job location dynamics, and on other factors that could influence travel behavior. Among these were the following:

- Households whose length of residence at the current address was less than 5 years were asked their previous city of residence.
- Persons who had worked at their work location for less than 5 years were asked for the city in which their previous workplace was located.
- Workers were asked about how much flexibility they had in their work schedules.

This survey obtained a somewhat lower response rate (about 60%) than the earlier surveys. The cost of the survey was about $70 per household for single-day trip diaries, and about $120 per household (including a small cash incentive paid to participants) for multi-day trip diaries.

Lessons from Recent Surveys

Recent experience in the collection and use of household travel survey data has provided some lessons on what constitutes good practice for household travel surveys. These are discussed in the following areas: information to be gathered, sampling, response rates, and survey conduct.

Information from Survey

The main aim of a household travel survey has, up until now, been the collection of data for use in estimating travel demand models. But, as discussed in the next section, there are other potential uses of these data that may over time be more important than modeling. Moreover, the survey should gather enough information about the household, its members, and its travel, to minimize the extent to which future model development options are foreclosed.

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[41] The total sample was derived from an on-board survey of transbay BART riders during the period of the Bay Bridge closure after the 1989 Loma Prieta earthquake. So-called "latent" riders were assumed to be those who were riding BART at this time, but did not ride BART before or after the Bay Bridge was closed.

Information gathered from a household travel survey falls into three categories:

1. Household
2. Persons in the household
3. Trips by persons in the household on the given travel day(s)

The accompanying tables present lists of the information that was gathered during the 1990 MTC and BART travel surveys. Table 3.7 lists information on the household, household occupants, and trips by household occupants.

Note that the information that was obtained goes beyond that needed for development of existing state-of-the-practice travel models. Information on previous household or workplace location was sought to obtain better information on residence and job movement patterns within the San Francisco Bay Area. The question on flexibility of work schedules was asked to gain information on the sizes of markets for transportation demand management measures such as flextime and ridesharing. Questions on parking were intended to obtain not only parking cost but also the extent to which subsidized parking exists for work trips. All of these data will be used in model improvements over the next few years.

Ideally, activity questions should be asked for both the trip origin and the destination. This aids checking the continuity of an individual's travel for the day and is also necessary in instances where a day's travel begins at a place other than home. In the 1981 Bay Area Travel Survey, activity questions were asked for both origin and destination. In the 1990 survey, however, only a single question was asked for each trip: trip purpose.

Survey Design and Sampling

Conducting a telephone survey is considerably less expensive than a home interview survey. But it introduces several biases of its own:

- Obviously, persons without a regular telephone number are excluded from the sample. This includes households without telephones and homeless persons. (The latter group will be missed in most home interview survey designs as well)
- Persons living in institutionalized residences (nursing homes, residence hotels, etc.) are excluded from the sample.
- There is a greater likelihood of establishing contact with larger households (since there are more people available to answer the phone.)
- It may be more difficult to interview non-English speaking persons, either through lack of capability on the part of the survey team, or through inability of the interviewer to identify which language is being spoken.

Household Data

1. Number of persons

    - total number
    - number under five years of age
2. Location of residence (street address or nearest intersection)
3. Length of residence at current location (if under five years, place of previous residence)
4. Dwelling unit information
    - type (single-family house, duplex, multi-family, mobile home, etc.)
    - owned or rented
    - purchase price (optional)
5. Vehicles in operating condition
    - number of cars, vans, trucks
    - number of motorcycles
    - number of mopeds
    - number of bicycles
    - list of cars, vans, trucks:
        - make
        - model
        - year
        - fuel type
6. Income

Person Data

1. Age
2. Sex
3. Relation to head of household
4. Drivers license?
5. Handicapped? (if so, what condition?)
6. Occupation (e.g., employed full time, employed part time, student full time, student part time, retired, unemployed, homemaker, etc.) If more than one occupation (e.g., student and employed, or more than one job), record information for all occupations.

Trip Data

1. Beginning and ending trip times
2. Origin and destination activities (e.g., home, work, school). Distinguish different types of activities that would affect travel behavior (e.g., comparison shopping, convenience shopping, and grocery shopping should be treated as separate types of activities)
3. Trip origin and destination locations: street address, building, or nearest intersection. These are coded to a census tractor block group, or ideally, point coded in a GIS database.
4. Travel mode
5. Car trips:
    - identify specific vehicle used
    - number of persons in vehicle

- parking information:
  - parking type (e.g., street free, street meter, lot free, lot meter, employee lot free, employee lot paid, commercial parking structure subsidized, commercial parking structure paid, etc.)
  - parking cost to traveler

6. Transit trips:
   - a fare paid (or pass type)
   - number of transfers
   - waiting time for transfers

3.7 Information in the 1990 MTC and BART Surveys

It has been argued that the first two sources of bias may not matter for the purposes of travel modeling: The persons who are excluded from the sample very likely account for a small percentage of the population, and they tend to be persons who travel less often. Nevertheless, it should be made explicit when reporting household survey results what groups are excluded from the sample, and what the likely effect is on inferences drawn from the sample.

Because the proportion of single-person households has been increasing, survey bias against smaller households is becoming a more significant problem. This source of bias can be reduced by making numerous attempts to contact a household at a working residential telephone number. The 1981 and 1990 Bay Area Travel Survey designs each made a maximum of 8 attempts to contact persons at a working residential number. Each number was tried at different times of day, different days of the week, and on weekdays and weekends.

The method of drawing the sample can introduce biases of its own. As discussed above, the 1981 Bay Area Travel Survey used directory-based random-digit dialing to draw the sample, with a small supplementary sample from the reverse telephone directory. The 1990 Bay Area Travel Survey sample was drawn from a commercially purchased list of residential telephone numbers. Both of these methods provided adequate geographic coverage of the Bay Area; the socioeconomic characteristics of the households in the sample closely matched the Census data.

At the conclusion of the 1981 survey, an analysis was conducted to test the validity of the 1980 Caltrans survey sample, which was drawn using the reverse telephone directory. Each household in the 1981 survey was coded according to whether or not it could have been included in the 1980 Caltrans sample; i.e., whether or not the household appeared in the reverse telephone directory. The analysis showed that the Caltrans sample contained biases against households that had resided at the current address for less than one year, households in multi-family units, low-income households, and households without cars. Reverse directories also do not contain unlisted numbers, which are more likely to be held by households with lower incomes and shorter lengths of residence in the same place.[42] Hence, drawing a sample of telephone numbers from a reverse telephone directory appears to be an inferior method

[42] See Rich (1977).

when compared to a sample drawn either by random-digit dialing or from a purchased sample of telephone numbers. Furthermore, when using random-digit dialing, directory-based random digit dialing is more efficient than random-digit dialing within prefixes. Nationally, random-digit dialing within prefixes requires calling on average about 3.8 different numbers per working residential number contacted.[43] The 1981 Bay Area Travel Survey, using directory-based random-digit dialing, averaged fewer than 2 numbers per working residential number reached.[44]

Response Rates

Non-response to a household travel survey can significantly bias estimates obtained from the sample. In particular, it has been found that households that are less mobile are less likely to respond to travel surveys. Because non-response is correlated with endogenous variables, there is no objective way to estimate or correct for non-response bias in a travel survey. A high response rate is therefore an essential goal of travel survey design and implementation.

The 1981 Bay Area Travel Survey achieved an overall response rate of 70% from initial contact to completed interview. It has become increasingly difficult to obtain high response rates for a number of reasons, including the following:

- Persons are becoming more reluctant to respond to surveys. This is partly due to feelings of increasing invasion of privacy over the telephone by solicitors and by commercial surveys.
- Telephone answering machines are becoming more common. This makes it more difficult to establish contact with households that use them for screening calls.
- Persons with unlisted numbers may be quite suspicious of getting calls from strangers. A frequently encountered response from persons with unlisted numbers is, "How did you get my number?"

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[43] Telephone companies usually assign numbers in "blocks" of 1000 (e.g., 464-6XXX). Hence, random-digit dialing within prefixes can result in repeated attempts within blocks where few numbers have been assigned. Nationwide, random-digit dialing will average attempting to call 3.8 numbers per working residential household reached. See Glasser and Metzger (1975). Note that with the increased use of facsimile machines, car phones, etc., the number of attempts per working residential number is likely to increase.

[44] Crain & Associates (1981).

- A household travel survey goes into considerable detail on the socioeconomic characteristics of the household and the travel behavior of its occupants. Over the years, many persons have become reluctant to let a government agency know all about them, or to know exactly what they have been doing during the travel day(s); also, some fear that the information may be misused by unscrupulous persons who would want to know when they are away from home.

These were particular problems for the 1990 Bay Area Travel Survey and are reasons why the response rate dropped in comparison to 1981, to under 60 percent. In particular, respondents who cooperated with the first part of the interview on characteristics of the household would refuse to give out their address so that cards could be sent to them to record their trips. This was especially a problem with single-woman households.

Because high response rate must be a key goal of any survey effort, several methods have been developed to increase the response rate and to minimize non-response bias. Useful steps include the following:

- A publicity campaign should be carried out before and during the survey, consisting primarily of public service announcements in the media. Also helpful are press releases by public officials to explain the purpose of the survey and to encourage persons who are contacted by the survey to respond.
- A clear introduction to the survey should be provided on initial contact with the household. The caller should identify the sponsoring agency and explain the purpose of the survey. This implies that interviewers should be trained from the beginning to understand the purpose of the survey and the reason for asking each question, so that they can explain it to persons they contact. Persons who are contacted and who question the purpose of the survey are usually satisfied with the answer: "This survey is being used to provide information to transportation planning agencies in the region so that they can plan transportation facilities to serve you better." This "up front" approach is in sharp contrast to marketing surveys, where persons who are contacted are told neither who is collecting the information nor the purpose of the survey. Persons appear to be more likely to respond when they know how the information will be used, especially if it is to be used for public purposes.
- Respondents with unlisted numbers who say . ..... how did you get my number?" should be told that their number was reached by chance because telephone numbers were dialed at random. This explanation is usually sufficient.
- An envelope and cover letter bearing the letterhead of the sponsoring agency should be included with the travel diary.
- Callbacks to a household should be prompt, no more than two days after the designated travel day(s). These and any further callbacks should be scheduled to make it as likely as possible that someone will be on hand to answer the telephone.
- Respondents should be repeatedly assured that the information that is gathered will be kept confidential and will be used only in the aggregate for statistical purposes. To preserve confidentiality for persons who refuse to give their home address, interviewers should seek to

obtain the intersection nearest the residence; trip cards then can be sent to the person's place of employment.

- In some cases, a cash incentive may be effective in increasing the response rate. In the 1990 MTC travel survey, respondents who were asked to keep multi-day trip diaries were paid $10 for completing the interview. In the Puget Sound Transportation Panel, incentive payments of $2 and $10 were tested, and found to be about equally effective in encouraging responses.[45] In the Los Angeles regional household travel survey in 1991, each trip diary mailed to respondents contained a $1 bill. Experience with various types of surveys shows that the presence of any incentive, no matter how small, will encourage a greater response rate.

Obtaining Travel Data

Obtaining travel data is the most difficult and expensive part of a household travel survey. It is crucial that all trips are recorded if the survey sample is to properly represent the mix of travel in the region. Work trip data are typically reported with more accuracy than other types of trips. The problem for the survey is to obtain information on trips that are less likely to be recorded: mainly non-work and walk trips (e.g., a trip with walk as the only mode, a walk trip from a parking lot to the workplace).

[45] Murakami and Ullberg (1992).

There are two alternatives for obtaining trip information from a household travel survey conducted by telephone: sending out trip diaries to be filled out and mailed in, or conducting a second telephone interview of the household. The first method is less expensive, but there is the danger respondents may forget to record some trips; moreover, if detailed information beyond origin, destination, mode, purpose, and times are sought for each trip (e.g., type of parking, vehicle used, number of persons in car), the trip diary becomes more lengthy, which tends to discourage complete responses. The second method can be effective for gaining information on trips that would otherwise be omitted, especially if interviewers are instructed to prompt persons to remember all trips.[46] An important part of the second method is to send households cards on which to record the important parts of each trip (locations, times, modes), so that the written information serves as a reminder during the callback interview.

Recently, a third alternative has been developed and used to collect trip information. Households are sent diaries on which to record their activities (e.g., home, work, shopping), and how and when they traveled between them, on a designated day or days. These activity-based diaries have been found to be easy to fill out because persons are more likely to be aware of their activities than their trips. This method was used in the 1991 travel survey of 16,000 households for the Southern California Association of Governments. Nevertheless, it is still necessary to include safeguards to ensure that all legs of a trip, especially walk modes, are recorded.

Quality Control

The issue of quality control goes beyond simply developing a good survey design and ensuring that interviewers are doing their job well. Once the data are collected, it is necessary to edit, code, and enter them onto a computer medium. Careful control over this process will reduce the chance of errors.

The following are especially important elements of a good quality control program for a household travel survey:

- Survey data should be coded as soon as possible after the interview is completed. The most frequent problem encountered in coding travel surveys arises from recorded origin or destination locations that cannot be coded (e.g., an address that does not exist, or a location given as an intersection of two streets that are parallel). In such cases, it is necessary to call back the respondent to correct the error.
- Survey information should be cross-checked for consistency. For example, if an activity at a location is given as "home", the location of that activity in the trip data should agree with the residence location recorded in the household data section; similarly, a location where the activity is "work" should agree with the workplace location recorded under data for occupants of the household.

[46] In the 1981 and 1990 Bay Area Travel Surveys, interviewers were instructed to periodically prompt respondents during the trip interview with the question: "... and did you stop anywhere else along the way?"

- For each person's travel, trip starting and ending times should follow in sequential order; i.e., the ending time of each trip should be greater than the starting time, and the starting time of a trip should be greater than the ending time of the previous trip.
- Activities should follow in logical sequence for each person's trips when travel data are recorded as trips. For example, if the destination activity of a trip is recorded as “work”, the origin activity of the next trip should also be “work”.

The use of computer-assisted telephone interviewing (CATO can automate several aspects of quality control as well as reduce survey and coding costs. Use of this technique involves developing a questionnaire that appears on a computer screen. Skip patterns can be programmed in so that responses to questions determine which questions will be asked next; for example, if a trip is recorded as being made on transit, only transit-related questions such as fare and transfer information appear, and automobile-related questions such as parking cost are skipped. While this approach has considerable potential for time and cost savings, it is quite critical that the software have built-in safeguards (including checks such as those listed above) to prevent the entry of nonsensical responses due to typing mistakes or other errors into the computer files.

Survey Period and Scheduling

Interviews for household travel surveys typically require one to several months to complete. If the survey is to represent a “typical” travel day, it is usually desirable to schedule the survey for the fall or the spring, when school is in session. To minimize the effects of variations in weather or traffic conditions, the survey should span a sufficiently long period so that most travel interviews cover days that are as close to typical as possible. Holiday periods should be avoided; hence, spring is usually a better period than fall in which to conduct a household travel survey because of the lower incidence of holidays. Areas where recreational travel and/or seasonal residents are a significant factor may need to design and schedule surveys to capture these travelers and populations.

Alternative Uses of Household Travel Survey Data

Transportation agencies have tended to view the main purpose of household travel surveys as providing data for developing regional travel models. But these surveys typically collect a wealth of data that could be used for a variety of other purposes.

As one example, an important issue in air quality planning is estimating the operating mode of passenger vehicles, particularly the percentages by trip type of vehicle trips that begin in the cold-start mode. In practice, these percentages are derived from assumptions on characteristics of each trip type; e.g., almost all trips from home to work begin in the cold-start mode.

A household travel survey can provide significant information on operating modes because start and end times are recorded for each trip; hence, for auto driver trips, the time between trips can be used to infer what percentage of automobile trips begin in the cold-start mode. The trip diary could therefore be regarded as a sample of auto driver trips that could be analyzed to estimate the percentage of trips by purpose that begin in the cold-start mode.[47]

If the trip information also contains information on the particular vehicle used, as in the 1981 and 1990 MTC travel surveys, it is possible develop even more detailed information. The household travel survey data and the regional network can be used in conjunction to develop a database that effectively acts as a sample of trip-making by purpose. Developing emissions estimates from the data could be carried out in the following steps:

- Create a database for each vehicle in the trip file, containing the following information for each automobile trip:
    - running time and mileage driven on the previous trip
    - amount of time the vehicle was idle before beginning the trip
    - running time and mileage driven on the current trip
    - vehicle type

[47] By extension, it would be possible to define one or more intermediate modes between cold-start and hot-start based on the resting time between trips, and to estimate the number of trips that begin in each of several operating modes.

- Using an appropriate algorithm, determine whether each trip began in the hot start or the cold start mode.[48]
- As a further refinement, estimate of emissions for each vehicle trip based on vehicle type and start mode.
- Run statistics on the sample to derive estimates of the following for trips by type in the region:[49]
  - percentage of trips by type that begin in cold start mode
  - average emissions per mile.

New Directions in Household Travel Surveys

Transportation researchers are becoming increasingly aware that traditional household travel survey data present significant problems for analyzing and forecasting travel behavior. in particular, as they are collected and used, household travel survey data represent a cross-sectional sample of household travel behavior; yet they are used to infer longitudinal changes in travel in response to changes in travel supply. Furthermore, over time, individual households go through changes that affect their travel behavior. There is growing awareness that to accurately look at these changes and to infer behavioral responses to changes in the transportation system, it is necessary to develop longitudinal information on household behavior. This can be done by asking retrospective questions on household travel behavior, but a more reliable method is to make repeated observations on the travel behavior of a set of individual households over time. This is known as a panel survey.

[48] If, in future air quality analyses, it became common practice to define one or modes between cold start and hot start, it would be possible to use these data to determine in which mode (extreme or intermediate) each trip began.

[49] These data would not cover vehicles such as those that are part of a company fleet. But information on operating modes for such "off-sample" vehicles could be estimated from surveys of trip-making using fleet vehicles.

Panel surveys have been used extensively in medical research since the 1950s, for example, in long-range studies of heart disease, where observations on the same individuals are conducted at frequent intervals. Their use in travel behavior studies is relatively recent, although the technique was advocated as early as 1966.[50] A 1983 paper discussed a number of ways in which repeated measurement from a panel of households would improve our understanding of travel behavior.[51] As summarized by Duncan et al., these include the following:[52]

- Describing and analyzing changes in travel behavior in response to changing prices or the availability of public transportation.
- Analyzing the sequencing of joint decisions about the place of residence, place of work, and home-work trips.
- Understanding the changes in energy consumption in response to changes in energy prices.
- Forecasting car ownership and drivers' licenses.
- Estimating the price elasticity of public transportation by measuring behavior before and after price changes.

Panel surveys are often the only realistic method for collecting longitudinal data. For example, an on-board transit survey in Sacramento, followed up by a telephone survey of the same individuals, showed in many cases that an individual gave different responses to the same question on frequency of transit use.[53]

The most extensive panel survey to date is the Dutch Mobility Panel, which began with a sample of over 5,000 households. The initial intent of the survey was to monitor changes in travel behavior in response to transit fare changes. The survey consisted of week-long travel diaries administered at six-month

[50] See Garrison and Worrall (1966).

[51] Baanders and Slootman (1983), pp. 249-263.

[52] Duncan et. al. (1987).

[53] See Reinke (1985).

intervals. Since the first wave of the survey in 1984, a total of ten additional waves were conducted at six-month intervals through 1989.[54]

In the US the most extensive panel to date is the Puget Sound Transportation Panel, which consists of two waves of surveys from 1989 to 1990.[55] The sample covered 1,700 households in the first wave, and 1,800 households in the second wave; trip diaries covered two days. The survey was designed to over-sample bus and carpool commuters.

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[54] See Meurs and Ridder (1992).

[55] See Murakami and Ullberg (1992) and Murakami and Watterson (1992).

In what is likely to be the most ambitious panel survey in the US, MTC enlisted 9,600 households out of 10,900 surveyed during the 1990 household travel survey; this is in addition to the 1,100 households that comprise the BART portion of the survey, (intended to be the foundation of a BART user/nonuser panel.)[56] MTC recently has obtained funding for subsequent waves of surveys as part of a congestion pricing experiment to be funded by the Federal Highway Administration.

Panel surveys provide information on the dynamics of change that is simply not available from cross-sectional surveys. A longitudinal model of trip-making on five travel modes was estimated from the first three waves of the Dutch mobility panel; the model, which contained lagged variables to capture time effects, showed significant "inertia" effects (households tending to exhibit the same behavior despite changes in the transportation system), but also revealed an evolving relationship in demand for the different modes.[57] Discrete choice models of travel behavior developed from panel survey data show that it is possible to develop estimates of how travel market shares and elasticities change over time.[58] An analysis of several panel surveys in England showed that, despite the overall stability of household and travel characteristics such as car ownership and public transit use, there was considerable change among specific households and individuals in car ownership and movement in and out of public transit markets.[59] A longitudinal analysis of BART passengers who rode the system immediately after the 1989 Loma Prieta earthquake showed significant differences in household and travel behavior characteristics between persons who subsequently stopped riding the system and those who continued to ride.[60]

Panel surveys therefore provide significantly better data on travel changes in response to population and transportation system changes than do cross-sectional surveys. They can also be somewhat less expensive per interview to conduct once the sample is drawn, because the sampling cost for subsequent waves is limited to that necessary to replenish the panel, and subsequent interviews will not have to collect data on some characteristics such as age and sex. But panel surveys, and their use in transportation and air quality planning, present difficulties of their own, including the following:

[56] Purvis (1992).

[57] Golob (1987).

[58] Bradley (1992).

[59] Goodwin (1992).

[60] Cambridge Systematics (1991b).

- Although the cost per interview per wave can be lower than that of cross-sectional surveys, the cost per household in the panel will be significantly higher because of repeated interviewing. Moreover the cost per interview per wave may in fact be higher than that for cross-sectional surveys, because panel survey designs often call for the collection of travel information for more than one day.
- Panel surveys must deal with the issue of panel attrition or panel fatigue - i.e., households interviewed in earlier waves may drop out for subsequent waves. In most instances, the panel is replenished by new households to make up for those who dropped out. How to deal with panel attrition in designing a panel survey is an important area of current research.[61] Analysis of panel survey data with attrition also requires development of new analytic techniques.[62]
- Panel surveys have led to an increased understanding of the dynamics of travel behavior. But development and implementation of new regional travel models based on panel survey data is in its infancy.[63] More work will be required before truly operational longitudinal travel behavior models can be implemented by regional planning agencies.

These difficulties notwithstanding, household panel surveys appear to be the most effective means available of looking at the dynamics of changes in population characteristics and travel behavior.

Concluding Comments

This subsection has looked at the current state of practice in household travel surveys, ways in which these data could be better used, and at the most promising new direction in travel surveys: household panels. It is clear that new models and improved analytic techniques will be needed in the analysis of current transportation and air quality planning issues. But any improvements to current techniques must be based on up-to-date household travel survey data. And, while some areas such as the San Francisco Bay Area, Los Angeles, and Seattle have collected new data, other metropolitan areas continue to depend on travel models built on data sets that are 20 or more years old.

Several points should be considered by agencies debating whether to do a new survey:

Survey costs have dropped. Household travel surveys are much better and less expensive than the earliest home interview travel surveys. Household travel surveys from now on will rely mainly on telephone interviews for reasons of coverage and economy.

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[61] Meurs and Ridder (1992).

[62] An example of one technique is given in Brownstone and Chu (1992). Their paper uses a technique known as multiple imputation to correct for missing data. See Rubin (1987) and Little and Rubin (1987).

[63] An example of a model system based on the Dutch Mobility Panel data is presented in Goulias and Kitamura (1992).

Design and implementation of a good household travel survey requires considerable care. Accurate and inaccurate data look remarkably alike. There is no sure way to distinguish between them unless one knows how they were collected. An improperly designed or drawn sample can result in surveying a group of households that does not accurately represent the region. Non-response bias in a household travel survey can lead to significant overestimates of trip rates. Collecting all travel data requires care in collecting trip information. A well-conducted survey requires painstaking work by survey managers, interviewers, and data processing staff.

If household travel survey data are used only for developing travel models, they are not being fully used. Household travel survey data contain a wealth of information that can significantly inform transportation and air quality analyses (among many other possibilities.)

Panel surveys can provide a wealth of information about the dynamics of changes in population characteristics and travel behavior. Panel survey data will support both conventional and advanced travel demand modeling. Panel surveys also can support a variety of other analyses, from simple tabulations of the survey data to more advanced studies of changes in key socioeconomic or travel characteristics over time. Panels can be implemented so as to provide before-and-after data, for example, to study a transit fare change. Overall, their information content and flexibility are substantial.

