NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Report 365

Travel Estimation Techniques for Urban Planning

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Staff
Transportation Research Board

This report updates *NCHRP Report 187,* "Quick-Response Urban Travel Estimation Techniques and Transferable Parameters." It provides a thorough review of the four-step travel demand process and transferable parameters that can be used in simple planning analyses. It will be particularly useful to planners in smaller urban areas that cannot afford to develop area-specific parameters.

In 1978, the Transportation Research Board published *NCHRP Report 187,* "Quick-Response Urban Travel Estimation Techniques and Transferable Parameters." That report described transferable parameters, factors, and manual techniques for a simple planning analysis. This report and its default data have been used widely, in one form or another, in many transportation studies. The report has been an invaluable travel-data source. However, the manual techniques have been largely supplanted by microcomputer planning models, and the parameters and factors are based on data from the 1960s and early 1970s.

Under NCHRP Project 8-29, Barton-Aschman Associates, Inc., updated the travel demand estimation techniques and parameters presented in *NCHRP Report 187* using more current travel survey procedures and data. To provide the most reliable information to practitioners, the Federal Highway Administration provided funds for a follow-on effort, NCHRP Project 8-29(2). In this project, Barton-Aschman Associates, Inc., collected additional data to validate the trip-generation rates and trip-distribution friction factors developed in the initial project.

In addition to a thorough review of the four-step travel demand process with common extensions, the report provides transferable parameters for use when area-specific data are not available or need to be checked for reasonableness. The material focuses primarily on the needs of smaller urban areas, but some material will be useful to other areas. In general, more complex procedures will be needed for large urban areas, growing medium-sized urban areas, and severe air quality nonattainment areas. Area-specific parameters will almost always be preferable to transferred parameters, though it may not be cost-effective to develop them for smaller urban areas. The techniques and parameters are organized to be easy to use in many of the widely available travel demand forecasting programs. A case study illustrates how the techniques and parameters can be applied in a typical study.

Those interested in looking more deeply into transferable parameters should visit the 1995 Nationwide Personal Transportation Survey World Wide Website at http://www-cta.ornl.gov/npts. This website allows anyone to develop parameters like those in this report based on the 1995 NPTS data.

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William A. Martin, Principal Associate and John R. Hamburg, Vice President, were the principal investigators. The other authors of this report are Nancy A. McGuckin, Senior Associate; Hugh Morris, Associate; Shawn Sabanayagam, Senior Associate; Thomas Harrington, Associate; and Matthew Lawor, Intern. Other personnel who contributed significantly to this report were David Kurth, Principal Associate; Richard Donnelly, Principal Associate; and Eric Bierce, Senior Associate.

Sincerest thanks are extended to all the agencies and individuals who contributed time and effort in responding to interviews and contributing local data for the parameters set forth in this report.

CHAPTER 1

INTRODUCTION

PURPOSE AND ORGANIZATION OF MANUAL

This report updates *NCHRP Report 187,* "Quick-Response Urban Travel Estimation Techniques and Transferable Parameters," published by the Transportation Research Board in 1978. Like that guide, this report is organized to follow the traditional travel-demand forecasting steps of trip generation, trip distribution, mode choice, and traffic assignment. Unlike the earlier report, this report does not give manual techniques for applying the travel procedures significant attention. The parameters presented are organized in a format that allows for application in many of the widely available travel-demand forecasting programs that run on microcomputers.

The report provides transferable parameters for use when area-specific data are not available or need to be checked for reasonableness. The material focuses primarily on the needs of smaller urban areas, but some material will be useful to other areas. In general, more complex procedures will be needed for large urban areas, growing medium-sized urban areas, and severe air quality nonattainment areas. Area-specific parameters will almost always be preferable to transferred parameters, though it may not be cost-effective to develop them for smaller urban areas.