Where do we go from here? New policy initiatives will require new analysis procedures, which will require new data. There is no requirement at the federal level to carry out new surveys, but state and regional agencies now can use ISTEA's flexible funding for survey design and implementation. With this new opportunity, the following are several actions that could be taken:

Develop guidelines for household travel survey data collection. The past 20 years have given us a body of experience that should be distilled and disseminated to all US transportation planning agencies. A manual summarizing the lessons of these survey experiences should be developed and put into effect as a set of guidelines, for use by MPOs and other agencies wishing to conduct (or fund) surveys.

Make evaluation - and surveying as part of evaluation - an integral part of funding for major transportation projects. Evaluation of major transportation projects can provide important information for future policy analysis. A major component of any evaluation would be to analyze the effects on travel behavior. Travel behavior changes would be best assessed by a panel survey that includes observations before and at several times after implementation of the project so that, at least, short-term and intermediate-term effects of the project could be assessed. For transportation projects such as new rail starts, costing on the order of $100 million to $1 billion, it is asking very little to set aside one or two percent of the project funding for evaluation, including surveys. This would also provide the regional planning agency with an up-to-date data set for model development and other policy analysis.

Provide adequate funding for ongoing panel surveys. The Puget Sound Transportation Panel has been the only ongoing regional household travel survey panel in the US; the MTC panel survey, for which the second wave has only recently been funded, will be the second major travel survey panel. Funding to continue these ongoing panels should be secured, and experience with these panels should be carefully documented to serve as guidance for future panel survey efforts.

CHAPTER 4: MATCHING ANALYSIS TOOLS WITH ANALYSIS NEEDS

4.1 Introduction

The Clean Air Act Amendments of 1990 set forth a number of analysis requirements for transportation, including: 1) development of a baseline emissions inventory; 2) VMT tracking; 3) VMT forecasting; 4) long-range plan analysis; 5) TIP analysis; 6) TCM analysis; and 7) project-level CO analysis. The statutory basis for these analysis needs was reviewed in Chapter 2. In this chapter, each analysis need is discussed in turn and issues to be considered in fashioning an analysis response are set forth.

Two broad assumptions color the treatment of issues: 1) Carrying out an analysis only to meet a requirement is not good practice, and ultimately could undermine both the goals of the Clean Air Act and the credibility of the analyst; and 2) resolution of some issues is hampered by deficiencies in the state of knowledge, and it is important to distinguish such deficiencies from ones which could be overcome with straightforward investments of resources. It is assumed that conformity analyses should be substantive, not simply "going through the motions"; hence analysts should consider all factors which might reasonably be expected to have a significant effect on the outcome, including factors whose evaluation may necessitate improvements to data and models. On the other hand, certain difficulties in analysis posed by Clean Air Act requirements (or other public policy concerns) may not be totally resolved or resolvable; analysis has limits. The objective thus must be to interpret CAA requirements in ways that are consistent with what models can do, as well as what MPOs can do.

The following sections go into some detail about analysis issues and approaches, emphasizing practical ways to meet the spirit of the Clean Air Act. However, the material presented is intended to supplement, not substitute for, guidance on modeling and analysis promulgated by FHWA, FTA, and EPA. Moreover, no attempt is made to dictate a uniform "best practice". Instead, it is acknowledged that local conditions vary to a degree that requires each region to chart its own course through the analysis imperatives of the Clean Air Act. This will require a meeting of minds among local governments, regional planners, state transportation officials, environmental and other interest groups, EPA, and FHWA/FTA on a strategy for data collection, model development, and model application that yields needed improvements at a rapid but prudent pace. Thus, the primary goal of the chapter is to clarify the issues that must be resolved specifically for each region.

In the tailoring of a strategy for local conditions, a number of points should be kept in mind:

- *Precision Does Not Guarantee Accuracy* - The Clean Air Act now provides incentives to be both as precise and as accurate as possible in emissions calculations. However, precision must not be confused with accuracy. Considerable resources could be wasted pursuing precise, but inaccurate, numbers. Sound data and models are a prerequisite to producing accurate results, and in some cases sketch planning approaches producing reasonable but not very precise estimates may be preferable to the exercise of highly detailed models which have been poorly specified or which can be run only on low quality data.

- *The Validity of Current Procedures Should Be Reviewed* - The Clean Air Act through its facilitation of citizen enforcement, among other aspects - provides incentives for completeness and validity in the analysis procedures used where the accuracy of analyses is at stake. In other words, when there is agreement in the profession that a specific modeling procedure or element could be important to the outcome of emissions analyses, it may be risky for the MPO to ignore it; where an existing modeling procedure is hard to justify theoretically, its continued use also may be risky. MPOs will need to assess the validity of their current approaches considering potential omissions as well as in-use procedures.

- *A Plan for Model Improvements Should Be Developed* - There has been a pervasive under-investment in regional transportation models and data over the past 20 years. The large MPOs have not been able to afford needed model improvements and emergent MPOs typically have developed only rudimentary modeling capabilities. In general, model developments have focused on a narrow set of project planning capabilities rather than the broad spectrum of analysis issues raised by the Clean Air Act (and ISTEA). As a result, few MPOs are prepared at this time to apply "state of the practice" methods to the full spectrum of analysis needs. Most MPOs will have to identify needed improvements and develop a plan for implementing them.

- *Resource Constraints Must Be Acknowledged* - The greatly expanded planning resource base provided by ISTEA will help the MPOs to improve their data bases and models, but in many cases resources still will fall short of what would be needed for immediate improvement of modeling capabilities across the complete spectrum of issues. Improvements will have to occur incrementally over a number of years.

- *Many Improvements Will Take Time* - Even if unlimited resources were available, some types of model improvements would take years to complete. For example, good survey data, Census data for corroboration, and well crafted networks are prerequisites for model development. Yet it typically takes two years to conceive, design, test, administer, code, check, weight, and tabulate a good home interview survey. And, as all experienced modelers can attest, the process of model development itself requires time and flexibility for experimentation with alternate specifications and for identification and correction of model deficiencies. An MPO beginning the survey process right now (1993) likely would not be able to produce a full set of new models until 1995 or later. In the meantime, interim analysis methods (post-processing of model outputs, use of sketch planning techniques, etc.) may be necessary.

- *A Strategy for Implementing Improvements Should be Agreed Upon* - Investments in transportation infrastructure and services are too important politically and nomically to be suspended while planning capabilities are improved. On the other hand, such investments are too important to the environment and the social fabric of a region for important analytical deficiencies to remain unaddressed. To reduce the potential for conflict over modeling procedures, and given the likelihood of resource constraints and the time requirements previously noted, MPOs may find it advantageous to negotiate with interested parties: 1) a commitment to a strategy for making critical model improvements as quickly as resources will allow; 2) an agreement on reasonable assumptions about phenomena that the MPO cannot model, at least in the near term (e.g., trip chaining, time of travel for each trip purpose); and 3) an agreement on interim modeling and analysis approaches to be used while model improvements are implemented.

- *The Size of the Area May Affect Modeling Choices* - The size of a metropolitan area is an important determinant of the resources available for transportation planning. However, the cost of developing good planning tools is not necessarily correlated with size (network development is; survey data collection and demand model development may not be). Moreover, the nature, extent, and severity of an area's air quality problem is not necessarily correlated with size. Size alone, then, should not dictate modeling capabilities, even though it may affect the level of detail and the timing of improvements.

- *The Nature of the Air Quality Problem Should Influence Modeling Choices* - The specific pollutants for which a metropolitan area is nonattainment should be taken into consideration in fashioning an analysis capability. Also, the severity of the air pollution problem and the locations) at which it occurs should be taken into account.[64]

- *Regional Growth Dynamics Should Be Considered* - Rapidly growing and rapidly changing areas are more likely to show land use effects of transportation investment than are areas where overall growth is slight. Slower-growing areas nevertheless may exhibit other important land use changes which should be reflected in modeling efforts, e.g., shifts of population and jobs to suburban areas.

- *The Mix of Modal Alternatives Should Be Reflected in Model Design* - Areas exhibiting high utilization rates for a broad mix of modal alternatives require a more complex modeling approach than areas dominated by auto travel. On the other hand, various forms of ridesharing may be the chief travel alternatives in auto-dominated areas, calling for a sophisticated approach to the modeling of auto occupancy.

- *The Mix of Policy Alternatives Should Influence Model Development* - Areas considering more complex policy options - such as land use and urban design interventions, or extensive or innovative

[64] The area(s) required to be modeled for air quality purposes may not exactly correspond to the area(s) the MPO currently models. When the nonattainment area is larger than the MPO boundaries, the MPO generally should take steps to enlarge its analysis area accordingly. In some cases this may require special arrangements with neighboring jurisdictions. When the nonattainment area is smaller than the MPO modeling area, it usually will be possible to adjust model runs and/or outputs to focus on the nonattainment area.

transportation pricing measures - will require more sophisticated analysis strategies than areas relying on capital investments and operations changes to conventional highways and transit.

These complex - and sometimes conflicting - considerations underscore the need to fashion a modeling and analysis response that is matched to the conditions of the particular metropolitan area.

4.2 General Data and Modeling Needs

4.2.1 Introduction

A number of modeling issues are common to many or all of the transportation planning requirements of the Clean Air Act. The purpose of this section is to introduce these modeling issues. Subsequent sections deal with each type of analysis in detail.

The section begins with an enumeration of basic elements that should be present in every transportation model, whether a region is large or small, fast-growing or slow growing, multimodal or auto dominated, severely polluted or moderately polluted. It then discusses the principal variations in modeling requirements that arise from differences among regions. For example, many of the small MPOs will need to make improvements simply to acquire basic modeling skills, but may not require more extensive modeling investments. In comparison, most of the large, well established MPOs already satisfy basic modeling standards, but will require significant investments to address their more complex policy questions. Recognizing that no region is in a position to fully address the Act's analysis requirements or to immediately correct all deficiencies, the section ends with a discussion on setting priorities for model improvements and devising interim analysis approaches to compensate for known shortcomings in the models.

4.2.2 Review of Basic Modeling Issues

The transportation requirements of the Clean Air Act pose significant challenges for transportation modeling and analysis. Based on their experiences with new conformity determinations, on early drafts of EPA Clean Air Act guidance, and on efforts to date with transportation control planning (both under the new federal legislation and under state law, especially the California Clean Air Act), MPO staffers have reported broad concerns about the degree of accuracy of transportation and emissions models in comparison with the reliance being placed on them in transportation/air quality planning. They worry that reviews of the standard four-step travel model system, focusing on the theoretical, econometric, and statistical validity of the model hierarchies, component models, and data, have been sharply critical, and that “accepted” practice may be open to successful legal challenge if it ignores key phenomena or treats them in a way that is known to be inaccurate. Some of the specific issues they have raised are as follows:

- Basic data such as household travel surveys reporting demographics, employment, income, and trip-making; link volume and transit passenger counts; vehicle occupancies; parking prices; land use and employment data; emissions inventories; and pollutant concentration data are frequently missing, dated, or too sparse to support the detailed analyses being sought.

- The historical performance of large scale model systems has not been well documented, but several areas have had problems, reported in the literature, with forecasts of new transit ridership and predictions of other transit policy changes. Forecasts of highway volumes and speeds have been less often publicly critiqued but at least in some key instances have reportedly been no more accurate.

- Some individual model components are more reliable than others. For example, mode choice models often perform well, but the explanatory power of trip distribution models is troubling.

- Many models use only highway travel time as an accessibility measure, even when transit accessibility is arguably very important.

- Models often lack detail on household demographics which research indicates as being important: for example, the number of children in the household, age and sex of the traveler, etc. Some areas even lack data on household income (except, in the aggregate, from Census data.)

- Network coverage varies considerably in terms of comprehensiveness (what percentage of facilities are represented) and detail (how many categories of volume-delay formulae are used to describe the facilities); many areas believe they lack sufficient detail for some of the analyses they are expected to do.

- The accuracy of model estimates of link volumes and especially link speeds is often poor.

- There are major gaps in knowledge about trip timing and trip chaining, and large, weak assumptions must be made to handle these matters. For example, most areas assume trip timing will remain the same in future years, and deal with trip chains only in terms of the percent of trips that are non-home based.

- The ability to represent TCMs is mixed. Pedestrian and bicycle measures and many urban design options typically cannot be analyzed using the regional models. In some areas, pricing measures also are difficult to model because data sets lack detail on parking and other auto operating costs, and/or models do not include price and income variables (except in mode choice.)

- Regional models also are not well suited to assess many of the large changes in transportation systems and operations being contemplated for the future, including:

- Intelligent Vehicle-Highway System (IVHS) technologies, i.e., “smart highways”

- Widespread road pricing — fundamental change in land use policy.

- Few models have been validated as integrated systems, although individual component models are checked.

- Emissions calculations require inputs in far more detail than current transportation data or models can produce, and therefore require numerous assumptions and extensive post-processing.

- Documentation of models and applications generally is not extensive or detailed enough for outside reviewers.

While this list of common shortcomings may seem formidable, many MPOs have in fact made significant progress in improving practice in a number of these areas. Thus the list can be viewed more favorably as the set of improvements, many of them with good examples already available, which many MPOs will want to implement over the next few years.

4.2.3 A Basic Ensemble of Data and Models

Every region affected by the Clean Air Act will need, at minimum, a well-crafted network-based travel modeling capability which can respond to air quality model input requirements and can be used in carrying out conformity analyses. Sound modeling capabilities also are needed for long range planning under ISTEA. The following features of such a model should be considered basic.

- *Zone System* - The zone system should provide a spatial structure that: 1) is consistent with census data aggregates; 2) is consistent, to the extent possible, with the boundaries of major political jurisdictions; 3) maximizes the between-zone variation and minimizes the within-zone variation of key attributes; and 4) minimizes the proportion of vehicular travel occurring within-zones. In general, smaller zones (and larger numbers of zones) will more easily satisfy these requirements. While the number of zones has often been constrained by computer software and hardware limitations (e.g., computer time for traffic assignment and matrix operations increases with the square of the number of zones), modern RISC-based work stations have brought ample computing power within reach of every MPO, including the smaller ones.

- *Highway Network* - The highway network should include all facilities in position to carry significant interzonal traffic - limited access, arterial, and in many cases, collector. Enough categories should be defined within each facility type to support a representative range of volume-delay curves. Volume-delay parameters should be selected to reflect actual rather than nominal performance, including free-flow speeds in excess of 55 mph and effective lane capacities in excess of hypothetical values. Critical or unusual facilities (such as major intersections and toll booths) should be coded individually to ensure that delay is modeled correctly.

  Zones and networks need to be compatible; finely grained zone structures should be matched by equally detailed network descriptions. The adequacy of this match will be evidenced by the quality of the validation check.

To the extent possible, analysts should code major collectors into their highway networks. A standard rule of thumb dictates coding facilities of one functional class below that for which reliable traffic loadings are desired. Hence major collectors should be coded if reliable volumes on minor arterials are needed.

While the number of links in a network has been an issue in the past, modern work stations with graphics-based topological editors make it relatively simple to manage very large networks. The burden of database management can be eased (or shared) by combining the link library for network modeling with the general purpose catalogue of street characteristics now maintained in some regions (typically for pavement management purposes).

- *Land Use* - The basic data needed are population, average income, average household size, workers per household, employment by major category, and housing stock; all should be available by zone for the most recent travel survey year, for the current year, for the base year (if different from the current year), and for the target year(s). Whenever possible, additional demographic variables (age, sex, number of children, household members with a disability, etc.) should be obtained on a household or zonal average basis, along with additional land use data such as square footage by land use category, measures of density, and measures of development quality (price, rents, office class, etc.), home ownership levels, tenure, etc.

- *Trip Generation* - At minimum, a simple (cross)-classification table should be developed for each major trip purpose. It is useful to distinguish at least five trip purposes, including: home-based work, home-based shopping, home-based school, home-based other, and non-home-based. The dimensions of the tables will vary with purpose, and will depend somewhat on the range of demographic data available for each zone. For example, school trips are predicted more accurately by children per household than by persons per household, but regional databases do not always include explicit variables for the number of children.

  A basic travel model invariably addresses vehicle trip generation rather than the larger universe of person trip generation by all modes. While this is understandable as a simplification of the process and as a short-term expedient, MPOs should be cautioned that direct vehicle trip generation leaves a model vulnerable to errors from changes in land use characteristics (especially residential and employment densities), which are highly correlated with vehicle trip making but not with person trip making. If significant land use changes are contemplated in future studies, then it may be sensible to initiate the model system on a more robust person trip basis rather than retrofit the model later on to compensate for errors in vehicle trip generation.

- *Trip Distribution* - A trip distribution model should be developed for each trip purpose. Transformed highway time (peak or off-peak) can be used as a simple impedance factor, although areas with significant transit use should consider a more sophisticated metric such as the logsum of the mode choice model, and areas contemplating pricing strategies should consider adding cost as well as time to the impedance. Trip generations (attractions and productions) can be used as simple attractiveness measures.

- *Peaking* - Average a.m. and p.m. peaking factors should be developed for each trip purpose, with adjustments for interdistrict movements that are large enough to support separate calculations.

- *Trip Tables* - Using the peaking factors, trip distribution tables should be reconfigured into total trip tables by time period (am peak, p.m. peak, off-peak). If the trip distribution tables represent person trips rather than vehicle trips, this conversion also requires knowledge of average vehicle occupancy by trip purpose. Inter-regional and off-model trips should be added to the tables to provide a complete picture of traffic in each period.

- *Traffic Assignment* - Constrained multi-path assignments should be carried out for peak conditions, and the resulting travel times should be recycled back to the trip distribution models until a quasi-equilibrium is reached. In order to avoid mindless repetition, this step requires a careful interpolation after a few iterations have been completed.

  In the model development phase, the trip distribution-traffic assignment loop should be tested and adjusted so that both volumes and speeds are "replicated" for a comprehensive sample of count locations.

- *Survey Data* - Up-to-date home interview survey data should be collected, to serve as a resource for model development and to provide a direct source of information on mobile source emissions. As a general rule of thumb a new survey every decade or so is desirable. More effective sample design and use of special-purpose surveys such as transit on-board surveys and employee commute surveys are a potential source of data for more frequent updates (or could be used as an interim data source for some analyses), although this rarely has been successfully carried out in practice. In addition, special surveys (or counts) will be needed to account for off-model (commercial and interregional) trips in the network.

- *Validation Data* - A comprehensive set of traffic counts (by vehicle type) and floating car speed observations should be assembled as a basis for model validation and VMT tracking. MPOs almost certainly will want larger and more rigorously gathered samples than now collected for HPMS (even under the updated HPMS guidelines). In addition, it may be desirable to collect data on a broader cross-section of the highway system, including local streets, and to do special studies to account for interregional travel and intrazonal trips (VMT and average speed).

- *Emissions Estimates/Inventory* - The final step in an analysis for air quality planning is the translation of link-specific travel estimates into emissions estimates, which are used, with adjustments to account for "off-model" emissions, both to prepare emissions inventories and to evaluate plans, programs, and projects. Typically this step involves gathering data from "representative" links and using these data to estimate the detailed link-level information that is sought as input to the emissions models. These inputs include: hourly data on traffic volume by vehicle class (light-duty auto, light-duty truck, medium-duty truck, heavy-duty truck, motorcycle, and urban bus), fuel type (gasoline, diesel), and catalyst/non-catalyst; average link speed; and trip start data. Post-processors complete with default values for the representative links are increasingly available for this step; their use should be preceded by a careful review of their suitability. Note that for emissions inventories and attainment demonstrations, it is necessary to account for all emissions, including “off-model” emissions (generally on local streets, collectors and arterials not represented in the model plus VMT generated by any travel not represented in the model system.) Postprocessors to add these VMT and/or emissions also are available.

To summarize, the minimum prerequisites for a credible estimate of emissions include: 1) a complete network for the region, in sufficient detail to capture at least 85 percent of the interzonal travel; 2) an ability to generate plausible vehicle trip tables based on current and future land uses and travel options in the region; 3) software to assign the full spectrum of vehicular traffic to the network; 4) sufficient field observations of traffic (average speeds, average daily volumes, average peaking factors for specific links that are directly identifiable in the network) to calibrate the traffic assignments for base year data; 5) software to calculate emissions based on network flows and link speeds, and as necessary, to refine speed estimates from assigned traffic; 6) software or procedures to account for additional “off model” transportation emissions; and 7) estimates of future land uses sufficient to allow projections of future emissions.

4.2.4 Variations

The previous subsection describes travel modeling capabilities as they should exist in every region affected by the Clean Air Act's transportation requirements, from the smallest to the largest. In many regions, notably the larger and more complex urban areas, additional features and capabilities are required to produce travel and emissions estimates with the desired level of accuracy and flexibility. Among the phenomena to which these capabilities must respond are:

- *Implications of Modal Complexity* - Additional networks, assignments, trip tables, and peaking analyses are required to represent transit systems and, where there is separate infrastructure, HOV systems (and their effects on the ridesharing mode). Mode choice models must be present in these cases, as well. Where transit is a significant contributor to interzonal accessibility (as it is in many large U.S. metropolitan areas, especially for the poor and for trips to the CBD), the accessibility indicator used in trip distribution should incorporate transit as well as highway times. As noted earlier, the simplest way to achieve such a complex hierarchical relationship is to use the log of the denominator of a logit mode choice model as the accessibility measure. This is both relatively simple computationally and recognized as the theoretically correct approach.

- *Implications of Land Use Complexity* - Where land use densities differ among zones by two or three orders of magnitude (e.g., as measured in persons per residential acre), variations in vehicle trip generation can be quite large. In these cases, it is necessary to add land use variables to vehicle trip generation equations (either by adding a density dimension to each vehicle trip attraction and production table, or by dealing with person trip generation and splitting out the vehicle trips in a later step). Without such adjustments, there will be a tendency to over-predict vehicle trips in denser areas and under-predict trips in less dense areas. It is desirable to adjust the granularity of the zone system (i.e., select zone boundaries) to provide for homogeneity of land use and population characteristics within zones. Typically, this implies more fine-grained zones and (possibly) trip generation and trip distribution modeling for several classes of workers (e.g., manufacturing, service, other).

- *Implications of Land Use Change* - If a region is growing or undergoing significant internal rearrangement of land uses, density attributes become even more important. For example, new development that is less dense than the regional average is likely to produce a higher-than-average number of vehicle trips per unit, yet most existing vehicle trip generation models do not allow land use characteristics to influence trip generation for a given household category. Models so configured are likely to under-predict VMT growth in the face of land use change.

  A more controversial issue is the degree of need for a land use allocation model and/or a regional growth model capturing the effects of investment and accessibility on the spatial arrangement and amount of economic activity. As Chapter 3 makes clear, the dominant style of analysis involves the use of one or more fixed future projections of land uses, treated as a "given" unaffected by transportation investments. Yet most planners recognize that the location and level of infrastructure investment will have at least some influence on the locus of economic activity. This implies a potential effect on VMT and emissions forecasts, and on the outcome of conformity assessments.

  There is not a consensus among practitioners on the "right way" to model the land use effects of infrastructure. However, workable models based on tested theories of spatial interaction are available. Many of the largest MPOs have implemented or are in the process of implementing such models simply to be in a position to offer an informed opinion about the extent of land use effects from (and on) transportation plans.

  In one mode of operation, the land use models serve largely in a sensitivity testing role. Analysts run the land use models to evaluate whether and to what extent the land use pattern would shift in response to proposed transportation changes. If the shift is significant, they then re-run the transportation models with a new land use pattern to determine the resulting travel changes, or in some cases simply adjust the core transportation model outputs by hand.

  Looking at their conformity obligations, as well as their broader multi-modal planning responsibilities under the ISTEA, a number of larger MPOs likely will implement land use models in the next few years no matter what (some are already doing so). As the models are improved and their range of validity is established, it may become feasible both to bring them more explicitly into the core modeling framework and to make them available to smaller MPOs.

- *Variations in Travel Cost* - Basic models typically assume that auto travel costs are roughly proportional to highway travel times. In a region with few priced parking spaces or toll facilities, this assumption is approximately correct by definition because the out-of-pocket expense of driving an automobile is roughly proportional to distance and speed (hence, time). However, where parking charges and tolls are present, travel choices will reflect the resulting price variation.

Where toll facilities exist or are contemplated, or parking prices exist or are expected, the MPO must ensure that prices are adequately represented in transportation models. For parking price, this implies a presence in the mode choice models and, to the extent parking prices are a factor in destination attractiveness, a presence in trip distribution. A linkage with trip distribution occurs automatically if the mode choice logsum is used as the attractiveness variable.

For tolls, the modeling implications are somewhat more complex. Tolls not only have the same mode choice and destination choice effects as parking prices, but usually influence route choices as well. Given a suitable conversion factor (e.g., an average value of time), tolls can be included in the generalized price (utility) of each affected link or can be converted to a time equivalent and inserted as a link penalty. The resulting traffic assignments will reflect the influence of tolls on route choices.

The appropriate treatment of tolls in mode choice becomes somewhat unclear in the presence of demonstrable route choice effects. When tolls influence some but not all of the feasible routes between points, average time and cost for the mode choice model must be calculated as weighted averages for tolled and non-tolled paths.[65]

In general, price effects (hence value of time) have been shown clearly to diminish with increasing income. Thus, wherever price appears in the model structure, its influence should be inversely proportional to income. This can be accomplished in the mode-choice models by dividing the price by some function of income. Such an approach is not possible for route choice under commonly used traffic assignment methods, and route choice results simply must be taken as representative of the average traveler. (Because income is not among the available variables in route choice (assignment) in the most commonly used software packages, it can be incorporated only by contracting for special programming.)

- *Peaking* - Field studies show a significant variation in peaking characteristics with the degree of congestion in a corridor. In a region like the San Francisco Bay Area, peak hour flows will range from 11 percent of daily totals in uncongested corridors to 7 percent in a highly-congested corridor such as the Bay Bridge. Modelers in the Los Angeles and New York areas report peak percentages as low as 6.5 percent. While there are no accepted models of peaking available for general use, any region that expects to experience a change in the level of congestion over time or among alternatives should have a well documented procedure or simple model in place for adjusting the peak hour percentages, for example, estimating the peak hour percentages as a function of the 24 hour volume-to-capacity (V/C) ratios.

[65] A more rigorous approach would involve representing the choice of route as subsidiary to the choice of mode, using a formal nested choice framework. Such a model has not yet been developed for practical use.

4.2.5 Getting From Here to There

As of this writing, no region's model exhibits all of the desired features, and no region is close enough to a "state-of-the-practice" modeling capability to have it all in place for the next round of transportation-air quality analyses. Planning resources are increased significantly under ISTEA, but not enough to "buy" all of the needed improvements immediately. Furthermore, some of these improvements will require several years of data collection and model development for complete realization. This suggests a pair of questions: 1) In what sequence should data and model improvements be implemented? and 2) How can informed decisions be taken before a region's data and models are improved? Neither of these questions can be answered in detail without reference to a particular region's context, but a number of general observations are possible.

Prioritizing improvements

Substantive model improvements should begin right away in each region. In most cases, the initial steps will involve data collection and data analysis. With few exceptions, each region will need the following items:

- an up-to-date travel survey, to provide information for local model development. The survey should elicit key household information, including income, vehicle availability, and household structure, and should include at least a one-day diary of vehicular and non-vehicular trips in sufficient detail to support accurate geocoding. Sample size will vary from region to region. After a period of economizing with small samples, many regions have gone back to collecting the largest samples they can afford (e.g., 5000 or more observations, and as many as 10000-1 5000 observations in the largest regions), both to ensure the maximum flexibility in later use and to have adequate samples for subarea and corridor analyses. However, useful information can be extracted from samples as small as 500, if that is all a region can afford. Also, a well-designed supplementary survey of perhaps 500 observations could be used to obtain missing data and then could be combined, via rigorous statistical procedures, with the larger survey for analysis and forecasting purposes. (i.e., an MPO could collect a survey which includes data omitted from their larger survey - in some regions, this would include data on incomes; prices paid, including parking price; and characteristics of the vehicles owned.)

- an expanded set of traffic observations, to allow for accurate VMT and speed monitoring and to provide data for model validation. Data about fleet mix by time of day must be one of the observations made.

- an OD survey at regional cordon lines, to provide estimates of internal-external traffic origin-destination patterns.

- an expanded highway network, covering all freeway, arterial, and key collector facilities. (A key collector facility is one which carries significant interzonal traffic, e.g., 1000 trips/day.)

- a set of zonal demographic and economic data, updated to reflect the most recent (1990) Federal Census results.

As soon as they are available, household survey data should be used to develop an improved understanding of travel behavior in the region, and to make incremental improvements to existing models. For example, an outdated (or "transferred") trip generation model might immediately be replaced with a revised cross-classification table based on the new survey, with a more sophisticated trip generation model developed as time and resources permit.

Household survey data also should be used to develop a deeper understanding of the origins of mobile source emissions. With full geocoding and verification, and after base network level-of-service information is attached, the raw survey data can be used in a sample enumeration framework to make accurate emissions estimates for a variety of trip categories. Such an approach can draw on the survey for trip type, household, and vehicle data; on the networks for trip speeds and distances; and on EPA's most recent MOBILE series model for running emissions and trip start emissions by trip type.[66] In both San Diego and the Bay Area, where extensive analyses of this type have been carried out, numerous high-emitting trip categories (such as high school and college trips) have been identified.

With all of the data in place, the MPO can undertake a (possibly) more far-reaching set of model improvements, designed to achieve the level of complexity and sophistication deemed appropriate for local conditions. For a small MPO with recently-acquired modeling responsibilities, this may be a basic model that simply meets the core structural requirements listed above (but with "home-grown" coefficients). For a large MPO with a sophisticated model already in place, this would imply a refinement of models to address omitted or problematic phenomena. For example, in highly-congested regions, a more formal representation of the relationship between corridor-level peaking and congestion may be sought in order to more accurately analyze future delays in a saturated network. Also, a number of areas will want to improve their ability to represent transportation-land use interactions in their models. For areas with complex transit choices, detailed nested models might be developed (e.g., auto vs. transit; within auto, rideshare vs. drive alone; within transit, rail vs. bus; within rail, light rail vs. heavy rail (or express vs. local); competing access modes for each.) For areas with little transit but much ridesharing activity, the rideshare options might be modeled in detail (e.g., rideshare vs. drive alone; within rideshare, vanpool vs. carpool; within carpool, household members only vs. unrelated individuals; access modes for each shared ride option.) In short, each MPO would decide what model improvements are most important, given its existing models and the transportation issues and options in the region, and would pursue improvements accordingly.

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[66] Currently, MOBILE outputs include trip start emissions in the overall running emissions. However, the analyst can produce trip start outputs by running the model for a number of scenarios - zero cold start, zero hot start (running emissions only); 100% cold start, zero hot start; 100% hot start, zero cold start - and comparing the results to produce estimates of cold start and hot start emissions. California's EMFAC program, in contrast, directly provides cold start, hot start, and running emissions estimates.

Interim Analysis Methods

As model improvements are being developed, the MPO may need to apply interim analysis methods to accomplish certain of its responsibilities. Such methods need to be credible even though they may be less detailed (accurate or precise) than the more sophisticated or more formal methods to be used later.

The most basic and immediate need is for a credible current emissions inventory and a projection of that inventory to the attainment year, as a basis for discussions over the level of emissions reductions to be assigned to transportation sources. Most major MPOs are in good position to produce at least a first-cut 1990 inventory, using HPMS data and/or their available models; however, in some regions neither available data nor models are adequate for this purpose, and the MPOs will have to catch up quickly.[67] One approach would be to use HPMS data and/or other historical traffic counts to establish baseline VMT and a trend in VMT growth, and use the trend estimate to produce emissions forecasts. (MPOs in general may wish to compare HPMS or other count-based estimates with estimates produced by their travel models, and to make adjustments, as necessary, to reflect observed trends.)

If model improvements are required for other purposes (such as TCM analysis or conformity assessment) but are not yet available, then it may be possible to "borrow" key models from another region with adjustment as necessary to replicate local conditions. Alternately, an area may choose to borrow an elasticity and either convert it to a parameter value or use it directly in off-model applications.

Many areas may choose to apply sketch planning methods for TCM analyses, at least in initial rounds. Sketch planning methods range from simple worksheets (available in various forms, from hard copy to calculator-based to microcomputer versions), to more complex methods such as the STEP model used in the Bay Area and the SRGP model used in Denver; a number of these methods are documented in various EPA, DOT, and Dept. of Energy reports (e.g., Sosslau, 1978; Harvey, 1978; Harvey, 1979; Atherton and Suhrbier, 1978; among many others). Caution should be exercised in using the simpler of these methods, since for some TCMs they have been based on very limited data or experience.

Use of sketch planning methods may be a sensible strategy even for areas which have adequate model systems. In the Bay Area, for example, the STEP model was used for much of the TCM analysis (e.g., to explore policy options) and only the final proposed policies were subjected to analysis using the full model system. (The full system also was used for conformity runs.) This combined approach saved tens of thousands of dollars of computer time.

[67] VMT forecasting guidance (US Environmental Protection Agency, 1992a) calls for MPOs to use HPMS data as the baseline and model-based growth factors for projections, unless HPMS data are inadequate; in the latter cases other approaches may be accepted.

4.3 Specific Transportation-Related Air Quality Analysis Requirements

In addition to the basic data and model improvements discussed in the preceding section, the specific analysis needs result from requirements of the 1990 Clean Air Act Amendments. These include emissions inventories, forecasts, and tracking; tracking and forecasting of VMT; TCM evaluations; and conformity determinations. The analysis implications of each of the major requirements is discussed briefly in the following sections.

4.3.1 Emissions Inventories, Forecasts, and Tracking

Under the 1990 Amendments, emissions contributing to violations of the national ambient air quality standards must be inventoried and tracked over time. Moreover, forecasts of emissions will be used in determining the levels of reductions needed, and actual emissions levels will be compared with forecasts in evaluating progress. Mobile source emissions will need to be estimated at both the regional level and at the "grid cell" level, for air quality modeling.

If aggregate regional totals were the only required emissions estimates, then a variety of methods would be available, including:

- Totals expanded directly from traffic count data - An improved HPMS-type sample (with added representation from local and collector streets) could be used to generate a direct estimate of the regional emissions burden. Detailed volume and speed data would form the basis for emissions calculations at each site, using MOBILE or EMFAC emissions factors. The HPMS expansion factors then would be used to expand the site-specific emissions calculations up to regional totals.
- Trip-based emissions summary from a current travel survey - Travel diaries generally provide a good picture of personal vehicle travel patterns. Given reliable network-based speeds and distances, MOBILE or EMFAC factors can be used to compute the emissions for each vehicle trip in the sample, and total emissions can be estimated by summing the emissions over all trips. In some ways, this method is likely to yield the most accurate estimates of emissions, because the MOBILE and EMFAC factors are really trip-based (i.e., they derive from the Federal Test Procedure, which was designed to represent a "typical" trip). Even with a good survey of personal vehicular travel, additional effort is required to determine the emissions from commercial and inter-regional travel. As a practical matter, it may be necessary to get at these off-survey elements through HPMS-type traffic counts. (Some areas, e.g., Chicago, have done truck surveys.)
- Trip-based emissions summary from base travel model run - This method resembles the sample enumeration approach described above, but draws the trip sample from the model's trip tables. If recommended modeling practices are followed, commercial and inter-regional trips will be present in the trip tables.
- Link-based emissions summary from base travel model run - This method also uses data from the regional model, but bases the calculation of emissions on final link volumes and speeds. Emissions are determined for each link and time period, based on the average link speed and volume by vehicle type, and are then summed to yield the regional totals. Experience in the Bay Area indicates that the trip-based method and the link-based method will differ by no more than 2 percent for CO

and ROG (VOC). The difference arises because of the greater speed variation among individual links than among paths through the network. It is not at all clear that MOBILE and EMFAC are as valid for the homogeneous link speeds assumed in transportation models as they are for average path speeds,[68] but there is a tendency for MPOs to rely on a link-based analysis because it more readily produces grid cell estimates of emissions.

There really is only one reasonable method for producing grid cell estimates of emissions, which is to use the link flows and speeds in the manner described above.

4.3.2 VMT Baseline, Forecasts, and Tracking

Forecasts and estimates of actual VMT (along with certain other travel parameters) are required under the 1990 Amendments as a way of monitoring compliance with transportation-air quality requirements. As discussed in Chapter 2, ozone nonattainment areas classified as Serious or worse must demonstrate that VMT, emissions, and congestion are consistent with the assumptions in the SIP, or SIP revisions will be triggered. Certain CO nonattainment areas (classified as Moderate or Serious with a design value over 12.7 ppm currently nine areas) have requirements for annual VMT forecasting and tracking; if estimated actual" VMT exceeds that forecasted, specific contingency measures must be implemented in these areas. Thus, it is urgent that these areas develop the ability to produce reliable aggregate regional "measurement" of VMT over time, with short- to medium-range forecasts of regional VMT growth that are as accurate as possible.

EPA guidance on VMT forecasting and tracking for CO nonattainment areas with design values above 12.7 ppm was issued in January 1992. While the guidance is not binding and states (or regions) can depart from it, departures would have to be justified whereas simply following the guidance would be accepted. The guidance specifies the use of ground counts from FHWA's Highway Performance Monitoring System (HPMS) for tracking VMT, and regional network models (or HPMS extrapolations) for forecasting VMT.

The use of HPMS for the baseline inventory and tracking and model-based VMT for forecasting appears to reflect a compromise. On the one hand, several of the affected areas lacked network models of sufficient accuracy or detail to produce good estimates of VMT and could not adequately improve the models in the amount of time available; therefore they were looking for other ways to obtain VMT baseline information. The HPMS system was an obvious option as it is already in use in all 50 states for VMT estimation, and is being improved under FHWA direction. On the other hand, the HPMS data base has recognized limitations (for example, local streets are not counted - a limitation shared with regional network models - and the area HPMS covers is usually smaller that the nonattainment area, with under-representation likely to be greatest in the urban fringe, the area where

[68] High speeds (>55mph) may be an exception, since driving cycles for such speeds would include relatively few accelerations/decelerations, etc.

VMT growth may be fastest.) Moreover it is especially problematic that the HPMS data for several of the states containing the CO nonattainment areas subject to the VMT forecasting and tracking requirement - in particular, California, Washington, New York, and Connecticut - are currently based on statewide sampling of grouped urbanized area data rather than regional samples (though urban area samples are now required and will be available in the future). Also, HPMS is not a forecasting model, so its use does not obviate the need for a forecasting method. While the guidance recognizes these problems, calls for fix-ups to overcome some of them (e.g., more counts, methods for estimating local VMT and VMT outside the HPMS-covered area, etc.), and allows alternative approaches under some conditions, considerable uncertainty over the reliability of the baseline VMT estimates may be a troubling problem for at least some of the areas.

Future VMT estimates are to be done by applying a model-based growth factor to the HPMS 1990 baseline estimates, or simply by extrapolating from HPMS samples. Thus errors in the baseline estimate would be carried forward into the forecasts. Similarly, inaccuracies in the expected growth rate (itself a complex function of expected changes in employment, population, household demographics and income, land use patterns, etc.) would produce erroneous future estimates. Whatever the source of error, it could have serious consequences, since overestimation of VMT would trigger more controls than actually are needed, whereas an underestimate could complicate conformity findings, trigger a SIP revision, and/or trigger the implementation of contingency measures.[69]

Because of the uncertainties and risks, most areas will need to invest in both improved counts and improved network models. In the meantime, areas may wish to double-check their VMT baseline estimates by comparing them to the results obtained via alternate methods. For example, VMT estimates can be derived from any or a combination of the following:

- Regional gasoline sales
- Odometer readings
- A separate sample of traffic counts (different from HPMS)
- A household survey repeated at necessary intervals, supplemented by a survey of commercial VMT
- Model calculations (i.e., from regional travel models, with revision of key inputs based on "measurements").

While each of these methods has limitations (see, e.g., Cambridge Systematics, Inc., 1991a; Smith and Ramadan, 1990), they may nevertheless be useful as checks on the reasonableness of HPMS-based estimates.

[69] The possibility of a discrepancy between forecasts and counts is likely to be quite high given the uncertainty attached to the many factors which enter into VMT growth forecasts or counts themselves. However, the EPA guidance allows only a five percent difference in forecasts and "actual", or in updated forecasts and the forecast relied upon for the attainment demonstration. In comparison, a study by FHWA found that the variability of VMT 1983-88 for 14 areas averaged +/-3.8% (Fleet, 1991).

Alternative approaches also might be applied to forecasting VMT, including:

- Trend extrapolation
- Aggregate econometric models
- Regional travel model calculations.

Here, too, each approach has limitations, but can be useful as a way to check forecasts.

4.3.3 TCM Assessment

4.3.3.1 Analysis of Section 108 Measures

As noted earlier, Section 108 (f)(1) of the 1990 Clean Air Act Amendments requires EPA, in consultation with DOT, to make information available on transportation control measures including, but not limited to, the following sixteen items:

1. Programs for improved public transit
2. Restriction or construction of certain lanes or roads for use by buses or HOVs
3. Employer-based transportation management programs, including incentives
4. Trip reduction ordinances
5. Traffic flow improvement programs that achieve emissions reductions
6. Fringe and corridor parking facilities serving HOV's and transit
7. Programs to limit or restrict vehicle use downtown or in other areas of emission concentration, particularly during peaks
8. HOV/ridesharing service programs
9. Time or place restrictions of road surfaces or areas to bikes and pedestrians
10. Bike storage, lanes, and other facilities, public and private
11. Programs to control extended vehicle idling
12. Programs to reduce extreme cold start emissions
13. Employer-sponsored programs to permit flexible work schedules
14. Localities' SOV trip reduction planning and development programs for special events and major activity centers including shopping centers
15. Pedestrian and non-motorized transport facility construction and reconstruction
16. Programs for voluntary removal of pre-1980 vehicles.

The EPA guidance documents address the relative effectiveness of various procedures and methods, their potential effect on the transport system and the provision of transportation services, and their energy, environmental, and economic impacts. Additional guidance addresses:

- ways to reduce emissions during air pollution alerts;
- other measures to reduce public health impacts;
- information on the extent to which strategies to reduce one pollutant might lead to increases in another.

Although with specified exceptions TCMs are not required, they nevertheless are likely to be needed in most metropolitan areas facing CO and ozone nonattainment problems, in order to meet required milestones and to attain the standards by the deadlines. Hence the Section 108 list will be a starting point for MPO evaluations.

Several observations are in order about the sixteen TCM categories listed in Section 108. For one thing, some of the categories are very broad, and within a particular category a variety of measures could be devised; for example in a study on TCM implementation issues conducted for EPA just before the passage of the 1990 Amendments, over 70 specific measures were reviewed (Eisinger, Deakin, et al., 1989). Each of these specific measures could require a different analysis approach. As one example, employer-based incentives could include reservation of close-in parking lots for HOW and visitors, with SOV drivers having to walk two or three additional minutes for each trip. Or the employer could subsidize transit and charge for parking, or establish shuttle services to transit. Each of these options would require a different set of analysis steps. Even more disparate are the analysis approaches that would be suitable for freeway operations controls, downtown traffic signal system coordination, and intersection redesign, all measures that fall under the improved traffic flow category.

On the other hand, a number of the TCM categories overlap. For example, trip reduction ordinances typically implement requirements for employer-based programs, which often (but not always) include such items as employer-sponsored flexible work programs and rely on local government commitments to improved transit, ridesharing assistance, etc. Similarly, localities' programs to facilitate non-automotive travel and reduce the need for SOV travel as part of transportation planning and development efforts are often implemented through trip reduction ordinances or employer-based transportation management plans mandated as a condition of development approval or building occupancy. Moreover some items on the list provide alternate institutional frameworks rather than specific emissions-reducing measures; the distinction appears in the implementation strategy specifics rather than in the way the measures would affect travel behavior (or the differences are too subtle to be modeled: the impact of a government-funded transit subsidy vs. an employer-funded transit subsidy, e.g.) In particular, TCMs #3, (employer-based transportation programs), #4 (trip reduction ordinances), and #14 (trip reduction programs and ordinances as part of localities' planning and development efforts) are ways to implement the more action-oriented TCMs.

These observations suggest the need to sort out TCMs into meaningful groups for analysis purposes. First, note that the ability to model the various TCMs varies considerably. At least six categories can be identified:

- Some of the measures are easily included in most currently available regional travel models. For example, improvements in transit level of service (TCM #1) can be readily modeled in most regional model systems.

- An additional set of measures could be modeled if additional data and variables were incorporated into the model structure, though only some regions currently have models with the requisite capabilities. For example: the modeling of pricing strategies is sometimes constrained by a lack of data on current prices and incomes, but available models can and do accommodate these variables. Similarly, certain TCMs can be analyzed by regional model systems if (but only if) special features are present in the networks: an example would be HOV facilities (TCM #2) or other vehicle restrictions on certain lanes or areas (TCMs #7 and 9). Bike and pedestrian network improvements (TCMs #10 and 15) could be represented in a mode choice model which included these modes, or even could be treated via separate network coding, although few areas deal with either mode so explicitly. In some cases "fix-ups" can be devised to roughly incorporate the measures of question into the model, for example, transfer of price coefficients estimated in another region or a special study, or use of scalar variables to reflect the presence and quality of pedestrian connections.

- Certain measures have been modeled in a few areas or in research projects, but models of these measures are not in common use by MPOs. Examples include models which incorporate variables to reflect the availability and nature of certain features of ridesharing promotion (e.g., presence of an on-site coordinator as part of employer-based transportation management programs - TCM #3, or of strong rideshare matching outreach activities as part of a shared-ride services program - TCM #8), and models which can reflect the availability of flexible work schedules (TCM #13). For these measures special studies may be needed; or the analyst may simply rely on inferences from available studies and data.

- Some measures are typically analyzed off-line on the basis of survey data, although future modeling efforts incorporate their analysis measures into the regional model system. For example, the decision to use park and ride (TCM #6) versus some other form of access has frequently been modeled for transit (e.g., via a transit access mode choice model), but similar models have not been developed for ridesharing; in the latter case most analyses estimate the impacts of park-and rideshare based on empirical results at other applications.

- Some measures are readily modeled but not via the regional model system. These include many traffic flow improvement measures such as traffic signal timing and intersection redesign, as well as ramp metering and freeway weaving section improvements (TCM #5). Special purpose models are best suited for these analyses. MPOs either extrapolate from studies done on specific facilities, corridors, or areas of the region, or commission special studies of the regional impacts of these TCMs.

- Finally, some measures are not readily modeled with transportation or traffic models and data, but call for analyses using emissions and vehicle fleet information. The measures addressing extended idling (#11), cold starts (#12), and pre-1980 vehicles (#16) would fall in this category.

One way to group TCMs, then, is by the extent to which they can be analyzed with available regional models, require model enhancements or fix-ups, rely on special studies or inferences from available ones, call for analyses using transportation or traffic models other than the regional ones, or call for non-transportation modeling and analysis.

The following listing suggests how various TCMs fit into each of these categories.

- *Transit and highway infrastructure improvements* (e.g., TCMs 1 And 2; TCM 5 with respect to major facilities) - These infrastructure improvements usually can be translated into changes in travel time, so a good regional travel model should be capable of representing the effects on VMT, emissions, etc. Analysis of HOV lanes generally will require the coding of specified links as HOV. (See Chapter 3.)

- *Transportation services and operations improvements* (e.g., TCM 8, some aspects of TCM 5) - This group of TCMs offers improvements in level of service, reliability, flexibility, etc., mostly without adding new infrastructure. Some of the strategies that would fall under this group influence variables present in conventional models: for example, increase in transit frequencies or discounts on fares. In such cases it is possible to use a good regional model for TCM assessment. Other service improvements provide new dimensions of service that do not translate well into existing variables (e.g., improved reliability due to guaranteed ride home programs) or risk extending existing variables well beyond the range reflected in estimation data sets (certain IVHS strategies might do this). In these cases it is necessary to make "off-model" estimates and then integrate the results with the base outputs from the regional model.

- *Traffic flow improvements* (TCM 5) - Improvements in traffic flow affecting facilities in the networks generally can be modeled by adjusting travel times and costs to reflect the new conditions. In many cases, analysts will use traffic operations models to estimate the time savings (e.g., applying FREQ or TRAFLO to analyze ramp metering or other freeway improvements; applying TRANSYT or PASSER to analyze signal timing improvements, etc.) In some instances the analyst may prefer to work directly with the outputs from these more detailed traffic operations models in estimating emissions reductions, since the operations models provide detailed information on changes in stops and delays accelerations and decelerations).

  For TCMs affecting facilities not included in the network "off-model" analyses must be used. For example, this would be the approach for analyzing the impacts of signal timing or intersection improvements on local streets.