In addition to the chapters devoted to the steps in travel-demand forecasting, a chapter is presented that identifies data requirements and sources of data for building the travel-demand database. The data requirements and data sources include both the transportation supply system (highway and transit networks) and socioeconomic data. The remaining chapters of this report are as follows:

- Chapter 2, Building a Transportation Database;
- Chapter 3, Trip Generation;
- Chapter 4, Trip Distribution;
- Chapter 5, External Travel Estimation;
- Chapter 6, Mode-Choice Analysis;
- Chapter 7, Automobile-Occupancy Characteristics;
- Chapter 8, Time-of-Day Characteristics;
- Chapter 9, Traffic Assignment Procedures;
- Chapter 10, Capacity Analysis;
- Chapter 11, Development Density/Highway Spacing Relationships; and
- Chapter 12, Case Study Application of Default Parameters.

TRAVEL-DEMAND FORECASTING: TRENDS AND ISSUES

The practice of travel-demand forecasting is roughly 35 years old. Travel-demand forecasting started in the United States with areawide transportation studies in Chicago and Detroit. Since then, the practice has progressed through various schools of thought, while the advent of the microcomputer has dramatically changed the environment in which such analyses are carried out.

The early impetus for the development of travel-demand models was to provide an objective tool for evaluating major infrastructure investments and preparing long-range, regional transportation plans. These travel forecasts were produced with mainframe software underwritten by the federal government. The shift from large, cumbersome computer models to quick, manual techniques was advocated by many professionals, especially for planning in smaller urban areas. The best-known approach for such quick-response techniques was embodied in *NCHRP Report 187.*

Perhaps the most significant development in the field of travel-demand forecasting has been the microcomputer revolution, which has brought desktop computer power to all transportation agencies. With few exceptions, these packages rival their mainframe and minicomputer counterparts in features, quality, and performance. Because of the wide extent of microcomputer applications in travel-demand forecasting, the focus of this manual is on travel parameters and their uses, rather than on packaged techniques for applying the models.

Just as the availability of travel-demand forecasting techniques has been dramatically increased by the microcomputer, the demands placed on the results of travel-demand forecasting also have increased significantly. No longer is the regional travel-demand model run every few years to update the regional transportation plan. Today, daily demands placed on travel-demand forecasting include

- Project-level studies requiring hourly volumes used in geometric design;
- Subarea traffic circulation studies requiring peak-hour (period) turning movements;
- Feasibility analysis of public transportation investments (e.g., sketch-planning ridership estimates of light rail, busway, and commuter rail systems);

procedure, the assumption is made that the traffic assignment is done by a travel demand package and that the default parameters required are the relationship of travel time to volume and capacity. Different functions are presented for different facility types, including freeways and multilane arterials. The corridor diversion and screenline smoothing techniques presented in *NCHRP Report 187* are presented in this report.

Capacity analysis is presented from two views—the analysis of intersection level of service and the development of link capacities that can be used as input to the building of the highway network in the modeling process. The revised 1985 *Highway Capacity Manual* was the source for the intersection procedures and the user is referred to that document as the primary source for applications.

A case study has been developed in order to illustrate the application of the parameters and techniques described in this report. The data included in this case study were provided by the State of North Carolina for the City of Asheville, North Carolina. The applications of the study parameters and techniques to this case study are presented at the conclusions of Chapters 1 through 9. This case study allows the user to follow the development and application of the travel forecasting model beginning with the data collection phase, where the highway networks and the socioeconomic data are presented. Subsequent chapters follow the model development through trip generation, where standardized trip generation rates are applied, and trip distribution, where standardized friction factors are applied. Ultimately, the final traffic assignment is presented, along with screenline comparisons of the existing traffic counts to the model results.

The final chapter of this report presents the case study in its entirety, from data collection through traffic assignment. As can be seen in this report, the results of this demonstration are quite reasonable when compared with the observed traffic volumes.

For trip generation analysis, two sets of parameters are presented. The first set represents vehicle trips generated by specific site activities. The data for these rates were extracted from the Institute of Traffic Engineers' *Trip Generation Manual,* 5th Edition. The second set of rates are typical for trip production and attraction models. These rates represent average daily person trips and were arrived at by using both the data from the recent National Personal Transportation Survey and several home interview surveys taken since 1985. An interesting finding in this study is that, although the trip rates are divided by urban areas with different populations, the variation between small and large urban areas was not as great as presented in the *NCHRP Report 187.* The rates are more closely grouped around an average of 9.0 daily person trips per household. Different rates are presented for the population ranges of 50,000 to 200,000; 200,000 to 500,000; 500,000 to 1,000,000; and greater than 1,000,000.