- *Programs instituted at the work place* (TCMs 3 and 13) - Employer-based transportation management programs are a way of implementing TCMs rather than a TCM per se (although it is recognized that the very presence of an employer-based program may support the use of travel alternatives.) Specific measures included in an employer-based program could range from supplementary transit services to parking pricing to transit pass subsidies to ridesharing marketing, and could extend in some cases to employer-funded traffic signals, etc.

  Measures that alter modal availability or change the times and costs of travel modes generally can be represented in regional travel models, if the programs are ubiquitous (or apply to all employers in particular zones, or apply to all employers of a particular type of job category represented in the model, e.g., all service workers). If the programs are applied only to certain kinds of employers or employees, however, it may be necessary to do extensive post-processing of results or to deal with the whole measure "off-model" (e.g., by extrapolating from available evidence of effectiveness, perhaps using a cross-classification approach to account for differences in geographic area, employment size and type, etc.), and then integrate the results with base outputs from the regional model. Such off-model approaches are also needed to account for the effects of marketing and promotion, in-house coordinators, etc. (unless the MPO happens to have one of the few models including a variable for these factors, or chooses to implement such a model.)

Flexible work schedules also must be analyzed "off-model" and then integrated with base outputs from the regional model. Data on flextime programs indicate potential effects on peaking (hence network characteristics experienced) and mode choice. (Here, too, a few regions have access to models, or at least heuristics, for estimating flextime effects.)

- *Programs implemented or mandated by local governments* (TCM 4, 14, etc.) - Like employer-based programs, local government programs can encompass a wide variety of infrastructure improvements, service improvements, vehicle use restrictions, pricing strategies, etc. The analysis of such approaches is according to the substantive elements of the action rather than their implementation approach.

- *Bicycle and pedestrian facilities and programs; auto restricted zones* (TCMs 9, 10, 15) - Since few regional models represent the bicycle and pedestrian modes in their models, bike and pedestrian facilities and programs generally must be analyzed "off-model", with the results used to adjust the regional model (e.g., vehicle trip distribution tables would be adjusted downward, particularly for intra-zonal trips and trips between adjacent zones.) Most areas will rely on evidence from implementations in their region or reported in the literature. In areas where these modes are particularly important or are of key interest it may be useful to estimate special mode choice models, add proxy variables to models, etc.

  Pedestrian malls (auto-restricted zones) require somewhat more complex analyses, depending on their size and the specifics of the restrictions proposed. Vehicle trip productions and attractions could be modified, and traffic conditions on nearby portions of the network could be altered. While several detailed studies involving modeling of auto-restricted zones have been carried out, a serious proposal to implement such a measure on a significant scale would likely be the subject of a special study.

- *Pricing measures* - Pricing strategies will be analyzed in some areas as possible economic incentive programs called for as contingencies under the 1990 Amendments. In other areas pricing may be considered as an alternative to the command-and-control TCMs. Price, of course, also enters into mode choice and other travel decisions in the form of fares, tolls, parking prices, vehicle operating costs, etc. While the inclusion of price variables in regional travel models is highly variable from one region to another, a state of the art model would have price represented ubiquitously in the model system, from traffic assignment through population and employment allocation, with price responses appropriately tempered by income. Given such a model, the analysis of pricing measures should be about as straightforward as the analysis of conventional infrastructure improvements. Without such a model, it will be difficult to produce a convincing analysis of pricing strategies. Since price and income are absent from some models because the data are not available, alternate approaches may have to be considered. One quick fix (recommended as a short-term option only) is to convert prices to equivalent times for input to a conventional model, using an income-variant value of time. A second approach would be to transfer model(s) from other regions with as much customization to local conditions as can be supported by local data or studies. (See below for further discussion of pricing.)

- *Vehicle controls* (TCMs 11, 12, 16) - Measures aimed at controlling extended vehicle idling, reducing the impact of extreme cold starts, or removing older vehicles (or high emissions vehicles of any age) typically will be analyzed by reference to motor vehicle registry data (e.g., data on how many vehicles are pre-1980), special purpose studies (e.g., patterns of use of vehicles of different ages, studies of idling in taxi lines), and/or data on the effectiveness of technology applications (studies of emissions reductions from pre-heated catalytic converters, investigations of in-use monitoring and enforcement program effectiveness.) MPOs may leave these TCMs to air quality agencies, or may work closely with them in conducting special studies, but relatively few MPOs are likely to take the lead on their development and analysis. MPO data and models may be of interest in studies of these TCMs if, for example, the number of trips made by different categories of households is at issue, or if travel survey data report which vehicle was used for each trip.

As this list indicates, a number of TCMs, particularly those that can be represented as changes in vehicular travel times or travel costs, can be analyzed by typical regional travel models; several more, especially detailed pricing options, could be analyzed as long as the region has invested in the requisite data collection and model development. Several of the more commonly used TCMs are best analyzed via traffic operations models rather than travel demand models or network models, and a number call for special purpose studies or reliance on evidence from previous implementation experiences rather than regional modeling. In several instances “quick fixes” or simple indicators could be used as an interim measure, while more detailed approaches are implemented. Overall, the choice of how to model a particular TCM will depend on 1) the nature of the TCM itself, 2) the quality of available models and data and their suitability for analyzing the TCM, 3) the importance of the TCM in the region, and 4) the time and other resources available for model development or refinement. For further guidance, see the references to TCM guidance documents.

4.3.3.2 Other TCM Analysis Issues

Several other issues may need to be considered by TCM analysts. Of particular importance are pricing strategies; TCMs' impacts on land use and development, and conversely, the potential of land use and development measures as TCMs per se; and various TCMs' implementability and its impact on the emissions reductions credits that can be claimed. Each of these issues are discussed briefly in this section.

Pricing

Economists have long argued that many functional problems in the transportation system stem from inaccurate price signals. Diverse strategies for improving the pricing of transportation have been proposed. Among them are tolls; use of congestion pricing techniques to allocate space on crowded urban highway facilities; market-based pricing of parking and elimination of favorable tax treatment for subsidized parking; and emissions fees for vehicles operated in areas which have not attained air quality standards. Such strategies increasingly find endorsement from other experts, and interest in transportation pricing has been growing in recent years both as ways to generate revenues and as means of moderating travel demand and reducing emissions.

In several parts of the country, new roads are being built as tollways in order to pay for the needed facilities and deliver them faster than would be possible relying on public funds alone. In some areas, tolls and other fees are increasingly seen as ways of generating revenues for a variety of transportation projects including transit. In addition, pricing has been proposed as a way of dealing with congestion, air pollution, energy dependence, and other problems associated with heavy use of the automobile.

But a presumption of political infeasibility has tended to make pricing strategies the exception rather than the rule. Arguments challenging the practicality and fairness of transportation pricing schemes include concerns that toll booths create delay and increase accidents, that pricing might simply divert traffic to other "free" routes and cause problems there, that setting congestion prices accurately would be near-impossible, that congestion prices would be so high that only the rich could drive in many areas, and that emissions and congestion pricing would be prone to fraud. While advances in technology could overcome some of the objections raised (especially those concerning delays and cheating), other concerns would remain.

Nevertheless, a number of metropolitan areas will consider pricing strategies as part of their TCM analyses. For example, Los Angeles and the Bay Area have found that fees, tolls, and the like would be necessary to meet state-mandated air quality standards. As proposed in the Bay Area, the pricing approach would use congestion charges, smog charges, parking fees, and gasoline taxes. These fall into two conceptual categories: charges that are firmly rooted in the economics of transportation (i.e., "market-based") and fees that exploit a convenient institutional framework for revenue collection (i.e., "fee-based"). With the exception of toll increases, pricing proposals have not been adopted yet, but they have received serious public airing and garnered substantial media support. Similar proposals are under consideration for Los Angeles.

Pricing is also likely to be considered because of the demonstration projects authorized by ISTEA. At the time of this writing a number of MPOs are actively developing proposals for the demonstration funds.

If market-based measures do receive consideration in Federal TCM planning, a number of supportive actions may be necessary. In particular, suitable analysis tools will be needed; currently a surprising number of MPOs lack data on such basic factors in travel choices as household incomes and travel costs, and hence cannot adequately model any pricing policies.

A full-fledged pricing program would have far-reaching effects on the pattern of mobility in a region, by altering the perception of accessibility and the cost of auto ownership in a way that depends on household income. The major questions for analysis are whether available travel models can represent the role of price in accessibility in a systematic and comprehensive way, and whether such models adequately capture socioeconomic variation in the population. The following is a brief review of modeling issues in a pricing study.

One key issue is, What variables are critical? Clearly, the price of travel is central to the analysis and must appear in appropriate places throughout a model system. Components of price for a vehicle trip should include parking costs, tolls, and perceived out-of-pocket auto operating costs, the latter specified carefully to assure comparability with less subjective parking and toll costs. In addition, the annual cost of operation (both fixed and variable) should appear as a determinant of auto ownership.

Household or personal income is a second key variable that should mediate the effect of price wherever it appears in a model system. Under best practice, household income typically is included to make the coefficient of price inversely proportional to income.[70] Unless income appears jointly with price, the distributional consequences of pricing strategies cannot be studied.

Congested travel time is a third key variable. Models should be capable of representing the effects of predicted changes in demand on travel time, with as much time-of-day detail as possible.

Behavioral responses to pricing strategies also need to be considered in building price sensitivity into the model system. Under the conventional paradigm of travel behavior, price could have noteworthy effects at several levels of the model hierarchy:

- route choice/traffic assignment - Tolls and congestion fees influence the “impedance” of each route, which will produce changes in path assignments as fees are differentially changed.
- time of travel - Fees that vary with congestion will induce some drivers with scheduling flexibility to shift to less congested periods.
- mode choice - Price is a key determinant of modal competition for all types of travel.

[70] This is done by constructing a composite variable that is some function of price and income.

- trip distribution - Differential price increases will cause a spatial shift in the trip distribution from any given location, and a general price increase will lead to shorter trips overall.[71]
- trip generation - For non-work trips, a general price increase could reduce the amount of discretionary trip-making. For work trips, a significant price increase (either differential or general) could foster work-at-home policies, four-day work weeks, or other reduced trip scenarios.
- auto ownership - By directly or indirectly raising the cost of auto ownership or decreasing highway accessibility, price increases could reduce the incentive for multiple auto ownership.
- residential and employment location - Significant price increases may cause lower income working households to seek less expensive work places or residential locations. Conversely, reductions in congestion may induce higher income households to locate farther from their work places.[72]
- residential and commercial construction - Pricing-induced changes in residential demand or work force availability might shift the locus of regional growth, or perhaps alter the overall rate of regional demographic and economic change.

It seems likely that some of the postulated phenomena are more important than others, but, unfortunately, the literature does not provide much help in sorting out the first-order effects. Depending on the specifics of the pricing policy and the time period in question, impacts could be focused primarily on time of day, route choice, and mode choice, or could extend to the shape and size of the region. Moreover the same hierarchy of effects could be posited for other large or long-term changes in the transportation system, such as the cumulative effect of gradually increasing congestion over a long period.

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[71] The behavioral process is quite different for work and non-work trips. In the non-work case, people have the option to shift locations of discretionary activities. In the work case, people have fixed origins (residences) and destinations (places of employment) in the short run, but can change either or both in the long run. In effect, a work trip distribution model is an attempt to represent long-run residential and employment location behavior, given estimated numbers of dwellings and work places.

[72] Note that some elements of this spatial response would be covered in a conventional modeling framework by work trip distribution. Caution is required in order to avoid double-counting these effects.

Finally, structural features of the models need to reflect pricing impacts in accordance with theory. Key structural attributes of models involve linkages among elements of the behavioral hierarchy, and degrees of disaggregation among places, people, times, and facilities:

- model linkages and feedback - The models have implicit linkages which should be reflected in the results of a pricing analysis. Perhaps the most obvious is the presence of time and price at many levels of the model hierarchy. If time and price influence demand at many levels, and demand determines time and price (through assigned link volumes and estimated levels of congestion), then it becomes necessary to perform a recursive analysis that checks for consistency among the input and output assumptions. In rigorous terms, models should be run to "equilibrium", but since at present this often is computationally impractical, there must be at least a systematic effort to achieve consistency between predicted times and costs and those used in calculating the various elements of demand.

- disaggregation - In all transportation modeling there is a tradeoff between the detail required for accurate representation of supply and demand and the resource requirements of increasingly disaggregate analysis. For pricing studies, it is essential to have a detailed representation of the income and vehicle fleet distributions, and helpful to have as much specificity as possible about highway links (for micro-analysis of congestion pricing), analysis zones (e.g., for exact representation of parking prices and other land use-related measures), and times of day (for careful representation of time shift effects). In a given analysis setting, the trick is to find the highest level of aggregation that can support an evaluation of the "first-order" effects.

In short, full analysis of pricing strategies requires good data and sophisticated models.

TCMs and Land Use and Development Patterns

The transportation measures listed in the 1990 Amendments as potential TCMs range from major capital investments such as HOV lanes and transit improvements, to operations-oriented approaches such as traffic flow improvements and vehicle restricted areas, to minor capital projects such as pedestrian and bike facilities, to vehicle technology options. However, the Amendments note that TCMs are not limited to the Section 176 list. Consequently at least some metropolitan areas will consider additional measures, among them measures which use urban design and land use planning as opportunities to reduce vehicle dependence.

Land use approaches have been part of the dialogue about emissions control since the 1970 Clean Air Act Amendments. They often are dismissed as impractical because of the fragmented institutional setting of most land use decisions in the U.S., and because of the long implementation horizon. Yet recent debates about air quality and other aspects of the urban environment have made much of the linkage between low density land uses and high rates of per capita travel. Data from large cities worldwide show a consistent, strongly negative correlation between residential density and measures of metropolitan average per capita vehicular travel. (See, e.g., Kenworthy and Newman, 1990.) Environmental groups, in particular, infer from the data that infrastructure investments will worsen per capita emissions when they support development at the urban fringe (where the lowest density, highest travel consumption districts are found) and will improve per capita emissions when they create arrangements of land uses that require less vehicular travel (either by placing compatible uses in close proximity or by linking activity centers and residential areas through mass transit). While the studies on which these inferences are based have flaws and in any event may be reporting correlations rather than causal relationships, the heightened interest in the topic may put land use strategies on the TCM agenda in some metropolitan areas.

Statutory authority differs in each state and metropolitan area, and available land use control mechanisms also vary. In Minnesota and California, state law allows air districts to establish indirect source review (ISR) programs for oversight of land use and facility location decisions. ISR in these states presumably could be used to elicit design features beneficial to air quality, such as mixed uses at employment centers, high-quality pedestrian treatments, bicycle facilities, and direct links to transit lines. Alternatively, locally-originating policies and programs could have the same effect. Such cities as San Diego, Portland, OR, Seattle, and Boston have many of these policies already in place. In a few cases state planning acts or regional planning laws may provide yet another way for land use and transportation to be more closely coordinated, though to date few areas have taken strong land use policy stances in response to air quality concerns.

Whatever the implementation mechanism, the overall intent is similar. Urban design and land use approaches to transportation control are intended to moderate travel demand and influence mode choice by creating desirable urban development patterns in which lifestyles less dependent on the automobile can flourish. Specific strategies at the small scale include transit-oriented development; closer attention to street layouts and street widths and provision of sidewalks and bike facilities, to create improved environments for pedestrians and cyclists and greater ease of operation for transit and paratransit; restraint in the amounts of parking provided and location of parking to minimize conflicts with pedestrian flows; and site planning for a balance of housing, jobs, and services, to reduce trip lengths and permit trip linking. At the larger, community-wide or regional scale, the strategies include:

- Urban limit lines and urban development reserves.
- Mandatory consistency between local land use plans and local and regional transportation plans.
- Requirements for the provision of adequate public facilities concurrent with development, and/or attainment of minimum level-of-service standards.
- Minimum as well as maximum development densities and floor-area ratios to ensure adequate development for transit to work.
- Incentives and bonuses for desired land uses and for developments that provide desired transportation and land use amenities.
- Mandatory city, county, and regional balancing of job growth with housing development, priced and located to match the needs and incomes of the work force.

Advocates of these techniques believe they would produce both transportation and land use benefits, by encouraging the efficient use of land, reducing infrastructure costs, and creating supportive environments for the operation and use of transit, and reducing trip lengths so that walking and cycling are feasible.

Advantages to society overall are thought to include decreased requirements for travel, lower energy consumption, less air pollution; urban sprawl would be reduced, sparing valued agricultural lands and other open space. Costs also would accrue. In some cases, development would likely spill beyond the urban boundaries into unregulated, rural towns, or perhaps would shift to other metropolitan regions. Empirical evidence is accumulating, but remains too scattered and partial for effective use by policymakers; here is clearly an area for future research and evaluation.

Currently, few metropolitan area model systems are well equipped to investigate either the regional planning-level or the local-level transportation and land use policies. As noted in Section 4.3, only a few MPOs currently have formal land use allocation models, much less models of the regional economy which would allow them to explore the impacts on employment, population growth, land prices, etc. as a function of public policy interventions. This, too, has been identified as an area where research is needed.

Modeling capabilities for urban design options are mixed. Occasionally, urban design changes can be suitably represented in available models, e.g., strategies which would increase housing in the vicinity of transit stations could be modeled lowering access times to transit. However, since few urban areas model walk or bike trips, many other urban design-level transportation improvements (e.g., high quality walk access to shopping) would simply not be modeled, or would require off-model "adjustments" to vehicle trip rates. Similarly, land use policies such as purposeful mixing of retail and office uses typically would not be analyzed with regional models because suitable land use variables are absent.

Even when models including land use variables are available, they rarely are fine grained enough to do a credible job of evaluating such options as the effects of mixed use on trip making or the impact on auto use of good pedestrian linkages to shopping areas. Some areas do have models which can address these issues in approximate, heuristic ways (e.g., Montgomery Co., MD has a model which incorporates pedestrian and bike friendliness as a scalar variable). But the performance and replicability of such models have not been fully tested. Other areas have done special studies of the issues (e.g., the recent Portland, OR study of alternatives to the Western By-Pass, coordinated by 1000 Friends of Oregon, has included modeling of a variety of land use options), and the Federal Highway Administration is sponsoring a research project on urban design, demand management, and travel which should produce additional case examples over the next few years. However, the most common approach for analyzing land use planning and urban design strategies has been to extrapolate from existing examples. For example, a study for Central New Jersey's MSM Regional Council (Howard/Stein-Hudson Associates, et al., May 1991) applied findings from Hooper's study of trip generation in suburban activity centers (Hooper, K.G., et al., 1989) to adjust downward the estimated vehicle trip rates in mixed use developments, then estimated impacts. Such approaches amount to well-informed scenario testing, i.e., a particular level of travel shift or reduction due to land use planning is inferred from experiences in comparable situations, and the consequences of such shift or reduction is then analyzed.

Overall, then, capabilities of modeling of either regional or localized land use - transportation policies are quite limited, and more research is needed.

The impact of land use strategies on travel demand is only one of several concerns about land use-transportation interactions and their environmental consequences. For one thing, not all transportation control measures are thought to support compact development and pedestrian orientation. In particular, traffic flow improvements (including those created by HOV lanes which sort multi-occupant vehicles from SOVs during peak periods, and act as additional mixed flow lanes at other times) have come into question in some areas.[73] More generally, large scale transportation investments are seen by many as instruments for the shaping of metropolitan structure; for example, rail transit proponents express high hopes that major capital investments in a new round of rail projects could redirect urban growth patterns toward more compact, centered development, while highway proponents hope that major roads will stimulate economic development. The issue is whether transportation investments, large or small, alleviate pollution problems by reducing congestion and smoothing out flows (or, in the case of transit, shifting modes), or whether they ultimately lead to higher emissions by stimulating development patterns and changes in travel behavior that would offset any gains.

Theory says that transportation improvements (whether transit or highways) will tend, simultaneously, to increase employment at benefitted sites and to decentralize workers' housing. Conversely, worsening transportation services will favor decentralization of jobs but support higher densities of housing. Empirical studies find that transportation availability and quality are factors in location and development, but investments will do relatively little absent other critical factors including appropriate land, labor, and capital. Environmentalists sometimes argue that it is the shift in development potential that is of immediate concern, in particular if development is induced to relocate from high-density areas where many trips would be made by foot or transit to low-density areas heavily dependent on the auto. Scenario testing exercises and a few modeling efforts using real data have explored this issue sufficiently to report that such an effect could occur. But the magnitude of the effect remains unclear, and controversy continues over when and to what degree a highway improvement (or a rail transit line) will induce trips, shift modes, and alter destination choices. This is an area that is high priority for research.

While TCMs' impacts on land use and land use measures' potential as TCMs are likely to be at issue in a number of nonattainment areas relatively few areas will be able address the topic through detailed model-based analyses. A state-of-the-art model would have variables accounting for the effects of density and mix of use on travel behavior, but probably would not be able to address broader growth-related issues. In the absence of a state-of-the-art model, off-model estimates of land use effects will have to be developed and then integrated into the base model forecasts. In the longer run, research on this topic is much needed.

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[73] The 1990 Amendments themselves contain the stipulation that the Section 108 guidance documents are to address those traffic flow improvement programs "that achieve emissions reductions", with the implication that such programs would not necessarily reduce emissions.

TCM Implementation Analysis

Full analysis of a TCM cannot stop with the modeling of its expected transportation and emissions impacts. Implementation of a TCM requires:

- a full description of the measure and how it is intended to work
- a schedule for completing all steps of the analysis, for obtaining authority to proceed, for securing funding, and for implementing the measure
- identification of responsibility for planning, analyzing, programming, funding, and implementing the measure
- analysis of the TCM and quantification of its emissions impacts as well as assessment (quantitative or qualitative) of its other social, economic, and environmental costs and benefits
- assurances of legal authority to carry out assigned responsibilities on the part of each identified responsible party involved in implementation and/or identification of steps to be taken to obtain such authority and a schedule for completing such steps
- enforceable commitments of needed fiscal, personnel, and other resources on the part each identified responsible party involved in implementation and/or identification of steps to be taken to obtain such commitments and a schedule for completing such steps
- allocations of funds necessary to carry out each step of the planning and analysis and/or a schedule for obtaining such commitments in cases where funding is contingent on the results of an analysis, or on implementation of related TCMs or other projects
- a program for monitoring and feedback to assure the TCM is operating as intended or to identify problems and develop changes, as needed.

In many cases the analysis of legal, institutional, and related matters affecting implementation will lead to adjustments of the more technical analyses. For example, for certain TCMs legal authority to proceed may be lacking or uncertain, some parties may be unable or unwilling to proceed, and/or funding may not be readily available. Pricing and parking management strategies, vehicle fleet strategies, controls on idling and extreme cold starts, and employer-based trip reduction programs are among those for which the ability to implement is not always immediately available or complete. In such cases it is critical to develop a schedule for obtaining the authorizations and commitments needed for the TCM to proceed, in order to be able to take credit for estimated emissions reductions. Alternately, emissions reductions estimates may have to be scaled back to reflect partial implementation or delayed implementation. In addition, political aspects of implementation need to be recognized: Certain measures may be legally feasible but sufficiently unpopular that rigorous implementation is unlikely, and this may need to be taken into account by adjusting estimates of emissions reductions downward.

4.3.4 Conformity Assessment

Conformity provisions of the 1990 CAA Amendments are considerably more detailed and exacting than the provisions of the predecessor 1977 Amendments. Specific directives for making findings of conformity are now provided for plans, programs, and projects, and both federal agencies and MPOs are explicitly given responsibilities. Conformity is to be viewed in reference to the overall purpose of eliminating or reducing the severity and number of violations of the national ambient air quality standards (NAAQS) and attaining the standards as expeditiously as possible. Activities must not 1) cause new violations, 2) increase the severity or the number of violations, or 3) delay of attainment of standards or interim milestones. Furthermore, the most recent estimates of population, employment, travel and congestion levels must be used in assessing whether delays may occur.

Plans and programs can be found to be in conformance only if the emissions expected to result from their implementation are consistent with the estimates of emissions and reductions contained in the revised SIP, and the three findings listed above can be made. Note that the interim milestones provision brings the Reasonable Further Progress required emissions reductions into the conformity determination. Programs furthermore must provide for timely implementation of TCMs contained in the SIP, consistent with SIP schedules. Projects must either come from a conforming plan and program, and have been described in terms of design concept and scope in sufficient detail at the time of the conformity analysis for emissions to have been determined; or must be subjected to an analysis which shows that emissions together with those in conforming plans and programs will not cause an exceedance of emission reduction projections and schedules. Until such time as an acceptable SIP is available, conformity requires plans and programs to be consistent with most recent estimates of mobile source emissions, provide for expeditious TCM implementation, and contribute to annual emissions reductions; projects must come from a conforming plan and TIP and, in CO nonattainment areas, must eliminate or reduce the severity and number of CO violations in the area substantially affected by the project.