The trip distribution section presents the standard gravity model formulation. The report assumes that the user will be developing the zone-to-zone travel times from a network-based travel demand package and the default data required are the travel impedance friction factors. The friction factors are presented as both a gamma function and a lookup table. Presented in this section is a discussion of how the gravity model can be calibrated to match observed trip length distributions. Unlike the trip generation section, the default friction factors are not grouped by urban area size. The trip distribution within an urban area depends heavily on both the local highway (and transit network for areas with significant transit shares) network and the geographic location of the households and employment.

External travel estimation has been the least documented component of the travel demand models. A chapter has been included that presents a procedure for estimating through, internal-external, and external-internal trips for small urban areas. The research concluded that, although the procedure works adequately for small urban areas, it is not applicable for larger areas. Research into external travel revealed that very little has been done in the advancement of external travel estimation, yet for many areas, external travel is not easily transferable between urban areas—particularly through-trip estimation, which depends heavily on the urban area location (in relation to other urban areas) and size. It is recommended that local external travel data be collected to the extent possible and that further research is needed into the collection and estimation of external travel.

Mode choice is a step in the modeling process that has been largely ignored in small- to medium-sized urban areas. These sizes of areas have transit systems that carry a small percentage of total person trips and the data have not been collected from which a locally calibrated model can be derived. Advances in mode choice modeling have largely been tied to the analysis of major investments in fixed-guideway transit systems such as new light rail starts. The chapter on mode choice presents a discussion of the logit formulation of the mode choice model as well as a presentation of the incremental logit model structure that can be used for the analysis of transit and HOV alternatives in corridors and subareas. It is in these analysis areas that mode choice analysis using transferable parameters is most applicable.

Auto occupancy and time-of-day parameters are presented in separate chapters. The research resulted in a conclusion contradictory to the *NCHRP Report 187* assumption that auto occupancy would increase. During the last decade, auto occupancy has actually been declining. This is reflected in an average occupancy rate for home-based work trips of about 1.11 versus the *NCHRP Report 187* rate of about 1.35. The time-of-day factors can be used to construct trip tables for peak and off-peak periods. Also included in the time-of-day chapter is a discussion of procedures for converting production-attraction formatted tables to origin-destination tables.

The traffic assignment chapter presents refinements to the standard BPR formulation for travel times as a function of volume and capacity. As with the trip distribution

TRAVEL ESTIMATION TECHNIQUES FOR URBAN PLANNING

SUMMARY

This project was conducted in two phases. The first phase was to identify the critical travel estimation areas that would require updating or adding to the earlier *NCHRP Report 187.* The second phase was to collect the necessary data, update the travel estimation parameters and techniques, and prepare the revised report. During the first phase of this project a survey was conducted of the metropolitan planning organizations (MPOs) and state DOTs with the objective of identifying

- If and how *NCHRP Report 187* was used,
- What issues the transportation planners are facing that place added demands on the travel demand model, and
- Any travel surveys that the agency had conducted in recent years.

The survey found that the great majority of applications of the quick response techniques and parameters were for trip generation, either the site-specific vehicle rates or the general household-based trip production models. The mode choice procedures contained in *NCHRP Report 187* had never been used by almost 90 percent of the respondents and only 3 percent of the respondents are still using the model choice technique.

With the rapid growth in the capacity and deployment of microcomputers, the use of manual application techniques has been minimized. This report concentrates on travel parameters that can be applied in any of the available travel demand programs. The extensive, non-network-based, manual procedures (e.g., trip distribution and traffic assignment) contained in the earlier report are not included in this report. The travel parameters and techniques presented in this report follow the basic four-step process: trip generation, trip distribution, mode choice, and traffic assignment.