Conformity analyses are heavily model-dependent, as evidenced by experiences to date with conformity determinations in several metropolitan areas.[74] Although data and models varied, there was notable consistency in the results of the conformity analyses. Key findings are as follows:

- Anticipated transportation investments were not found to alter either travel patterns or emissions in a major way. Regional-level build/no build emissions differences were modest - generally on the order of one percent or less.
- The small differences are due, in part, to the modest overall changes being proposed in most TIPs, and in part to the offsetting effect of travel shifts induced by the transportation investments.

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[74] Interim guidelines on conformity were issued by EPA and DOT in June 1991. Final guidelines were still under review as at the time of this writing (October 1992). Metropolitan areas therefore are carrying out conformity analyses under the interim guidelines. In addition, since the SIP revisions required under the 1990 CAA Amendments have not yet been submitted and approved, metropolitan areas are operating under their previously adopted SIPs.

- Growth-inducing effects of transportation investments, and their consequences for travel and emissions, have been an issue in several urban areas. In general, where models have been run with and without equilibration through trip distribution (to capture effects of alternative levels of accessibility provided by transportation investments), the feedback effects were found to alter emissions estimates significantly within the narrow range of improvement discussed above. In a prototypical case, emissions benefits of the "build" scenario might be estimated at about 1 percent before equilibration but at only ½ percent after taking the travel shifts into account.
- A basic change in the emissions vs. speed relation or in the method of calculating emissions (e.g., to emphasize accelerations) might reverse the result in favor of the no-build alternative in some areas.
- Disaggregation of regional emissions analyses of TIN (which is done to prepare input to air quality models which calculate ambient concentrations of various pollutants) can reveal substantial variation in impacts at the subarea, corridor, or project level, with some areas or corridors showing emissions reductions and others showing increases. Since pollutant concentrations are affected not only by emissions but also by temperature, wind speed and direction, topography, and other factors, these subarea emissions changes do not necessarily indicate the direction of change in concentrations. Additional analyses beyond the basic aggregate emissions comparisons may be called for, however.

Thus, while the MPOs generally have been able to carry out acceptable conformity and TCM assessments, they recognize that a number of issues are likely to arise as those outside the traditional transportation planning community begin to look more closely at the inner workings of transportation models and at their results.

The costs of conformity analyses have varied widely. Some MPOs have needed to develop improved methods just to be able to produce an acceptable conformity analysis. They have reported costs of as much as $250,000 and time requirements of four person-months to complete the conformity analyses in the first year. In contrast, MPOs with ready-to-use models have reported costs on the order of $30,000 and one person-month or less. Because the higher estimates include costs of model updates and improvements that will be of more general application, it probably is not fair to attribute all of these costs to conformity requirements.[75]

Conformity assessments nevertheless will require a major effort for most MPOs. In the near term this involves build/no-build (action/no action) comparisons of the RTP and the TIP; over the longer run the conformity assessment will focus primarily on making sure that the TIP projects do not cause mobile source emissions to exceed levels assumed in the SIP. Project conformity raises an additional set of issues, especially in the interim period; the most complex requirement will be to show that the project, when taken as a whole, will reduce or eliminate the number and severity of violations of carbon monoxide standards in the area substantially affected by the project. (The "area substantially affected by

[75] Los Angeles reported conformity analysis time and dollar costs of several times the "high" amounts reported here, but their totals included particularly large amounts for network preparation and for repeated calibration runs, neither of which are ordinarily needed to support conformity findings.

the project" includes both the vicinity of the project in which receptors are located which could be affected by the carbon monoxide emissions coming from vehicles using the completed project, and other affected streets and arterials on which traffic could be expected to change significantly as a result of the project.)

In this section, analysis issues raised by RTP and TIP conformity assessments are briefly reviewed. The particular issues raised by project-level CO assessments are discussed in Section 4.4.

4.3.4.1 RTP Conformity

The basic goal of RTP conformity analyses is to determine whether a region's adopted long-range transportation plan is consistent with attainment and maintenance of national ambient air quality standards. In all cases the RTP conformity determination must be based on the latest planning assumptions and emissions models, and must show timely implementation of TCMs from the applicable SIP. In addition, the analysis must include all regionally significant transportation facilities and operations expected to be in place by the target years of the analysis (interim milestone years and attainment and horizon year(s).)

In the interim period before a SIP revision is available, the conformity determination must be based on a build-no build comparison, as well as on a comparison with 1990 emissions levels (since a contribution to annual emissions reductions is required). The build-no build comparison generally will require that projects be specified in more detail than has been the practice at the planning level in many areas, in order to be analyzed in a meaningful way. For example, the location of new facilities will have to be identified in sufficient detail for an accurate analysis of the impact on route choice to be carried out; the number of hours of operation and vehicle occupancy requirements for both new and existing HOV lanes will need to be specified in order to determine their effects on mode choice and on travel times on both HOV and other lanes. TCMs can be credited in the plan analysis, but only if implementation is assured. In addition, plans will have to be more grounded in fiscal reality than has been the practice (a requirement that ISTEA has imposed, in any case); projects which are not formally adopted or which lack funding sources which are reasonably expected to be available cannot be considered as part of the plan.

The no-build scenario is fashioned in a similar way, specifying the facilities and operations that will be in place whether or not the plan proceeds. Once the two scenarios are adequately specified, models can be run with each of them for the various analysis years and the emissions estimates can be compared (and also compared to 1990 emissions.)[76] Networks also may need to be coded to reflect expected

[76] Recognizing the wide variation in the level of detail currently provided by regional transportation plans, the interim conformity guidelines permit a qualitative analysis at the plan level. However, many MPOs will use modeling.

capacity improvements, and the models run for the specific milestone years of the analysis. If problems are identified plan revisions may be needed, e.g., delay of certain projects, acceleration of others, addition of TCMs, etc.

Once a SIP revision is approved, the test is whether the plan is consistent with timely attainment of the standards as well as with estimates of emissions and reductions, i.e., the emissions budget, assumed in the SIP. Analysis is done for the plan (i.e., the build scenario) for the various analysis years and emissions estimates are compared to the emission budget levels. Again, identified problems may necessitate revisions. Subsequent changes in the transportation plan (or in underlying assumptions) may occasion an updated plan analysis to determine conformity with SIP assumptions; similarly, a SIP revision which alters the transportation emissions budget will generally trigger a redetermination of conformity.

A number of specific assumptions will need to be made in applying regional travel modeling in either period. One area where there may be particular sensitivity concerns the assumptions made about population and employment growth rates, and land use patterns. As noted elsewhere in this report, most areas have treated these as exogenous inputs in their travel models. Increasingly, however, pressures are mounting for areas to explicitly model the impact of alternative transportation investments on urban growth and form. Nowhere is this pressure likely to be greater than for the long-range plan analysis, where the possibility of land use change is greatest. Large urban areas, fast-growing areas, and areas with particularly troublesome air pollution problems are most likely to face demands for formal land use modeling (at least reflecting impacts of transportation investments on trip distribution, and in many cases going as far as a fully integrated land use -transportation model system). However, other areas where land use policies are explicitly used to shape urban development and/or land use policies are politically controversial may need to develop land use modeling capabilities as well.

Developing capabilities to consider land use impacts will take time, whether the capabilities needed are merely feedback of travel time changes to the trip distribution step or more extensive feedbacks to trip generation, auto ownership, and location choices. Areas lacking these capabilities may find it appropriate to describe, as part of the build scenario, how land uses and activities are expected to change as a result of the transportation investments contemplated, and to estimate the anticipated impact of such changes.

4.3.4.2 TIP Conformity

TIPs, like RTPs, must be analyzed using the most recent planning assumptions and emissions models , and must show timely TCM implementation. TIN also are subject to a build-no build comparison in the interim period and a comparison to emission budgets after SIP revision. During the build-no build comparison phase, new ISTEA provisions calling for greater fiscal realism in plans and programs will also make a difference; past practices of showing extensive capital investments for which funding is unidentified will no longer be an option, for example. In at least some areas, this may well make future plans look less bright than they might have in the past.

As noted earlier, several MPOs that have conducted a thorough build-no build TIP analysis have found the difference in emissions (and other performance indicators) to be surprisingly small - on the order of one percent. The statistical significance of such small differences is often difficult to ascertain, especially in a complex multivariate, recursive model system. This in turn could create problems for an MPO able to show only a small improvement in the build scenario. For this reason, MPOs will want to move quickly to address the basic modeling issues raised in forums such as the MTC lawsuit,[77] and/or will need to move past the interim phase as quickly as possible.

In carrying out the TIP conformity analyses after a SIP revision is in place, emissions from all projects and activities in the TIP taken as a whole must be estimated for the analysis years (milestones, attainment) and compared to emissions budgets. Conformity requires emissions to be no more than the budgeted amounts.

[77] Citizens for a Better Environment et al. v. Peter B. Wilson et al., Civil No. 89-2044-TEH, and Sierra Club v. Metropolitan Transportation Commission, et al., Civil No. C-89-2064-TEH (consolidated.) MTC was ordered to devise a rigorous quantitative approach to assess the impacts of proposed highway investments. The plaintiffs' experts harshly criticized the conventional four-step modeling approach as inadequate to the task and not in keeping with accepted theory. MTC's response was to apply a modeling approach with detailed feedback effects explicitly represented in the model system, and this approach was accepted by the court. See Harvey and Deakin (1992) for a discussion of the case and its implications for analysis.

It should be noted that for ozone nonattainment areas classified as Moderate or higher, 1993 SIP revisions must include provisions for a 15 percent reduction in VOCs from 1990 levels, after accounting for growth; areas classified as Serious or higher must further show annual VOC reductions of at least 3 percent a year until the attainment date.[78] Hence, conformity with the SIP will require that such reductions are demonstrated. While both plans and programs must be consistent with the "necessary emissions reductions contained in the [SIP]", CAA Section 176(c)(2)(A), the TIP analysis is likely to be much more important to the required demonstration.

4.3.4.3 Project-Level Conformity

Projects which come from a conforming plan and program are subject to review only for CO (and PM10 in areas where that is an issue), since ozone is a regional problem and project-level ozone analysis is not meaningful.

Occasionally an MPO may wish to proceed with a project which does not appear in the conforming plan and/or program. In such cases an analysis must be done showing that emissions from the project would be consistent with the emissions budgets in the applicable SIP, after accounting for the TIP and plan projects. In general, this will require a model run or runs with the project added, as well as interpolation as needed for additional analysis years (e.g., milestones, attainment year(s)). In short, the addition of a project not in the RTP or TIP would almost always require a substantial amount of additional work.

CO analyses also must be done for project-level conformity. Because CO analyses are complex and may involve the MPO in carrying out or reviewing analyses of a type it has not traditionally dealt with, the issues involved are addressed in some detail the following section.

4.4 Project-Level CO Analysis

4.4.1 Basic Issues

[78] A reduction of less than 15 percent by 1996 can be approved by EPA only if the plan includes stringent new source review and RACT rules as required for Extreme areas, for "major sources" emitting 5 tons or more per year of VOC, and further includes all technologically feasible measures for each source category. See CAA Section 182(b)(1)(A). For areas classified as Serious or higher similar provisions apply to plans which show VOC reductions of less than 3 percent a year after 1996. Section 182(c)(2)(B).

Project-level CO analyses present several complicated issues for MPOs. Because of the localized nature of many CO violations, project-level analyses are sensitive to specific design and operations characteristics of the project, including not only size and location of the facility per se but also such details about the facility as vertical and horizontal alignments, ramp or intersection location, intersection controls including signal parameters, and operating speeds. In addition, CO concentrations are sensitive to meteorological conditions such as wind speed and direction, mixing height, and temperature. As a result, project-level CO analyses call for the application of special-purpose models which account for these specifics.

A basic question that often arises is how to define a project so that the CO analysis is meaningful and not misleading. In general, the project to be analyzed should be taken as a whole even if it is phased or divided up for funding purposes. In addition, projects which divert traffic either to or away from particular intersections or facilities appropriately call for an analysis of all significantly affected routes/facilities as part of the "project" analysis. In this way any potential for shifting a CO problem from one spot to another should be identified. Most analysis measures produce outputs for each segment or link of the project, facilitating location-specific assessment. Note that a change in operations or design could change the results of the CO analysis, given the CO models' sensitivity to these factors.[79]

In some instances it may be appropriate to group "projects" together in conducting localized CO analyses. Certain projects may best be analyzed as part of a corridor or area study. For example, a coordinated set of signal installations or other operations improvements along a major arterial would fall into this category. Even if the various improvements would make sense on their own accord and the proposal is to fund them separately, a corridor or area analysis may be more efficient to carry out and more meaningful, since it is hard to isolate project effects when a series of projects are interdependent and have cumulative impact.

Projects with intersecting or overlapping project areas or which are dependent on one another, e.g., timed transfer centers and transit priority treatments, also might best be analyzed together. Similarly, projects which would not be useful or needed except for other projects, e.g., park and ride lots, light rail crossing barriers, also might be analyzed together (or with due regard for their role enabling other projects or programs to proceed or function successfully.) Defining the "project" in this way would help internalize mitigation.

Certain projects are exempt from the conformity requirements under the interim guidelines. These projects include such items as planning efforts, safety projects, land acquisition, program administration,

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[79] Note that a significant change in the design concept or scope could trigger a new TIP analysis. For project-level CO analyses, more modest design and operations details may be important to the results.

and research programs and projects. Final guidelines may alter the project list and their treatment somewhat.

Exemptions for other projects, including some projects of the TCM variety, would probably not be permitted; however, such projects might be first subjected to a quick response (screening) analysis, with a detailed analysis only if a potential problem is identified. The screening process might ask a series of questions, with a “no” answer resulting in a conclusion that no further analysis is needed. For example, if auto use is not involved or is trivial, e.g., pedestrian projects, then no further analysis would be done; if the project involves auto use but does not increase the number of cold starts and reduces VMT, no further analysis would be needed, etc.

Some MPOs have developed procedures which call for an initial screening (review of potential impacts) of all projects, including those on the interim guidelines' exempt list. This approach was developed in response to a concern raised by some participants in the planning process, who worried that in some situations “exempt list” projects might create CO problems. The initial screening is seen as a simple, low cost way to either alleviate a concern or assure that analyses are carried out as needed.

4.4.2 Alternate Analysis Methods

At least six methods are in widespread use for modeling CO from transportation projects. They are CALINE4, CAL3QHC, TEXIN2, GIM, IMM, and VOL9MOB4. A number of other methods are available, however, and additional ones are reported to be under development (including FHWA and EPA sponsored software.) In addition, several studies of methods for project-level CO analysis are underway or planned, including a model evaluation being done for EPA and a major NCHRP study to be undertaken in FY '93.

In general, CO project-level methods are used in conjunction with traffic volume estimates produced separately. Traffic performance estimates may be produced by a separate modeling effort as well (e.g., applying HCM), though for some methods, e.g. CAL3QHC, TEXIN2, and CALINE4 this step is built into the software used to analyze CO. Usually this is simplified, e.g., CAL3QHC uses a reduced form of HCM and CALINE4 uses a modal emissions approach which omits certain factors which would be considered in an intersection traffic analysis. Similarly, emissions estimates may be separately produced by applying the appropriate version of MOBILE (in California, EMFAC) or may be built into the CO analysis method (the case for TEXIN and IMM).

Several of the models have borrowed extensively from the CALINE model, which was first developed by the California Department of Transportation in the early 1970s. Hence substantial similarities are found among the models. Differences are due to 1) the number and type of refinements added, such as ability to model street canyons; 2) the treatment of traffic performance in or out of the model and the level of detail with which traffic is modeled (e.g., whether approach lanes are fully represented, signal timing is considered, etc.); and 3) whether emissions analyses are integrated directly into the model, or separate runs with MOBILE or EMFAC are required.

The general approach is to assume Gaussian dispersion of pollutants, as adjusted by such factors as wind speed, wind direction/angle, stability, temperature, surface roughness, elevation, etc. This treatment is an abstraction (simplification) of a complex set of phenomena, but simplified though they may be, the models are quite data hungry. They require very specific project descriptions (centerline location, elevation, width/number of lanes, traffic controls, etc.), substantial traffic data (volumes, speed limits, signalization, etc.), and for some models, estimates of anticipated traffic performance (expected average speeds, acceleration and deceleration times, idle time, stops and delays, etc.) In addition, in order to use the emissions factor models (or model components) estimates of the vehicle fleet mix are needed. Hot/cold weighting, inspection/maintenance program parameters, and other inputs also are required.

Most models which have extensive requirements for input data and assumptions do provide default values to reduce the burden on the user. Generally, the defaults are worst-case assumptions (very low wind speeds, etc.) The level of analytical skills required to apply the models is largely a matter of whether default or other pre-specified assumptions and inputs are to be used, or whether the analyst will exercise discretion. The latter case calls for training or study in traffic engineering as well as air quality modeling (though such education and training are certainly helpful even if defaults are used.) Even well trained users report difficulties in applying some of the models, however, in part because documentation is not very extensive.

Most of the models now run on desktop or work station computers as well as on mainframes, so computer resources are not a major problem. However, some of the desktop versions are notably slow and some have reduced set of features (i.e., features were removed to enable quick transfer from the mainframe to the PC environment.) Also, for some of the models the programming is not particularly user-friendly (e.g., it is easy to lose input data files or to accidentally abort a run.)

Studies currently being done for EPA suggest that most of the models perform reasonably well under worst-case scenarios. CALINE4, CAL3QHC, and TEXIN2 appear to be the better of the available programs, based on statistical tests of model results vs. measured results. The preliminary reports suggest that CAL3QHC and TEXIN are somewhat more accurate than CALINE for isolated intersection analysis, though statistical differences are not large. However, direct comparisons among the models are not a straightforward matter because of the different ways traffic performance is handled. Differences probably stem from the traffic steps rather than the emissions calculations and dispersion analysis components, which are highly similar (all are based on the CALINE routine).

Overall, model results are highly sensitive to the project description and assumptions about conditions. Early results from the testing studies suggest that all of the available models tend to under-estimate emissions in comparison to field measurements when "actual conditions" data are used. This probably is due to the difficulty in measuring "actual conditions". For example, such items as wind speed and direction can and do change over a typical monitoring period: "actual conditions" modeling is in fact modeling "average" or "typical" conditions for the period. In addition, recent evidence suggests that estimated emissions rates from the vehicle fleet may not be highly accurate. Moreover, the vehicle fleet in use at a particular location is generally assumed to be the same as for the fleet for the region (or

state!); yet observation suggests that the mix of vehicles in use at any particular location can and often does differ from the average.
CO analyses underscore some of the difficulties that arise in transportation-air quality planning. Emissions modeling can never be more accurate than the data on which it is based, and CO analyses depend on transportation or traffic measurements and models which are widely understood by transportation professionals to be of varying accuracy. For example, traffic counts on major facilities are more likely to be available, and accurate, than on minor ones.

Emissions estimates prepared for future years reflect the uncertainties of the baseline transportation and emissions data, plus uncertainties stemming from the estimates of future conditions. Forecasts of future traffic volumes are dependent on a number of factors ranging from anticipated increases or decreases in vehicle use per capita and mode choices, to expectations for growth of the economy and population. Forecasts of future vehicle fleets and emissions depend on expectations for technological change, fleet turnover rates, and assumptions about the driving patterns (driving cycles) for which vehicles will be used, among other things.

Given these uncertainties it is important to exercise reasoned judgment in selecting and applying CO models. It is not reasonable to insist on higher accuracy in CO modeling than is feasible for the input data.

4.4.3 Particular Analysis Issues

A number of particular issues arise in CO analyses. They are reviewed briefly in this section.

Identifying Receptors in the Area Substantially Affected by a Project

A receptor location is the point at which pollutant concentrations are monitored or estimated. The general rule is to locate or analyze receptors at a reasonable sample of sites where people might realistically be exposed to high pollutant concentrations for a number of hours corresponding to the ambient standard in question. EPA guidance suggests that reasonable receptor sites would be residences, hospitals, rest homes, schools, playgrounds, and the entrances and air intakes to other buildings. On the other hand, while CO might build up in a tunnel no one would be exposed for very long inside it, and so it would not be an appropriate spot for a CO analysis.

For many projects a great many receptors could be identified in the general vicinity of the project. A strategy for carrying out the analysis would be to identify the receptor locations) likely to measure the highest ambient concentrations. In case of doubt about what the worst case receptor might be, the analyst would be well advised to examine all high-risk receptors. in general, receptors more than 300 meters from a facility are unlikely to be significantly impacted (though some experts have recommended a screening-level examination of all “sensitive receptors” - schools, nursing homes, convalescent homes, etc. - within 1 km.)

Analysts should look especially carefully at areas where pollution is likely to build up (e.g., street canyons; major intersections; other areas previously identified as over or near the standards).

The location of "future receptors" is an issue in modeling CO concentrations for future years. One concern is what to do about areas where receptor development is permitted under local land use plans and zoning, is anticipated as of the target year (i.e., is forecast to be in place by the regional land use model or assumed to be in place in future year land use input data), but is not yet approved. One view on this is that the project proponent must consider such development to be extant for the purposes of future year analyses. Another view is that the project sponsor need consider the same traffic assumptions as would result from the development, but would not be held responsible for future CO impacts (and mitigation) on such not-yet-approved future receptors. The latter approach would appear to be consistent with environmental impact analysis regulations, under which only developments already approved at the time of the sponsor's analysis must be considered "real". This would have the effect of shifting the burden of dealing with CO concerns to sponsors of future projects on the affected now-unbuilt parcels.

Estimating Current and Future Year Levels of CO

Analysts frequently have doubts about whether to use data from permanent monitors to estimate current levels of CO for a particular project area, or to collect new data specifically for the project area. In many urban areas, there is concern that permanent monitors are too few and far between to simply rely on the closest one (especially in cases where hills or valleys intervene.) In some areas data from permanent monitors have been supplemented by data from mobile monitoring, project-specific monitoring, and other special studies to form a more extensive data base than the permanent monitors alone would provide, and air agencies permit this data base to be used. In other areas, project-level monitoring is frequently done.

It is not a simple matter to collect good project-specific CO data. Because it is extremely difficult to "translate" data collected, say, during the summer to estimate winter month readings, it generally is necessary to carry out the data collection at the time of year when violations are most likely (winter). EPA generally asks for a minimum of four months of good data collected during winter months in order to be assured of the statistical validity of the monitoring findings. State and local agency requirements may differ; some California air districts, for example, seek at least one full year (and preferably two or three years) of monitoring data. Given the time and costs involved, it seems realistic to expect original data collection only for larger projects, and then only if available data are insufficient or problematic.

Once a current level of CO has been estimated, estimated CO levels for future years, with and without the project, must be produced. This is often a difficult step. The rollback method, which treats future concentrations as proportional to current ones in the same ratio as future emissions are to current emissions, is frequently used. However, there are known problems with the rollback method, which has been shown not to predict well. One limitation is that the rollback method treats meteorology as constant. (Other reasons for poor predictions may be that data underlying emissions estimates, including estimates of future VMT and emissions factors, have not been especially accurate.)

Air district staff could greatly assist in this step of the analysis process by 1) mapping areas in which data from each monitor could, in their view, be used appropriately; and/or 2) providing grid cell emissions estimates or isopleths of CO levels, as well as forecasts of future year levels for the no-build alternative.

Emissions Factors

CO models require use of a set of emissions factors for the vehicle fleet, both for current estimates of project emissions and for forecasting future impacts. For most models analysts also must make a number of adjustments to the vehicle fleet data to reflect project-specific conditions. In particular, the share of heavy duty trucks is a key assumption for CO analyses. In addition, the fleet may vary by time of day; the percent cold starts can be expected to vary as a function of project type; and corrections may need to be made to the emissions factors to account for altitude. Data on these matters usually must be collected for the project, although some states provide guidance on these choices.

Shifting CO Violations

A very difficult issue is what to do if the project shifts the location of a CO violation. One view has been that this situation should be treated as a “new” violation, which would prevent a positive conformity finding. An alternative view is to consider the net impact of the project, and apply a “no net increase” test. This would permit a conformity finding if the new location would be no more severe a violation than the eliminated one. A third option is to require a showing that the number of violations has been reduced (not increased) and/or the severity lessened, i.e., to show a net improvement in air quality, taking into consideration the overall objective of the CAA in reducing or eliminating the number and severity of violations. The issue was not resolved in the interim conformity guidelines and at the time of this writing this issue is still under debate among the drafters of the final conformity regulations.

Dispersion Modeling Assumptions

A large number of assumptions need to be made in running dispersion models, and it can require a significant effort to determine what are reasonable worst-case assumptions for each project. In general, however, the models are relatively insensitive to variables such as surface roughness and quite sensitive to wind speed, wind direction, stability class, and temperature.

It generally is recommended that worst-case assumptions be used for screening purposes. If a project is marginal or problematic using the worst-case assumptions, then the analyst would develop the data base for project-specific worst-case conditions and conduct further analyses.

Mitigation

Mitigation of project-specific CO violations may be difficult because of their localized nature. Nevertheless, mitigation may sometimes be a useful option, i.e., mitigation measures might be added to a project in order to reduce CO estimates to acceptable levels. (When mitigation elements are already present or expected due to SIP provisions or other planned actions, their effects should be accounted for in estimating the "baseline" emissions for the project area.)

What measures are appropriate as mitigation will depend in large part on the specifics of the project. Some areas are known to be prone to CO buildups, hence projects located in those areas are more likely to be problematic than projects located elsewhere. When projects are located in violation areas or areas prone to CO buildups, alignments that reduce the exposure of the population to CO should be sought whenever possible.

For some kinds of projects specific traffic mitigation measures are appropriate. For example, traffic flow improvements (intersection redesign, signal retiming, grade separation) could reduce or eliminate CO problems related to queuing. Restrictions on idling or use of clean vehicles might be considered if a CO problem arises with regard to a terminal, e.g., a bus timed transfer facility. Time of day restrictions might be suitable mitigations in some cases. Tougher ridesharing requirements for use of an HOV lane might be imposed in some circumstances.

Mitigation measures must be in addition to those already accounted for in the analysis "baseline." If mitigation measures are TCMs, it will be necessary to show that the effort is in addition to that already committed in the TCM or contingency portions of the SIP.

CHAPTER 5: LOOKING TO THE FUTURE

Improvements in modeling practice will be needed in the near term, and much can be accomplished by upgrading data bases and implementing available methods. Advances in software and hardware should greatly aid the effort. Such improvements will, however, require a commitment of staff resources and funding for data and analyses. In addition, applied research and development will be necessary to address remaining limitations and shortcomings of modeling practice, and basic questions should be raised about longer term research needs, the role of modeling, the possibilities for alternative paradigms, and the need for institutional change. All of these matters are discussed in this chapter.

5.1 Selecting a Strategy for Model Improvements

Currently, the quality of models in practical use varies significantly. In the short term, efforts might be directed toward bringing all metropolitan areas' models, and the data that support them, up to acceptable levels. Improvements should be selected and prioritized based on the current capabilities and most pressing needs in each area, which will vary depending on current and anticipated travel conditions, policy options of greatest concern, air quality attainment status, and resource availability.

As a starting point, each urban area should be encouraged to maintain a network-based travel forecast model system which incorporates key phenomena in a model structure that is in keeping with theoretical considerations and empirical evidence. Models should feed back travel times resulting from the traffic assignment step to the mode choice and trip distribution (and possibly, to the trip generation) steps, and should be run to an approximate equilibrium. Model systems which omit such feedback loops in most cases should be upgraded.

In addition, individual models should be upgraded, where necessary, to incorporate key variables that are widely agreed to be strong determinants of travel behavior and that are needed to analyze key policy options. For example, common shortcomings of models in current use include: (1) no trip generation variables beyond auto ownership and income (e.g., household composition: workers per household); (2) inadequate representation of trip attractions; (3) trip distribution models which omit transit and walking accessibility (needed in areas where transit and walk modes are important); (4) lack of peaking information on trips by type and market segment; (5) simplistic representation of socioeconomic variables affecting travel behavior; and (6) simplistic characterization and modeling of non-work travel.[80] Improvements to address these shortcomings would be in order.

Among the variables that some areas have omitted from their models, and should add as soon as possible, are: (1) household income (a key variable that should appear wherever cost appears); (2) parking charges and auto operating costs (without which analyses of parking pricing strategies, congestion pricing, toll roads, etc. can only be done off-line); and (3) the number of workers in the household (a key variable affecting ridesharing).

For many areas, better models of land use allocation or residential and employment location choice also would be appropriate. Here, one of the difficulties is the political sensitivity of land use forecasts. Local land use plans are rarely tempered by economic analyses of regional and intra-regional development competitiveness; regional land use forecasts may conflict with overall growth claims and/or with individual localities' hopes for a large share of the growth. Many areas instead use politically-negotiated land use forecasts which are assumed not to change regardless of infrastructure investments. Such practices may be politically pragmatic, but they are not necessarily theoretically or empirically defensible. Indeed, in some areas these practices are being challenged by outside groups who view them as ways to perpetuate the status quo in transportation investment (and land development) policy. Overall, land use modeling is likely to be a ticklish problem for many areas, requiring careful work with elected officials and interest groups as well as on the models themselves.

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[80] These shortcomings were identified by participants at the National Association of Regional Councils' November 1991 Conference on Modeling Practices, which was attended by about 100 modeling experts from regional, state, and federal agencies, universities, and the private sector.

Although it would be desirable for every urban area to quickly develop state-of-the-art modeling practices, the reality is that there will be wide variation in practices among areas at the start and undoubtedly for years to come, even if an aggressive program of improvements is undertaken.[81] Moreover, variation in practice is desirable, to match activities with context-specific needs. For example, as discussed in previous chapters, practice might differ with: (1) required transportation and Clean Air Act analysis activities, which vary with area size, pollution types, and pollution severity; (2) the magnitude and location of anticipated growth in the region; (3) travel characteristics (e.g., transit share); and (4) other related policy issues of importance to the community (e.g., location of employment growth, housing affordability).

Determination of what analysis practices are appropriate for an urban area might be done by agreement among interested parties. For example, before beginning transportation-air quality analyses, agencies might negotiate the analysis approach with EPA, DOT, and perhaps other concerned parties such as environmental groups. Agreements reached on the scope and complexity of travel forecasting to be achieved over a specific time frame would be documented in a strategic plan or a work program for improving data and analysis tools, including a reasonable, negotiated schedule for implementing improvements. The agreement might specify, for instance, that current practice is the best that can be achieved over the next six months, but within the next 18 months a specific set of improvements will be implemented, and over the longer term new data and models will be developed.

5.2 Data Needs

Models are only as good as the data on which they are based, and better data are urgently needed in most urban areas. Part of the model enhancement effort therefore must be to develop and maintain high quality databases.

Data on current land uses and land use regulations, as well as land market information, should be updated regularly. More specific and detailed data on economic and demographic characteristics and changes would be useful in preparing population and job forecasts. improved network representation would in turn improve travel forecasts and impact analyses; networks and their underlying data bases should represent all facilities down to arterials (and in many instances, major collectors). Travel surveys should be done perhaps once a decade, via household surveys of adequate size to support the detailed analyses contemplated. Data from special purpose studies or from a smaller panel could be used to track changes and provide interim updates.

[81] The state of the art also will change as research adds to the knowledge base, analysis techniques are improved, and advances are made in computer hardware and software. In addition, changes in vehicle technology and in transportation systems potentially could transform transportation-air quality planning and modeling. For example, alternate fuels and electric vehicles would drastically change emissions modeling. Intelligent vehicle highway systems (IVHS) could transform network specification, route choice, time of day of travel, and potentially many other factors. The introduction of sophisticated congestion pricing also could require advances in the state of the art of modeling.

Monitoring data will be particularly important in carrying out the growth tracking requirements of recent legislation. As discussed in earlier chapters, the 1990 CAA Amendments set forth a number of requirements for data and analyses to which MPOs will need to respond over the next few years. These include: (1) development of emissions inventories and forecasts; (2) VMT, speed, vehicle emissions, and congestion checks; (3) TCM analyses and implementation; and (4) determination of conformity of transportation plans, programs, and projects with the State implementation Plan for air quality.

Monitoring TCMs could be a relatively inexpensive, high payoff activity. Before-and-after studies, if carefully targeted and controlled, could provide valuable information on TCM effectiveness and could help improve analysis capabilities.

The monitoring and evaluation requirements of the CAA imply the availability of detailed and accurate information on both the highway network itself and network operation (link volumes, vehicle mixes, speeds by time of day, locations of high acceleration, locations of parked vehicles, trip start information). Many areas will need to update and enrich this information. Among other items, speed validation and congestion assessments should be done through a robust sample of floating car studies; VMT should be checked by comparing model outputs to traffic counts at a number of locations.

Currently, the accuracy required for VMT forecasts and comparisons to be meaningful for air quality planning purposes is not achieved in practice. The data base for monitoring VMT is inadequate in most areas, with counts off the Interstate system and in new growth areas particularly problematic. A monitoring program that provides a reliable time series of data collected in a consistent way is needed. The HPMS data base has been used for needs studies but in many urban areas it contains too few samples to accurately monitor VMT for the purposes called for under the CAA. Improvements to the HPMS data base, including more and better traffic counts, are being implemented and should be an important step toward better monitoring capabilities. Most urban areas will want to compare the findings of these counts with model outputs and other sources of information, if available, since large discrepancies could prove to be problematic.

As a second example, many areas have assumed speeds not exceeding legal speed limits (posted, or 55 mph on urban Interstates) even on off-peak networks; in most areas this would fail a “reality check”. (The impact on emissions estimates is uncertain; while high freeway speeds generally result in increased emissions, higher arterial speeds could reduce emissions estimates.)

In addition, many high growth areas significantly underestimated their population increases in the '70s and '80s. Such inaccuracies if repeated in the future would pose major problems for conformity findings and SIP attainment demonstrations.

Better data will take 2-3 years to collect, and even more time - as much as 5-10 years - will be needed where time series data or panel data are required. Also, data collection activities, and in particular surveys, are very expensive; the case for them will need to be clearly articulated.

5.3 Other MPO Resource Needs

In addition to good data, many MPOs will need additional funding and staff in order to carry out enlarged responsibilities for data collection, analysis and forecasting. In many areas this will mean overcoming some significant resource constraints, although the flexible funding for planning available through the Intermodal Surface Transportation Efficiency Act (ISTEA) may ease this problem.

One issue is that models are neither user friendly from a computer applications perspective nor simple from an analytical perspective. Because the computer skills needed to run transportation models are extensive, many areas have assigned these tasks to programmers and data processing staff, many of whom have had little training in transportation systems analysis. Consequently these staff are not well prepared to deal with questions and concerns about the theoretical and empirical validity of the models. Training for the computer staff to improve their understanding of the models they are running would be helpful, but should not be considered an adequate substitute for an expert modeling staff. Many MPOs may need to add staff positions to handle CAA (and ISTEA) analysis obligations, and to supplement staff with consultant contracts.

Another issue has to do with the need to "translate" models and analyses for non-expert decision-makers and reviewers. Models can be difficult to explain to elected officials whose decisions they are intended to support, but increasingly these officials want to know how reliable the model forecasts are and how they were developed. Environmental groups and community groups also seek a clear understanding of the models and their strengths and weaknesses. Providing this information will necessitate resources specifically for this purpose.

Lack of documentation and inadequate documentation could be a barrier. In past years documentation of data, models, and analyses often has been under-funded or has fallen by the wayside when deadlines are tight. However, lack of documentation makes it more difficult to repeat analyses or monitor trends, and may be a serious problem if analyses are challenged. Greater expenditures in this area could have an important payoff.

Several issues are likely to arise concerning documentation. First, documentation for some software is provided only to registered owners. However, other groups may wish to examine the software in detail. This could create difficulties for the agency, and possibly necessitate the preparation of extensive "model reviews" to explain the details of the programs to outsiders.

A related issue is that, in some cases, documentation is of the "how to run the model" variety rather than "how the models work". Someone may need to prepare a description of the latter.

Documentation and explanation of TCM analyses are particularly difficult when a variety of methods in addition to the regional modeling system are used to estimate impacts, then folded back into the overall analysis. Nevertheless, having a clear explanation of the analyses may prove to be key in building support for TCMs.

5.4 Hardware and Software Advances: An Opportunity

Hardware and software advances should speed up and lower the cost of many of the analysis steps, and at the same time should support far more sophisticated analyses than have been possible in the past. On the software and data base management side, for example, TIGER (Topologically Integrated Geographic Encoding and Referencing) files - digitized block boundaries or segments - are now available from the Census Bureau and permit block-level data (of whatever variety is coded, Census and other) to be aggregated to any zone system desired through the use of a GIS system. Some areas have already begun to use GIS to encode such additional information as tax parcel data, structures data, zoning, land use, slope and soils, environmental conditions, sidewalk and bike facility inventories, conditions of approval including traffic mitigation requirements, crime rates, and many other factors, in addition to the Census data on housing, trade, employment, and the like. These flexible, extensive, integrated data bases and data management tools would support advanced modeling, but only if the advantages of the advances are recognized and seized. (This may require R & D sponsored by federal agencies or consortia of MPOs

Computer hardware also has greatly increased modeling capabilities, with desktop models now superior to the mainframes of a decade ago and work station versions capable of running most models quickly and efficiently. Unfortunately, the programming of many in-use models and model frameworks does not always take full advantage of these advances, and hence loses some of the benefits of hardware gains. Re-programming may be an important option.

Hardware and software for data collection and analysis is a third area where significant strides have been made and more are expected in short order. Automatic data collection via roadside markers or roadbed counters, traffic signal detectors, speed sensors, and ticketing databases are but some of the available methods that have yet to be fully exploited in most areas. Computer-assisted telephone surveying combined with data-checking software is only beginning to be used by transportation agencies and deserves further refinement and application.

5.5 Research Priorities

5.5.1 Applied Research and Development

Significant improvements in practice could be accomplished through more widespread implementation of advanced methods that already are in use in some areas. However, more basic improvements will require applied research and development. Such R&D might be supported with federal funding or might be undertaken by MPOs with funds drawn from other (perhaps local or foundation) sources.

Possible R&D topics include the following:

- *Review and Enhancement of Location and Land Use Models*: Identify key variables and relationships which must be present in land use models, and their relative contribution to the quality of estimates. Assess the sensitivity of model results to variations in major input variables, as well as the relative accuracy of each model component. Evaluate whether simple land use models that are easy to apply and require low levels of input data (in contrast to available procedures that are highly complex and data intensive) perform acceptably. Examine how both local plans and economic base models might be integrated into a realistic land use forecasting process. Assess the leads and lags which occur in transportation-land use relationships, and how they might be taken into account. Explore how to handle growth distribution in areas where new construction is not the key or sole issue, i.e., where major changes are taking the form of change of use of existing buildings or shifts in the location of activity among existing buildings (the latter should include ways of assessing which buildings will fill up first in areas where office space supply will greatly exceed demand for some time.)

- *Zoning Controls and Urban Design*: Identify and rank small scale urban design options that could have important impacts on travel patterns, and improve methods for analyzing these measures. Assess the role of zoning controls in land use forecasts and in transportation policy implementation. Develop methods for analyzing such policies as zoning for higher density around transit stations, or the use of mixed-use, high- and medium- density zoning to create less auto-dependent communities.

- *Data*: Identify and evaluate data sources and surrogates which could reduce data costs for model development, forecasting, and monitoring. Assess ways to make better use of available data such as on-board transit surveys and traffic signal data bases. Assess panel data applications and evaluate whether the results justify the added expenses.

- *Network Models*: Develop better methods for estimating travel times as a function of network congestion, accounting for speed changes resulting from shifts in route choice, time of travel, and growth impacts. Evaluate methods for accounting for the impacts of traffic incidents (non-recurring congestion). Identify ways to achieve more detail and comprehensiveness in network specifications and/or roadway classification schemes, and to assure consistency between, or adjust for inconsistencies in, network specifications for periodic conformity determinations.

- *Socioeconomic and Lifestyle Issues*: Assess the importance as travel determinants of such variables as age, sex, race, ethnicity, occupation, and household structure. Assess the role of auto ownership as a variable in models, considering both the areas where the number of vehicles equals or exceeds the number of drivers and the experience of very dense areas (e.g., Manhattan) where the correlation between rising auto ownership and trip making is weak.

- *Trip Distribution Models*: Assess the reasons that K-factors historically have been so important in calibrating trip distribution models, and evaluate approaches that might improve model fit with less dependence on these factors. Assess the performance and tractability of formal nested models through destination choice (e.g., with the expected mode choice utilities forming the accessibility variables). Develop models which utilize the improved land use and employment data bases becoming available to planning agencies due to Census innovations and GIS advances.

- *Walk Mode*: Evaluate methods to represent walking as a travel mode and to model strategies that alter pedestrian facilities and amenities.

- Time-of-Day: Develop behavioral models of the choice of time of travel. Develop better information about travelers' travel time options and constraints.

- *TCM Effectiveness*: Assess the accuracy of methods which apply findings from other urban areas, sometimes from a very limited number of studies, to estimate the effectiveness of TCMs. Evaluate short-term vs. long-term TCM effectiveness through carefully targeted case studies.

- *Supplemental Analyses*: Assess the role that can be played by "extra model" analysis tools for TCMs, such as spreadsheet tools based on empirical evidence of effectiveness. This is especially an issue for commercially available analysis tools which have not been fully evaluated by a disinterested third party (other than clients and sponsors, e.g.), and for which detailed documentation is not available to the general public.

- *Vehicle Emissions Factors*: Develop more accurate vehicle emissions estimation techniques, particularly to account for speeds above 55 mph and to reflect actual driver behavior (frequent accelerations, etc.)

- *Software Improvements*: Develop improved software, including both a more supportive software environment for transportation - land use modeling and a more powerful "post-processor" for emissions calculations.

- *Model Precision and Accuracy*: Assess the current precision and accuracy of data and models, identify sources of uncertainty, and evaluate how these conditions may change in light of CAA and ISTEA requirements. Develop approaches which could improve precision and accuracy and reduce uncertainty, including both model improvements and strategic planning (contingency) approaches.

5.5.2 Basic Research Needs

In the longer run, research to provide a deeper understanding of the regional transportation land use system is needed. Here, the controversy over the impacts of infrastructure development will be used to illustrate the issues and lay the basis for observations of a more general nature.

As noted earlier, debate over the land development impacts of transportation investments, especially in highways, has re-emerged in a number of urban areas. One side argues that transportation investments are major growth shapers; the other side argues that transportation investments are of limited impact except in special, unusual circumstances. How might research cast more light on the issues?

Some have proposed a "quick fix" research strategy which attempts to measure the actual impacts of a sample of infrastructure improvements, through measurements of changes in traffic flow and similar aggregate measures of system use and/or case analyses of land use shifts. The problem is that the changes are broader than that, reflecting a web of interactions among mode choice, route choice, time of day of travel, destination choice, location choice, and overall growth of the region. Such complexity cannot be revealed by simple observation; more fundamental analysis of travel behavior and location decision-making is needed. Moreover, many of the phenomena at issue occur gradually over long periods, and thus become difficult to separate from other trends. Hence, case studies of new infrastructure outside the context of high-quality longitudinal data sets are unlikely to yield definitive results.

Several large metropolitan areas - notably the Bay Area and Seattle - have initiated and begun to use the data from panels, but their efforts have been hampered by funding problems. One reason that funds have been difficult to come by is that it is hard to show a clear, immediate payoff from the substantial investment needed. Ironically, then, research on the fundamental social and behavioral effects of infrastructure is stymied by the lack of data from carefully maintained long-term panels in a number of urban settings, and such panels are stymied in part because their results will be long in coming.

Research is also limited by the constraints of available models. Most operational models were developed under conditions of: 1) scarce computational resources, requiring the most parsimonious problem definitions possible; 2) a limited pool of professionals with the ability to reliably apply sophisticated models; and 3) a focus on a specific set of applications for which a particular set of simplifications seemed appropriate. Conditions have changed, the models have not, and in most cases the state-of-the-art does not satisfy the need for improvement.

Although much can be done to improve model performance within the conventional "four-step" paradigm, a more fundamental examination of the issues is in order. For some time the travel behavior research community has recognized a need to rethink the basic paradigm of travel demand analysis in light of three decades of advances in the cognitive sciences, in economics, and in computational capabilities. The emerging theory might be described as activity participation in the face of time and monetary constraints. The implications for modeling are substantial: for example, models might focus on activities, with travel consumption as a by-product. This creates pressure for research on virtually every element of travel behavior.

If an understanding of the urban activity system is the goal, researchers and research sponsors must acknowledge the inherent complexity of the problem, which could be compared with research on global warming or human cognition. Other disciplines facing inherently complex problems have developed a research style that emphasizes a detailed understanding of specific, isolatable phenomena, together with computer simulation of feedback and similar complex interactions. In these disciplines, alternate theories of system structure are tested by evaluating the performance of their respective simulation models.

Similar research styles will be needed in transportation to explore, develop, and implement analysis approaches reflecting fundamental changes in knowledge and method. Research sponsors and their user-clients will need to tolerate work that may not have any immediate applications - some of which will not prove out - if basic advances are to be made. The emphasis on pragmatic investigations producing quick answers to pressing issues is understandable, but it should not be the only kind of research. At least some funding should be directed toward a broader disciplinary scope and a more basic, deeper, set of questions for transportation research.

One issue is whether current institutions are capable of supporting activities which may challenge established beliefs and ways of doing things. Research sponsorship is one matter; put in broader terms, the issue may well be whether current institutions permit a search for improved mobility along many dimensions. Provisions of the ISTEA challenge urban areas to begin such a search. Some institutional arrangements and assignments of responsibility may be better suited to the task than others, and this too would be a valuable topic for investigation.

A decision-making paradigm that is more informed than simple "fair-share" distribution of public capital, yet is less dependent on deterministic "knowledge of the future" than current rational planning approaches, would be another area for attention. Modeling assumes an ability to forecast the future that may not be realistic or necessary. Scenario testing approaches suggest an alternate use of modeling as a means of exploring policy implications; it gives explicit recognition to the "if-then" character of the models, clarifies the assumptions on which they rest, and provides opportunities for the introduction of qualitative information into forecasts. Control theory suggests another direction: data from monitoring could be used to make adjustments in operation and to identify needed improvements, perhaps selecting from a set of responses previously agreed upon in contingency plans. A broader look at such options might uncover new directions for transportation planning, policy, and institutions.

In the debate over the development impacts of transportation, it may be the case that both sides are right. Within the limited domain of current land use regulations, current pricing practices, current technology, and current financial resources, many (or most) congestion-relieving highway investments may well improve system performance. But a different social optimum may exist when the current constraints are relaxed. (imagine the sort of "bubbly" functional surface one might expect of a non-linear, multivariate, mixed-behavior, time-dependent system.) Moreover, present levels of public expenditures on transportation are insignificant in comparison with the aggregate of private expenditures, and it may be unrealistic to expect the public sector to have a strong influence on patterns of mobility under such circumstances. But ways to exert broad influence over private decisions are well known and available for use, if the public will to do so is present. A wider consideration of options might identify new approaches and open up new opportunities for advancement.

5.6 Putting Modeling into Perspective

As the preceding section indicates, transportation and its interactions with land use and the environment are highly complex phenomena for which substantial additional research, both basic and applied, would be appropriate. Research into these matters should reveal ways to improve models and analyses and their utility in decision-making. Nevertheless, it must be kept in mind that models are tools; they need to be interpreted with care and not expected to "make decisions." Moreover expectations for models must be tempered by practical realities including time and cost considerations. Thus a few words of caution are in order here.

The review of current modeling practices and their strengths and weaknesses raises questions about the requirements for modeling promulgated by federal and state transportation agencies, especially as these requirements are combined with those implied in the Clean Air Act. For example, current transportation planning regulations vary planning and analysis requirements with population of the metropolitan area. More detailed and demanding requirements apply to the larger urban areas. From an air quality perspective, however, the size of the metropolitan area is not necessarily a good indicator of the severity of the pollution problem(s) or of the complexity of the issues faced in air quality (or transportation) planning. Thus, small and medium-sized metropolitan areas might need to develop better planning and analysis capabilities than otherwise would be expected, in order to respond to air quality planning needs - or to the transportation and land use challenges of the region.

There are concerns that the technical and financial capabilities to support extensive data collection, model development, and model application are largely lacking among the smaller metropolitan areas, whereas large urban areas have greater resources to carry out sophisticated monitoring and analysis efforts. Clearly, there are exceptions in both directions. For example, data and models may be relatively up-to-date and sound in the urban areas with recent experience in transit alternatives analysis, regardless of area size (although some would challenge this claim). Conversely, some of the larger urban areas have not paid attention to modeling for a number of years and their practices may actually have declined in quality and sophistication. Size, in short, may be only one indicator of modeling capacity, and a rough one at that.