A chapter has been included that discusses the databases required to build a travel demand model. These include supply-side data (e.g., highway and transit networks) and demand-side data (e.g., zonal socioeconomic data on population and employment). A description of the data requirements is presented along with sources for building the database. Also in this chapter is a brief discussion of the use of geographic information systems (GIS) and the opportunities for using GIS in the building of the travel demand database and in model application. The survey of MPOs and state DOTs revealed that more than one-half of the agencies have GIS available.

- Evaluation of the impacts of transportation investments on development levels (that is, the iterative relationship of land use patterns and transportation systems);
- Air quality analysis for both regional conformity analysis and localized non-attainment areas (such as intersections in non-attainment for CO concentrations); and
- Analysis of travel reduction programs, travel demand management (TDM) strategies, and Congestion Management System plans (as required by the Intermodal Surface Transportation Efficiency Act [ISTEA] of 1991).

These and other analyses require more detailed results than the 24-hour volume estimates for major facilities traditionally associated with travel-demand forecasting. Factors that must now be considered in the travel-demand forecasting process include time-of-day analysis, peak-period spreading, automobile-occupancy rates, and feedback mechanisms for congested speeds and land-use changes. Unfortunately, few areas have current, locally generated travel behavior data. For these reasons, the parameters in this report give added attention to trip generation rates, treatment of external travel, time-of-day parameters, and automobile-occupancy rates.

AREAS OF DEVELOPMENT

At least two recent, significant developments have affected the travel modeling approach and process. First is the use of geographic information systems (GIS) in the forecasting process. GIS allows the user to digest and display data relevant to the task at hand. Before the modeling process, GIS may be used to

- Map a study area network to determine the level of roadway detail needed for the model,
- Batch out the designated network in a format accepted by the model,
- Map demographic data at census block/tract level,
- Convert census blocks/tracts to traffic analysis zones (TAZs), and
- Export TAZ structure to form a demarcation file for use in the model.

Post-forecasting uses for a GIS include display of model outputs, such as link volumes, and display of trip ends by TAZ.

The other significant development has been the changing urban form. Suburban sprawl has changed the travel direction from simply suburb to central business district (CBD) travel to suburb to suburb as well. This change has manifested itself in increases in automobile ownership as well as vehicle miles traveled (VMT). Trip generation rates, however, have remained relatively stable. It is not necessarily the number of trips that have changed, but rather the way those trips are made.

THE FOUR-STEP TRAVEL-DEMAND FORECASTING PROCESS

Travel-demand forecasting is often referred to as the "four-step" process. The steps are: trip generation, trip distribution, mode choice, and assignment. These are the four major model components of the travel-demand forecasting process. Other submodels that compose the complete model set are illustrated in Figure 1.

The purpose of trip generation estimation (Chapter 3) is to determine the number of person or vehicle trips to and from activities in an analysis area. Trip generation is functionally related to the use of land, which is described in terms of the character, intensity, and location of activities. Specific factors that influence the number of trips in a region include automobile ownership, income, household size, density and type of development, availability of public transportation, and the quality of the transportation system. The best trip-generation techniques use disaggregate socioeconomic data, such as households classified by vehicle ownership, family size, or income group. This step produces estimates of the trip productions and trip attractions for each zone in the analysis area.

Trip distribution (Chapter 4) links the trip productions to the trip attractions for each pair of zones in the analysis area. The critical factor in trip distribution is the ease of travel between the two zones being analyzed. This is influenced by the distance between the zones and the efficiency of the transportation system linking them.

Mode-choice analysis (Chapter 6) is the third step in the traditional four-step travel-demand forecasting process. Mode-choice modeling splits the total zone-to-zone person trips resulting from the trip-distribution model into trips using each available mode between the zone pair. Mode-choice modeling is also used to evaluate improvements in bus systems and analyze high-occupancy vehicle (HOV) strategies.

Several simple submodels can be used to refine the estimates from the first three steps on the basis of analysis needs. Auto-occupancy estimates (Chapter 7) are used to convert person trips to vehicle trips. Time-of-day modeling (Chapter 8) produces hourly estimates of travel. External travel estimation (Chapter 5) captures those trips that originate or end outside the analysis area.