Growth rates have not been considered as a factor in setting modeling requirements, but they may be an important indicator of needs. Very fast growth areas may need to develop sophisticated data collection, monitoring, and analysis capabilities, regardless of their pollution levels or urban size classification, in order to permit them to track changes in travel patterns, trip making, and VMT more accurately. Less complicated methods might suffice in slow growth areas, although even there, intra-regional shifts from city to suburb and from downtown to outlying commercial areas are often large and complex, and may well require sophisticated land use-transportation analysis capabilities.

Overall, despite the difficulties, it seems reasonable to recommend that urban areas large and small should be encouraged to improve their data bases and enhance their modeling capabilities, but common sense must be exercised in setting expectations. Smaller areas may not be able to afford locally-based research and extensive methodological innovation, but their travel demand models nevertheless should be good examples of the application of state-of the-practice models (i.e., trip generation, trip distribution, mode choice, and traffic assignment, with feedback through trip distribution.) Their land use forecasts should reflect key data on housing and employment trends and forecasts. Their network models should be checked against ground counts. Areas where fast growth is occurring or where air pollution problems are severe may need to enhance specific models to address those issues.

Where in-house resources are lacking, urban areas typically have turned to consultants for model development and calibration, with local staff taking over the applications in some cases and working with the consultants on applications in others. Developments in a few states suggest an alternate approach: cooperative agreements in which the state provides hardware, software, standardized model structure, and technical support; regional agencies and local governments provide data (sometimes, however, with state funding); and local universities provide training for staff and ongoing technical assistance. Florida and Texas provide examples of successful state-regional programs of this sort.

Transportation modeling regulations and needs are but one part of a broader set of issues concerning data and analysis requirements with which planning agencies must contend, however. A second set of issues stems from the transportation - air quality planning and analysis requirements set forth in the 1990 Clean Air Act Amendments. As discussed at some length in earlier chapters, this highly complex legislation sets different deadlines for attainment of national ambient air quality standards (NAAQS) depending on the pollutant (CO or ozone) and the severity of the violation, resulting in a patchwork of due dates and target analysis years both among metropolitan areas and, probably more seriously, within particular urban areas. Moreover, increasingly stringent requirements for planning, monitoring, and control apply to each classification. All ozone nonattainment areas except those classified Marginal must reduce VOCs (hydrocarbons) by at least 15 percent within six years. Although only those areas classified Severe or worse are required to identify and adopt TCMs, Serious non-attainment areas must adopt TCMs if emissions prove to be underestimated in the SIP, and even Moderate areas may need TCMs to meet the standards by the deadlines. The differing requirements match mandated actions to problems and reflect the greater difficulty of achieving the air standards in the more severely polluted areas, and hence are a pragmatic response; but they also create a much more complex and varied set of requirements than previously applied.

Conformity provisions also are significantly expanded in the 1990 Amendments, and require growth rates to be taken into account. Furthermore, changes in VMT must be monitored, reported, and taken into account in SIPs and transportation control plans. This may raise particular difficulties in fast growing areas.

Overall, the complexity and comprehensiveness of the requirements would appear to require extensive data collection, monitoring, and modeling.

From a modeling perspective, two issues arise. One is that the different clean air milestones and deadlines for attainment become target years for transportation planning and analysis, but these years do not necessarily coincide with available transportation data, forecasts, or planning horizons for the region. This has meant that analysts must extrapolate or interpolate their transportation forecasts. Since transportation plans and programs rarely are precise about the implementation year for particular projects and policies (and such precision, if imposed, would probably not be accurate, especially for actions to be implemented some years in the future), this step introduces numerous assumptions and approximations. The results are then treated as "givens", however, in calculating estimated emissions.

A second and perhaps larger issue concerns the requirements for emissions and air quality modeling and the way those models interface with transportation models. In particular, emissions and air quality models require as input hourly volumes by link, plus speed and fleet mix estimates. But transportation models produce much less specific output. Hence, post-processing of the transportation output must be done, and again rests upon numerous assumptions. Moreover many transportation models constrain freeway speeds to the legal limits (i.e., 55 MPH), and hence introduce inaccuracies with potential repercussions throughout the travel forecasts as well as in the emissions estimates.

Overall, the current precision and accuracy of data and models hardly seem to be in keeping with the expectations for them implicit in air quality planning and modeling requirements. While improvements in method could partly narrow the gap, a more fundamental assessment of the uses and limitations of transportation forecasts might be in order.

Despite these concerns, the possibilities for immense improvements are many. Today, there is reawakened interest in models and their performance, new mandates for analysis, legislative changes that open up important opportunities for institutional development, advances in a variety of disciplines which could be brought to bear on transportation problems, and funding to support both short-term and longer-term research and development. Both improved planning, modeling and analysis practices and a richer understanding of underlying phenomena should be the sought-after results.

APPENDIX A: GLOSSARY OF KEY TERMS AND ABBREVIATIONS

1990 Amendments - The 1990 Amendments to the Federal Clean Air Act.

AASHTO - American Association of State Highway and Transportation Officials.

ABAG - The Association of Bay Area Governments, a voluntary council of governments for the San Francisco Bay Area. ABAG carries out land use studies for the region and operates the region's land use allocation model, POLIS.

Accessibility - 1) An indication of the ease of reaching desired locations. Conceptually, accessibility is a function of some generalized price, which depends on standard measures of separation (time, cost), on modal characteristics which influence perception (such as comfort, speed, directness, consistency, degree of physical effort, and extent of waiting), on personal characteristics which influence perception (such as income, age, family status, work status, and physical condition), and on the quality of the desired activity at the destination location (e.g., the quantity and mix of retail stores, in the case of a shopping trip). Accessibility between two locations is sometimes measured as location-to-location time by a specific mode (usually highway), but also can be measured as cost or as a composite of time, cost, and other modal, personal, and locational attributes. The denominator of a logit mode choice model is a comprehensive accessibility measure for a specific trip. Accessibility of a location is a weighted composite of individual accessibilities for all suitable location pairs at that place. The denominator of a logit destination choice model or a gravity trip distribution model is a comprehensive accessibility measure for an origin location. 2) Suitability for use by a person who is "mobility limited" (see also mobility).

ADOT - Arizona Department of Transportation.

Aggregate Modeling - An approach to travel demand modeling that employs large population aggregates, defined in geographic, social, or economic terms, as the fundamental unit of analysis. In a typical application (such as the regional network-based travel models that rely on coarse-grained zone systems), the variation in key characteristics (such as income and household size) between population aggregates is less than the internal variation subsumed within population aggregates.

Algorithm - A step-by-step procedure for computing a solution to a mathematical problem. Solutions to some mathematical problems may be computed by applying any one of several alternative algorithms; the solutions will not necessarily be identical. For example, comparison of traffic assignments computed with different algorithms generally will reveal different numbers of vehicles assigned to a link.

All-or-nothing assignment - Allocation of the total number of trips between two zones to a single path, usually on the basis of the minimum travel time.

ALOGIT - A software package produced by The Hague Group for full information maximum likelihood (FIML) estimation of nested logit models.

Analysis of variance - Statistical technique used to investigate the components of variation in a multivariate sample.

ANOVA - see ANalysis Of VAriance.

Arterial - As used in this document, an arterial is a roadway that serves major traffic movements, and secondarily provides access to abutting land (precise definitions vary among localities and states). Arterials generally carry higher traffic volumes at higher speeds than collectors and local streets, but carry lower volumes at lower speeds than expressways, freeways, and other limited access and grade separated facilities. Arterials may be designated either principal (also called major) or minor, with principal arterials placing relatively more emphasis on service to through traffic, and carrying higher volumes, possibly at higher speeds. Principal arterials are frequently served by public transportation; minor arterials may also carry bus traffic. Regional highway networks for urban areas should include all arterials. (See also functional classification, collector, local street)

Auto ownership - In common modeling parlance, the number of passenger vehicles available to a household for routine daily travel. Because an individual's choice of transportation mode depends strongly on vehicle availability, average vehicle availabilities for households with similar income characteristics are considered a basic zonal descriptor. Note that the term “auto ownership” embodies a great deal of imprecision, since many vehicle types other than autos are used for urban personal travel and financial arrangements other than conventional ownership are increasingly common. Considering this, “vehicle availability” might be preferable to “auto ownership”.

AVO - Average vehicle occupancy. For a specific group of travelers, e.g., AM peak workers, AVO is the ratio of person trips to vehicle trips. It is often used as a criterion in judging the success of trip reduction programs.

AVR - Average vehicle ridership. see AVO.

BAAQMD - The Bay Area Air Quality Management District, the state-designated air agency for the San Francisco Bay Area.

BASIC - A programming language developed at Dartmouth in the early 1960s that has been the most common entry-level language for casual computer programmers. BASIC has the reputation of allowing a relatively sloppy programming style, but recent changes to the language (QuickBASIC, TrueBASIC, VisualBASIC) are capable of supporting a more formal and structured approach.

Biased - Not tending toward the true mean even with a large sample.
Block - A unit of spatial aggregation used by the U.S. Bureau of the Census in reporting decennial census data, corresponding roughly to its colloquial meaning.

Bottleneck - The point of minimum capacity along a highway segment.

Bounded Rationality - The proposition that rational behavior as typically postulated in economic models is limited, or bounded, because individuals consider only a restricted set of options and satisfy rather than optimize their choices.

BPR - The U.S. Bureau of Public Roads, now FHWA.

BPR Equation - A formula suggested by the BPR for calculating travel time as a function of volume on a highway link:

$$t = t_0 + \ddot{O}(V/C\ )_k$$

where:

t is the link travel time at volume V, usually expressed in minutes per mile
t_0 is the link travel time at zero volume
V is the volume on the link, usually expressed in vehicles per hour

C is the capacity at the most constricted point (bottleneck) on the link; note that actual volume might exceed this capacity for some period of time if an upstream portion of the link is available to accommodate a queue

à,k are parameters that determine the shape of the function

BPR suggested using k = 4 and à = .1 5t_0. Others have found that higher values of à and various values of k in the range 2.5ókó5.0 provide a better fit to real data under many circumstances. The need for a more accurate representation of travel time has led to experiments with different functional forms (see Small, 1992 for a concise overview of link performance functions).

Braess' Paradox - The fact that it is possible for the total cost of travel in a network to increase when a new link is added to the network or an existing link is significantly improved, under the condition that users minimize their perceived travel costs. Whether or not Braess' Paradox can occur in a particular network depends on network topology and on how the perceived link costs change as traffic volumes vary. It follows from Braess' Paradox that it also would be possible to decrease the total cost of travel on a network by increasing the travel cost on one link. While Braess' Paradox may seem counterintuitive, it follows from the simple fact that the total travel cost resulting from a user optimum in traffic flow sometimes can be reduced by forcing a few travelers to experience higher costs so that a larger group of travelers can experience lower costs (e.g., by metering a freeway on-ramp that causes a bottleneck on the main line).

C - A programming language in common use that provides both high-level constructs and extensive access to the elemental features of the hardware and the operating system.

C+ + - An enhancement of the C programming language that supports object-oriented programming.

Caltrans - California Department of Transportation.

Capacity restraint - A traffic assignment procedure that places trips on multiple origin-to-destination paths, taking into account the effects of congestion. A number of capacity restraint algorithms are available, most following the same general sequence of steps: compute an all-or-nothing assignment based on initial travel time estimates, compare the resulting link traffic volumes to link capacities, adjust link travel times based on the relationship of link volume to link capacity, and reassign trips to minimize travel time given the adjusted link travel times. The process is iterated in some fashion until an approximate equilibrium is reached.

CARB - The California Air Resources Board.

CART - Classification and regression tree analysis, a set of methods for analyzing hierarchical relationships in multivariate data.

Catalytic converter - A device which removes certain pollutants from vehicle exhaust through catalytic adsorption.

CATS - Chicago Area Transportation Study.

CBD - Central business district.

CBE - Citizens for a Better Environment, a San Francisco-based environmental group that sued Bay Area and California state agencies to force compliance with transportation provisions of the 1982 State Implementation Plan (SIP) for the region.

CCCTA - Central Contra Costa Transit Authority.

Choice set - the set of alternatives from which a consumer may choose.

CLF - The Conservation Law Foundation, a Boston-based environmental group with a strong focus on transportation in New England.

CMP - Congestion Management Plan.

CO - Carbon monoxide, a key air pollutant produced primarily by automobiles.

CO_2 Carbon dioxide.

Cold start - The starting of an engine which is significantly below normal operating temperature, of significance in understanding vehicle emissions because the rate and composition of emissions vary with engine temperature. Cold start mode, the period of operation to which cold start emissions rates apply, is defined by EPA for catalyst-equipped vehicles as the first 505 seconds after start of an engine which has been has been turned off for one hour or more (four hours for non-catalyst-equipped vehicles).

Collector - An urban street which provides access within neighborhoods, commercial and industrial districts, and which channels traffic from local streets to minor and major arterials. Collectors are typically low volume and low speed streets; however, they sometimes serve local bus traffic. Collectors meeting this definition are not usually explicitly represented in regional highway networks. (See also functional classification, arterial.)

Compensatory model - A choice model in which a consumer is assumed to trade off one variable for another (e.g., time vs. cost).

Conformity - In general, the agreement of transportation plans and programs with assumptions and commitments designed to attain federal and state air quality standards. Specifically, conformity to a SIP means conformity to the plan's purpose of eliminating or reducing the severity and number of violations of the national ambient air quality standards (NAAQS), and the avoidance of activities that might cause or contribute to a new violation of any standard, increase the frequency or severity of an existing violation, or delay timely attainment of any standard or interim milestone. In addition, transportation plans and programs can be found to conform only if: (1) emissions from such plans and programs are consistent with emissions projections and reductions assigned to those transportation plans and programs in the SIP, i.e., are consistent with the emissions budgets or targets; and (2) the plans and programs provide for timely implementation of SIP TCMs consistent with SIP schedules.[82]

Congestion - Interference of vehicles with one another as they travel, reducing speed and increasing travel time. Travel time on a link increases as an exponential function of the ratio of the number of cars on the link (volume) to the link's capacity. At low volumes, links are said to be uncongested, since vehicles do not interact much; as volumes approach capacity (defined as the maximum flow rate at the most constricted point on a link), congestion effects become increasingly apparent and travel time increases noticeably. The volume of entering vehicles may exceed the capacity of the link, in which case the excess vehicles form a queue within the link, link traversal times increase exponentially, and flow exits the link at capacity rates. (See also BPR function, capacity restraint)

Consistent estimator - In statistics, an estimator (such as the mean of a sample used to estimate the mean for a population) is said to be consistent if it converges on some specific value as the number of observations becomes very large. This value is correct only if the estimator also is unbiased.

Consumer price index - A measure of the price change for a package of goods specified by the Department of Commerce's Bureau of Economic Analysis. A variety of indices are published for the US as a whole and for numerous geographic subdivisions.

CPI - Consumer Price Index.

Cross-classification - A simple technique for exploring relationships among variables, sometimes called category analysis. Given a data set which includes observations on two or more variables of interest for each record, the range of each independent variable is established and subdivided into a small number of categories. A matrix is constructed, with each cell containing data for observations in that category. A typical application would be a cross-classification analysis of trip productions categorized by auto

[82] Conformity determinations differ in the interim period (until a SIP revision is approved) and thereafter. In the current, interim period, plans and programs must show expeditious implementation of TCMs and contributions to annual emissions reductions; projects must come from conforming plans and programs and, for projects in CO nonattainment areas, eliminate or reduce the severity and number of CO violations in their vicinity. Once SIP revisions are approved, conformity will be based on consistency with the area-wide transportation emissions budget for the area plus TCM implementation.

ownership and household size. The number contained in each cell of such a table would be the average trip productions per household. (See trip generation, regression.)

CTPS - The Central Transportation Planning Staff of the Massachusetts Executive Office of Transportation and Construction. CTPS performs the analytical functions of the MPO for metropolitan Boston.

Delay - The difference between the actual time spent traversing a link and the free-flow (unimpeded) time.

Destination - The zone in which any trip terminates (See also trip attraction).

Destination choice - Given that a trip will be made, the purpose of the trip, and the trip's origin (see trip generation), the destination choice process simulates an individual's choice of the location at which the activity associated with the trip's purpose will be carried out. Destination choice is believed to depend on characteristics of the individual (e.g. income, auto ownership), characteristics and locations of activities at which the trip's purpose can be accomplished, and characteristics of transportation modes connecting the origin to each candidate destination location. Some models use a series of purpose-specific logit models to perform destination choice (sometimes combining destination and mode choice for non-work trips), allowing characteristics of individuals and modes to weigh on destination decision. Other models perform destination choice using gravity models or intervening opportunity models, and generally do not consider characteristics of individuals and zone-to-zone accessibility in destination choice. (See also trip distribution)

Deterministic - Not stochastic.

Dispersion model - A model which estimates atmospheric concentrations of pollutants as a function of emissions rates and in some cases, emissions locations, meteorological factors, and rates of chemical reactions that may occur. Three common types of dispersion models have been used: 1) methods applying the continuity equation of physics to describe physical and chemical processes that govern emissions - concentration relationships, 2) methods using a probabilistic description of the motion of pollutant particles to derive estimates of concentrations, and 3) methods that use statistical relationships between emissions and concentrations to infer future relationships.

Direct demand model - An aggregate demand model that simultaneously predicts in a single equation all relevant travel choices.

Disaggregate models - In common usage, models developed to represent the behavior of individual decision-makers (persons, households, firms).

Discrete choice - A modeling approach depicting choice among readily definable and distinct alternatives.

Diurnal emissions - Vehicular emissions that occur on a daily cycle, and are not necessarily related to vehicle use (though usage patterns may affect diurnal emissions rates). As of this writing, diurnal emissions factors are available for evaporative hydrocarbon emissions only.

DOT - The United States Department of Transportation.

Doubly constrained - With reference to trip distribution models, a feature of the equation or of the estimation procedure which ensures that production and attraction totals by zone will be exactly replicated in the calculated trip matrix.

DRAM/EMPAL - Direct Residential Allocation Model and Employment Allocation, respectively; components of the integrated land use - transportation model system ITLUP.

DRCOG - The Denver Regional Council of Governments, MPO for the Denver Metropolitan Area.

Dynamometer - An apparatus for measuring mechanical force such as that produced by an engine, used in conducting tests of fuel consumption and emissions rates of vehicles. Dynamometers allow testing of vehicles under replicable and controllable conditions, but such tests often produce estimates of fuel consumption and emissions rates below those measured under field conditions, because it is not easy to replicate the complexity of actual driving patterns in an artificial environment. Dynamometer tests conducted under the standard Federal Test Procedure (FTP) are known not to faithfully simulate driving conditions involving accelerations associated with especially high emissions rates (so-called “off-cycle” accelerations).

EDF - The Environmental Defense Fund, a nationwide environmental group with a strong market-based perspective on air pollution problems.

Efficient estimator - An estimator that maximizes the use of information present in a sample.

Elasticity - In a causal relationship, the elasticity of i with respect to j is the percent change in variable i with respect to the percent change in variable j.
EMFAC - EMFAC is a computer-based mathematical model used to calculate motor vehicle emissions, for use in California. EMFAC7F is the version current in July 1993.

EMME/2 - A computer software package for transportation network and travel demand analysis.

EMPIRIC - A land use model.

EPA - The United States Environmental Protection Agency.

Equilibrium - Any complex system that has attained its highest entropy steady-state operating condition is said to be in equilibrium. The traffic assignment process has reached equilibrium when a change of route by any traveler would increase travel time, for the individual traveler if trips are assigned using the user-optimal decision rule, or the total time for all travelers if the system-optimal principle is used. Network equilibrium can be calculated directly using a programming method such as the Frank-Wolfe algorithm, or can be approximated by assigning increments of traffic based on path travel times and then feeding back the travel times resulting from one iteration as the input to the next. (See also feedback.)

ETC - Employee transportation coordinator. A person hired full- or part-time to oversee the implementation of vehicle trip reduction measures at an employment site.

ETTM - Electronic toll and traffic management. A term denoting automatic vehicle identification (AVI) and automatic debiting devices, and associated institutional and technical developments.

Expert system - A modeling approach that incorporates human judgment and expertise, both quantitative and qualitative, in a decision-oriented framework.

Feedback - Using the results of one step in the modeling process to recalculate a previous step. For example, the link volumes from traffic assignment can (and should) be used to recalculate first travel speeds and then trip distribution, since the first pass through trip distribution employs only an approximation of link speeds.

FHWA - The United States Department of Transportation, Federal Highway Administration.

FIFO - A queue discipline characterized by first in, first out service.

FORTRAN - FORmula TRANslation, a computer programming language designed for basic science and engineering applications.

Frank-Wolfe Algorithm - A method of quadratic programming that is used in calculating the exact user equilibrium in traffic assignment, by selecting link flows that minimize a function that is the sum of the integrals of the link cost functions.

Fratar method - A method used extrapolating trip distribution on the basis of growth factors for both the origin and the destination, named after its developer.

FREQ - Freeway Queuing model (A. D. May).

FTA - The United States Department of Transportation, Federal Transit Administration (formerly UMTA).

FTP - The Federal Test Procedure, a prescribed sequence of accelerations and decelerations used in certifying the emissions performance of new cars.

Functional classification - The classification of urban roadways by function. Roadways at the top of the hierarchy serve intercity and other long-distance movement of traffic, roadways at the bottom provide access to land. Traffic volumes and spacings typical of each level in the hierarchy are as in the table below. (See also arterial, collector.)

Facility	Spacing	ADT Design (miles)	Speed
Freeway	4	60,000 -160,000	>50
Arterial	1	10,000 - 30,000	30-50
Collector	1/4	2,000 - 5,000	25-30
Local St.	1/20	100 - 500	20-30

Gaussian plume model - A model using a modified Gaussian equation, along with a number of simplifying assumptions, to estimate the dispersion of a pollutant from a source, i.e., to predict pollutant concentrations. Gaussian plume models are used to estimate CO and NO_x concentrations.

Generalized price - A numerical expression capturing both the time costs and the dollar costs affecting travel behavior.

Gravity model - A trip distribution model which represents trip exchanges as a product of attractions and productions divided by an exponential function of travel costs (usually measured only by travel times).

Grid cell - The basic geographical unit of a regional photochemical dispersion model, analogous to zones in the regional transportation modeling process. Grid cell boundaries do not necessarily coincide with zone boundaries, however.

HBW - home-based work.

HCM - Highway Capacity Manual.

Hessian matrix - A matrix of second derivatives of a function, used in optimization search routines.

Home-based - Starting and/or ending at home.

Home-based work - a trip with one end at work and the other at home.
Home-interview survey - A survey seeking to determine the travel habits of a household, and characteristics of the household which are relevant to its travel behavior, such as auto ownership, number of occupants, income, etc. The survey usually consists of a questionnaire and a “travel diary” which asks each member of the household to record trips taken during the survey period (usually a day).

Hot-soak emissions - Emissions which occur after a hot engine is turned off.

Hot-spot - A location with higher-than-ambient levels of a pollutant. Hot spots may be attributed to such things as weather patterns, topography, and traffic intensity.

Hot-start - In vehicle emissions analysis, the opposite of a cold start. A hot start occurs when a vehicle's engine is started after less than an hour of rest from the previous period of operation (four hours for non-catalyst-equipped vehicles).

HOV - High-occupancy vehicle.

HPMS - Highway Performance Monitoring System, a federally-mandated database consisting of a representative sample of highway links.

IIA - Independence of Irrelevant Alternatives (q.v.)

Incremental assignment - a technique that loads a fixed increment of traffic onto the minimum paths, then recalculates minimum paths and assigns the next increment.

Independence of irrelevant alternatives - a property of logit models such that the ratio of probabilities between any two alternatives in unaffected by other alternatives.

Induced demand - demand alleged to result from added transportation capacity or reduced transportation price.

Input-output analysis - A method for analyzing the uses of capital and labor, the disposition of goods, and the flows money in an economy within a given spatial setting, and for obtaining a picture of the distribution of economic activity within a region and with respect to a system of regions, through a matrix of coefficients which relate inputs to outputs (essentially derived from a revenue expenditure accounting system.)

Intervening opportunities model - A trip distribution model that treats zones closer to the zone of origin as more probable destinations than ones at greater distance.

Interzonal - Between two different zones.

Intrazonal - Within a single zone.

Inventory - A catalog of existing conditions. Data from the inventory of such things as land use, roadway locations and geometrics, traffic volumes, composition of the fleet, transit routes and volumes, and measurements of pollutants are basic inputs to the transportation modeling process.

Inversion - A reversal of the normal atmospheric temperature gradient which restricts atmospheric mixing and limits the mixing height.

ISTEA - The Intermodal Surface Transportation Efficiency Act of 1991.

ITE - The Institute of Transportation Engineers. ITE publishes a manual of trip generation rates that is widely used for development impact studies and for calculating trip attractions in regional transportation models.

ITLUP - Integrated Transportation - Land Use Planning, a modeling package including an integrated land use allocation component (Putman, 1983.)

IVHS - Intelligent vehicle/highway systems.

K-factors - Adjustment factors applied to trip distribution models representing, in theory, social, economic, and geographic conditions that affect travel patterns but are not included in the model specification. In practice, K-factors are simply added to improve the fit of trip distribution models to observed data. Because their behavioral basis (if any) is not known, their long-term stability is in doubt and they attract much attention from critics of modeling. A logit approach to trip distribution, with heavy reliance on socioeconomic variables, can reduce the need for k-factors. However, at the current state of knowledge about travel behavior, no methodology can completely obviate the need for this type of adjustment.

Latent demand - Demand said to be suppressed by lack of capacity, high price, etc., which will materialize if such impediments are removed.

Level of service - In general, a set of metrics or qualitative descriptors of a transportation system's performance. Matrices of interzonal travel times and costs are sometimes called “level of service tables”; the Highway Capacity Manual (NCHRP, 1985) defines levels of service for intersection and highway operations, with ratings that range from A (best) to F (worst).

Lexicographic - Ordered in the manner of a dictionary, i.e., sorted according to a dominant criterion, then according to a secondary criterion, then according to a tertiary criterion, etc.

Life cycle characteristics - Social attributes of a household or person, such as age, marital status, and employment status, which define housing and mobility needs and preferences.

Linear regression - A type of regression analysis in which the functional relationship between two or more variables is described by a straight line, as opposed to a curve. Linear regression using the least squares method (defined at regression) is a procedure sometimes used to arrive at trip production and trip attraction rates as a functions of land use or household characteristics. (See also cross-classification analysis.)

Link - An element of a transportation network, a representation of a guideway segment, terminating in a node at either end. A link may have a number of attributes, including distance, number of lanes, capacity, and directionality, and is often assigned a function which relates travel time on the link to the volume of traffic using the link. (See capacity, congestion.) Some links implicitly represent several parallel guideways, and do not correspond to actual guideway segments.

Logit - A choice model formulation based on the principle that individuals maximize utility in choosing among available alternatives. The logit formulation involves specifying a utility function for each individual, with a deterministic component (that is, one which depends on characteristics of the individual and of the alternatives) and a stochastic disturbance (or error term). The form of the logit model, shown below, follows from the assumption that the error terms are independent and share the same probability distribution. This assumption under certain conditions may produce erroneous results, which can be overcome by using the nested logit or probit formulations.

$$P_n(i) = \frac{e^{V_{in}}}{\sum_{inC_n} e^{V_{in}}}$$

where:

$P_n(i)$ is the probability that individual n chooses alternative i,
e is the base of the natural logarithm,
V_{in} is the deterministic component of the utility mode i for individual n, and
$\Sigma_{inCn} e^{V}{}_{in}$ is the sum of the exponential term over all alternatives in individual n's choice set

Most transportation demand model systems use a logit formulation for mode choice; a few represent joint destination/mode choice and vehicle ownership using a logit or nested logit formulation. (See also multinomial logit)

Logsum - The natural log of the denominator of a logit function, sometimes used as a measure of accessibility when it comes from a mode choice model. The logsum is equal to the expected utility from the choice being modeled.

Longitudinal survey - A series of surveys or data that track a panel of respondents over time.

LOS - Level of Service.

Macroscopic model - a model that describes traffic flow in the aggregate.

Mainframe - a large, centralized computer, accessed through terminals. The four-step modeling process (and supporting software such as UTPS) was developed for a mainframe computing environment. These functions have since been incorporated in a variety of packages for use on workstations and personal computers, which now have more computing power than early mainframes did. Mainframe computers are still used for computations involving very large transportation networks, and for air quality modeling and for other problems which require vast storage or a vast number of computations.

Matrix - A multi-dimensional table of numbers.

MEPLAN - A land use model (M. Echinique & Partners, 1987.)

METRO - The Portland Metropolitan Service District, MPO and association of governments for the Portland, Oregon region.

Microscopic model - a model that describes traffic flow in terms of individual vehicles.

Microsimulation - a demand simulation focusing on the behavior of individuals and households.

Milestone - Under the 1990 Amendments, scheduled emission reduction requirements are termed "milestones". The first milestone is a 15 percent reduction from 1990 VOC levels, to be accomplished by 1996. Serious, severe, and extreme ozone non-attainment areas face additional milestones for every three years thereafter until attainment is demonstrated, and must show 3 percent annual average reductions in VOC levels unless specified actions are taken.

MinUTP - A workstation-based transportation demand modeling package.

Mixing height - The height above the ground over which pollutants can be mixed into the air and thereby diluted; mixing height is affected by atmospheric stability or turbulence and inversions.

Mobile 4.1 - The most recent previous edition of the EPA motor vehicle emissions factor computer program.

Mobile 5.0 - The current edition of the EPA motor vehicle emissions factor computer program.

Mobile source - A moving source of emissions, including but not limited to motor vehicles.

Mobility - Ease of locomotion, a function of available transportation and of the individual traveler. Individuals who are "mobility-limited" are those for whom it is difficult or impossible to use available transportation facilities without assistance or without modification of those facilities (e.g., individuals in wheelchairs, young children, many elderly), so that their zone-to-zone accessibility is decreased.

Mode choice - A process by which an individual selects a transportation mode for use on a trip or trip chain, given the trip's purpose, origin, and destination; characteristics of the individual; and characteristics of travel by the realistically-available modes. Mode choice is placed either before or after trip distribution in a conventional modeling sequence. Some model systems determine mode choice jointly with destination choice for some trip purposes. Multinomial logit is the formulation used for mode choice in the vast majority of cases. (See also logit, probit)

Mode split - The percentage, or share, of trips captured by the various transportation modes.

MPO - The Metropolitan Planning Organization designated by the state to carry out various federal urban transportation planning mandates.

MTC - The Metropolitan Transportation Commission, MPO for the nine-county San Francisco Bay Area.

MTCFCAST - The MTC travel demand forecasting system.

Multinomial logit - A logit model of choice among more than two alternatives. A logit model for choosing between two alternatives is “binary logit”.

Multinucleation - A process which results in urban areas having multiple major activity centers or business districts (nuclei).

Multiple inheritance - In object-oriented programming, the creation of an object which combines the attributes of two previously defined objects.

Multiple regression - Regression of a single dependent variable against two or more independent variables.

MV-Trips - A workstation-based transportation demand modeling package.

MWCOG - Metropolitan Washington (DC) Council of Governments.

NAAQS - A National Ambient Air Quality Standard.

NARC - The National Association of Regional Councils, a Washington-based voluntary association of MPOs and other regional planning organizations.

NCHRP - National Cooperative Highway Research Program.

Nested logit - Hierarchical application of the logit formulation. Nested logit is used for choices in which some alternatives are more similar than others (e.g., 2-person carpools and 3-person carpools appear to be more alike than either is to public transit). In these cases, the assumption of full independence in the utility error terms cannot be justified. Conceptually, nested logit analysis involves the grouping of similar alternatives into one or more “secondary” logit models, with a “primary” choice among the bundles of similar alternatives (as represented by the logsum of each secondary model, plus other relevant variables). There can be any number of levels and branches in a nested logit hierarchy, limited only by increasing complexity of the estimation procedure. It is possible to estimate nested logit models through methodical estimation of each standard logit model in the hierarchy (beginning with the lowest level of the hierarchy and proceeding upward). However, this approach has been found to introduce significant bias for some common specifications, and a more rigorous full information maximum likelihood (FIML) procedure is now recommended. Currently, the ALOGIT software produced by The

Hague Group is the only commercially available package for FIML estimation of nested logit models. (See also probit.)

NETSIM - Network Simulation, a microscopic traffic operations model.

Network - A mathematical representation of an area's transportation (or communication) facilities, composed of links and nodes.

NHB - Non-Home Based.

Node - A point where two links join in a network, usually representing a decision point for route choice but sometimes indicating only a change in some important link attribute.

Non-anthropogenic sources - Sources of air pollution not directly related to human activity, including certain flora, volcanic activity, etc.

Non-attainment area - An area that does not achieve one or more federal national ambient air quality standards.

Non-compensatory - A model in which variables affecting demand are not directly traded off.

Non-Home Based - A trip which neither begins nor ends at home.

Non-linear regression - A regression using functional forms that are not linear in their parameters.

NO_x - Oxides of nitrogen, a regulated pollutant and a smog precursor.

NRDC - Natural Resources Defense Council, an environmental group.

NYMTC - The New York Metropolitan Transportation Council, MPO for the New York State portion of the New York metropolitan area.

Object-oriented programming - A programming style which rigorously integrates data and actions which can be taken on those data into single components called objects.

Off-peak - Occurring during periods of relatively low traffic, not during a peak.

Origin - The location or zone at which a trip begins; the place where a trip is “produced”. (See also trip generation, trip production, trip distribution.)

Ozone - The 0_3 form of oxygen, a regulated pollutant and a key component of smog.

Panel - A sample from which repeated survey waves are collected.

Parallel Processing - A computer hardware configuration in which two or more processors (i.e., central processing units such as the Intel i486) are linked and operated with software that is capable of splitting computational tasks into sequences of instructions that execute simultaneously. Parallel processing offers great potential for efficiency in repetitive analytical tasks, such as the myriad computations in travel demand and network equilibrium analyses. It is probable that multi-processor desktop units will be common later in this decade, and will support a much higher level of computational intensiveness in transportation planning.

Path - A route through a network; a series of links and nodes connecting an origin and a destination.

Peak - Whether categorized by purpose or by geographic area, trips occur at different rates at different times of the day. A graph of trips by time of day typically reveals one or more peaks. These peaks play a key role in conventional travel demand analysis, which focuses on maximum infrastructure need in each corridor. The dominant weekday peaks are in the morning ("AM Peak") and the late afternoon ("PM Peak"), obviously related to the timing of work trips. A peak can be characterized by its maximum trip rate (in trips per unit time) or by a duration over which some threshold trip rate is maintained. The portions of the peak before and after the peak hour are called the "shoulders of the peak".

Peak hour - The hour during which the maximum traffic occurs. The peak hour during which traffic is highest varies from link to link and place to place, a fact which is not fully reflected in traditional travel demand analysis.

Peaking factor - The ratio of vehicle trips made in a peak period to vehicle trips in some given base period, usually a day.

Peak-hour factor - 1) The ratio of traffic volume in the peak period to ADT. 2) In critical movement analysis, a measure of peaking characteristics within the peak hour, usually calculated as the ratio of traffic volume in the peak hour to the traffic volume in the 15 minutes with the highest volume. Intervals shorter than 15 minutes are sometimes used, depending on the purpose of the analysis.

Peak Spreading - Lengthening of the peak period, usually accompanied by a flattening of the peak.

Performance - A general term for the "production" of service by or on an element of the transportation infrastructure. For example, highway link performance is measured in terms of speed or travel time, and a performance function for a highway link relates link speed to the volume of traffic on the link (see volume-delay function). Performance reflects service characteristics for a given physical configuration and operating plan; as such, it is intended to be a narrower concept than supply, which encompasses all of the decisions that influence physical and operating characteristics.

Person trip - The movement of a person from an origin to a destination, as opposed to the vehicle trip associated with the same origin-to-destination movement. A carpool carrying three people from origin-to-destination has made one vehicle trip, its occupants together have made three person trips.
Photochemical oxidants - Air pollutants commonly called smog.

PM10 - Particulate matter with a diameter of 10 microns or smaller.

POLIS - A land use forecasting model in use in the San Francisco Bay Area.

Probit - A choice formulation conceptually similar to logit, but theoretically preferable because it does not require the assumption of independence and identical distribution among the utility error terms. However, the theoretical advantage of probit has been offset in practice by much greater computational difficulty, with the result probit is seldom used. The computationally tractable nested logit formulation applies logit in a hierarchical structure to achieve results for practical purposes analogous to those of probit. (See also mode choice.)

PUMS - U.S. Bureau of the Census Public Use Master Sample. A fully-detailed 5 percent sample of decennial census responses, with home locations coded to large subregional districts.

Quadratic programming - An optimization method in which the objective function is quadratic and hence more easily solved, at least in principle, than a more general nonlinear formulation.

Recursion - Repetition of a step or sequence of steps until a specified condition is met.

Recursive - Involving recursion. A recursive computer algorithm is one which calls itself.

Regression - A mathematical technique for exploring relationships between sets of observations on two or more variables. A functional relationship between the variables is postulated, and a line or curve fit between the plotted observations so as to minimize some function (usually the square) of the deviations between the plotted points and the line or curve. The result is the equation of the best-fit line or curve describing the dependent variable in terms of the other variables, which is often used for predictive purposes; and measures of how goodness-of -fit. If the postulated relationship is a line, the technique is called linear regression.

Residential location - In the most widely employed paradigm of travel behavior, residential location refers to the household's choice of where to live. Residential location choice is thought to depend on proximity to work; on neighborhood, municipal, and sub-regional characteristics; on household and personal attributes; and on the spatial distribution of appropriately priced housing opportunities. There also is evidence that workplace choice and residential location choice vary in relative importance and in precedence, depending on job category and other household/personal attributes.

Revealed preference - A preference which is identified through analysis of actual choices and the conditions under which they were made.

RFP - Reasonable Further Progress. Annual incremental reductions in emissions as may reasonably be required for ensuring attainment of a national ambient air quality standard (NAAQS) by the applicable date.

Ridesharing - Providing multiple person trips per vehicle trip. Ridesharing modes include carpools, vanpools, taxis (sometimes), shuttles, jitneys, dial-a-ride, etc. Bus and rail transit, are technically forms of ridesharing although they are generally treated as a separate mode.

RISC - Reduced Instruction Set Computer. RISC chips are simpler and cost less per unit of computing power than conventional microprocessor chips, but require more complex software to replace the functions that are not hard-wired.

RMSE - Root Mean Square Error.

ROG - Reactive organic gases, a primary precursor of photochemical smog. ROG is sometimes called volatile organic compounds (VOC) or hydrocarbons (HC).

Rollback - A simple model which estimates the reduction in pollutant concentrations as proportional to the reduction in emissions. Since smog formation is a complex non-linear process, rollback analysis can be a poor guide to the effects of reductions in ROG and NOV

Route choice - The process of simulating the sequence of roadways an individual will choose for a trip, given the trip's origin and destination, and mode. Route choice is generally the task of the traffic assignment phase in the model sequence, and is based on the assumption that an individual will choose the route that will minimize travel time (or cost) for that trip. For mass transportation, route choice is usually straightforward for all but the largest systems, and does not require equilibrated traffic assignment procedures. (See also user-optimal, system-optimal.)

RTIP - Regional Transportation Improvement Program, a compilation of projects to improve a region's transportation system, designed to be implemented in the short-to-medium term.

RTP - Regional Transportation Plan, the long-range plan for investing in transportation facilities in a region.

Running emissions - Exhaust gases emitted by moving vehicles at normal operating temperatures, that is not in the cold-start or hot-soak modes.

SACOG - Sacramento Area Council of Governments.

Sample enumeration - A method of microsimulation based on calculations made for each individual observation which are later aggregated to represent the full sample or population.

Satisfice - Select a satisfactory, rather than necessarily globally-optimal, alternative.

SCAG - Southern California Association of Governments.

SCAQMD - South Coast Air Quality Management District.

SCLDF - The Sierra Club Legal Defense Fund, a national environmental litigation practice based in San Francisco. SCLDF sued Bay Area and State agencies to force compliance with transportation provisions of the 1982 regional non-attainment plan.

SEMCOG - Southeastern Michigan Council of Governments.

Shift-share analysis - A method of forecasting shares of economic activity (usually measures by employment) which uses information about competitive advantage and rates of change for each industry in each location.

SIP - A State Implementation Plan developed under the Federal Clean Air Act to improve air quality.

Sketch planning - Simple, approximate methods of analysis used to provide initial estimates of impact or to “screen” projects for which more detailed analysis would be worthwhile.

SOV - Single Occupant Vehicle.

Stated preference - A preference which is stated by the consumer when offered several hypothetical choices and a description of the conditions under which they would be made available.

Stationary source - A source of air pollution with a fixed location, such as a factory or a refinery.

STEP - Short-Range Transportation Evaluation Program.

Stochastic - Characterized by randomness; having a random component.

Strategic planning - A style of planning that assesses opportunities/strengths and constraints/weaknesses and identifies options for capitalizing on the opportunities and overcoming or minimizing the constraints.

Supply - The character of the transportation system that determines its operating performance.

System 2 - A proprietary transportation demand modeling system (developed by JHK & Associates).

System-optimal - A system-optimal traffic assignment is one which is computed based on minimizing the total travel time for all trips, as though a “system-manager” were to shift trips from one route to another based not only on the change in travel times for the trips shifted, but the change in travel times for other travelers on the affected links. At equilibrium, individual travelers might decrease their own travel times by changing routes, but their effects on other travelers would increase total travel time. (See also user-optimal.)

TAZ - Traffic Analysis Zone.

TCM - A Transportation Control Measure for emissions reduction.

TDM - Travel Demand Management.

Time budget - The amount of time an individual budgets for travel each day (or other relevant period of time). Time budget theory is theory of travel behavior rooted in the empirical observation that adults with similar incomes and life-cycle characteristics seem to average about the same amount of travel time per day under a wide range of infrastructure and land use conditions.

Time-of-day choice - In the most widely employed paradigm of travel behavior, time-of-day choice is the process by which an individual or traveling party decides when to make a trip. The term is a shorthand expression for the linked decisions about arrival time (when to begin the activity which follows a trip) and departure time (when to end the activity which precedes a trip). Time-of-day choice is not well understood, except in the case of workers whose employment conditions prescribe a specific beginning and end of the workday. In general, time-of-day choice depends on the nature of the activities which precede and follow a trip, on travel time variability in the relevant travel corridor, and on individual and household attributes (such as income and cost sensitivity).

TIP - The regional Transportation Improvement Program, a Federally-required MPO listing of pending highway and transit projects.

TON - Time of Day Factor.

TOPAZ - A land use model (Brotchie et al., 1981.)

Tour - See trip chaining.

Tract - A unit of spatial aggregation used by the U.S. Bureau of the Census in reporting decennial census data, consisting of groupings of contiguous blocks.

Traffic assignment - A process by which trips, or flows among zones, are allocated to feasible routes (paths) through a network. (See also capacity restraint, user-optimal and system-optimal.)

Tranplan - A software system for transportation modeling.

Transit - Urban mass transportation (usually, but not exclusively, provided by a public or quasi-public operating entity).

TRANSYT - a traffic operations model used to time systems of traffic signals and to assess traffic performance.

TRB - Transportation Research Board.

Tree logit - nested logit.
Trip attraction - The process of attracting trips to a zone. A trip terminating or originating in a zone whose existence is due to an activity carried out in the zone is said to be “attracted”. Trip attraction is generally a function of the land uses in a zone.

Trip chaining - The traveler's process of linking trips into tours. A trip chain, or tour is defined such that the destination of the first trip is the origin of the second, the destination of the second trip is the origin of the third, and so forth. For instance, a traveler who drives from home to work in the morning, then leaves work, picks up a child at day care, stops at a store, and goes home has created a home-based trip chain with four legs (individual trips). Traditional travel demand analysis, which defines trips as, e.g., home-based work, home-based shop, and nonhome-based, and which concentrates on peak hour travel, does not account well for trip chaining. (See also trip purpose.)

Trip distribution - The process of determining trip exchanges, that is, the number of trips between each pair of zones. Trip generation results - trip origins and destinations, or trip productions and attractions, depending on the methodology in use - are input to the trip distribution process, the outputs of which are trip tables (matrices) with each cell containing the number of trips between a pair of zones. The most common trip distribution analysis technique is the gravity model, although intervening opportunities and logit formulations are also common.

Trip frequency - The number of trips per unit time.

Trip generation - The process of determining the number of trip origins and destinations associated with a given set of activities in a given area, usually by applying trip rates (or a cross-classification or regression model) to an land use inventory or projection. In a regional travel demand study, trip generation is done at the zone level and requires detailed descriptions or projections of land use for each zone. For a traffic impact analysis, it is done at the project level and requires a tabulation of the square footage devoted to each activity the project accommodates. The outputs of trip generation analysis are one-dimensional arrays of origins and destinations for each zone which become the input of trip distribution analysis.

Trip length distribution - A graphical or tabular display of trip distances, sorted by distance category. Such a display shows, for example, the percent or number of trips (in a given area for a given time period) shorter than five miles, or longer than 10 miles, etc. Trip length distributions are used in calibrating trip distribution models. In the calibration process, analysts expect the trip length distribution calculated from the output of the distribution model to do a good job of replicating the observed trip length distribution. Significant differences will necessitate adjustments of the model's parameters and K-factors.

Trip production - The process of producing trips from a zone. A trip originating or terminating in a zone whose existence is due to the traveler's residence in the zone is said to be “produced” there (the terminology is less clear for nonhome-based trips). Trip production is generally a function of the residential land uses in a zone. (See also trip attraction, trip generation, trip purpose.)

Trip purpose - A classification of trips by their preceding and/or following activities (“purposes”). For computational reasons, conventional travel demand models typically employ a small number of trip purposes such as “home-work”, “home-shop”, “home-other”, and “non-home-based”. (A category such as “home-work” usually comprises both home-work and work-home trips.)

Trip rate - For a given type of land use or geographic area, the number of trips per unit time per unit size. The Institute of Transportation Engineers maintains a widely-used catalog of average trip rates for a large number of land use types. Trip rates are estimated via any of a number of techniques, including cross-classification, linear regression, and multiple regression. (See also trip generation, trip production, and trip attraction.)

Trip table - A table, or matrix, showing the number of trips made from every zone in a network to every other zone, in a given time period, and for a given trip purpose or set of purposes. Trip tables are the product of the trip distribution phase of the travel demand process. (See also grid cell, matrix.)

TRO - Trip reduction ordinance.

TRRL - Transportation Road Research Laboratory (UK).

UMTA - The United States Department of Transportation, Urban Mass Transportation Administration; renamed the Federal Transit Administration (FTA) in the Intermodal Surface Transportation Assistance Act of 1991 (ISTEA).

Unbiased - Tending toward the true mean.

User-optimal - A user-optimal traffic assignment is one which is computed based on the principle that an individual traveler will choose the route offering the lowest generalized price (often simplified to travel time) between a traveler's origin and destination. The resulting assignment is such that no traveler can save time by changing routes. (See also system-optimal.)

Utility - In transportation modeling, the value (positive or negative) of a particular option, usually estimated as a function of the travel option's characteristics as well as traveler or population characteristics.

UTPS - The Urban Transportation Planning System, a transportation modeling package developed in the 1970s by the U.S. Department of Transportation for use on mainframe computers. While UTPS continues in use by a number of large MPOs, it is no longer officially maintained.

Vehicle availability - The number of passenger vehicles available to a household for routine daily travel. Because an individual's choice of transportation mode depends strongly on vehicle availability, average vehicle availability, often by household income level, is considered a basic zonal descriptor. Research has shown that household vehicle holdings vary with income, household size, life-cycle factors, and accessibility by highway, transit, and walk modes.

Vehicle trip - An origin-to-destination journey by a single vehicle, as opposed to a person trip, the origin-to-destination journey of an occupant of the vehicle. A bus carrying 40 people from an origin to a destination makes one vehicle trip, while its occupants make a total of 40 person trips.

VMT - Vehicle-miles traveled.

VOC - Volatile organic compound. VOC emissions, also known as hydrocarbons (HC) or reactive organics (ROG), are major ingredients of smog.

Volume-delay function - A functional relation between the volume and the speed of travel on a facility. (See BPR function and performance.)

Workplace choice - The decisions of individual workers about where to work. Workplace choice is thought to depend on salary, on job availability, and on proximity to place of residence. (See also residential location.)

Workstation - A term in popular use generally referring to a self-contained desktop computing station with greater computational capacity and much greater graphics display and manipulation capability than a personal computer.

Zone - The basic geographical unit for conventional travel demand analysis. A study area is divided into zones, the number and size of which depend on the size and land use patterns of the area, the geometry of the roadway network, the nature of the problem, the computing resources available, census boundaries, and political boundaries. Zone boundaries are defined so that land uses and activities within are homogenous, to the extent practicable.

APPENDIX B: REFERENCES

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