The last of the major steps in the traditional four-step process is traffic assignment, both for highways and transit (Chapter 9). The assignment of trips to the network is the final output of the modeling process and becomes the basis for validating the model set's ability to replicate observed travel in the base year as well as to evaluate transportation improvements in future years.

The simple four-step modeling process has undergone some refinements in an effort to create a process that more accurately reflects the interdependency of its components. Specifically, the introduction of feedback loops in the modeling

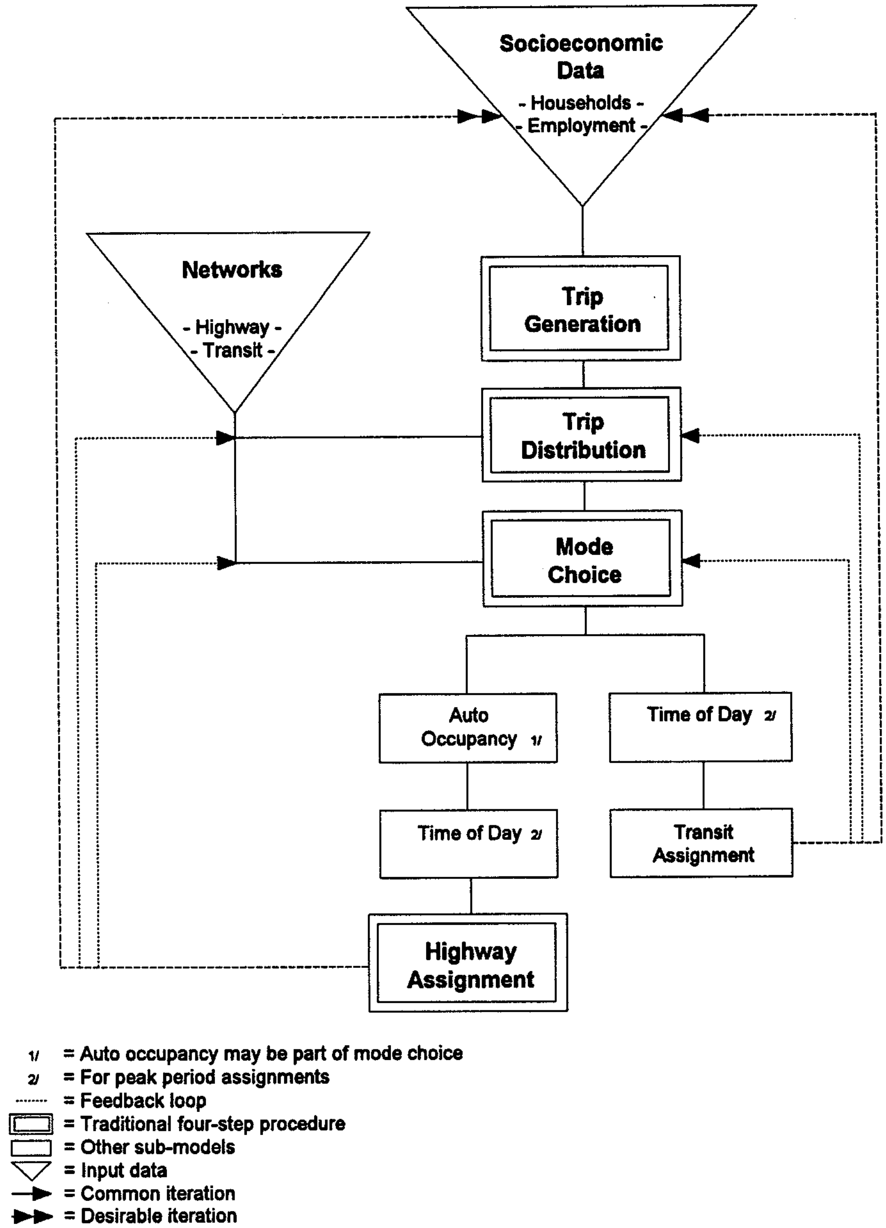


Figure 1. Travel-demand forecasting process.

process allows for dynamic interaction and adjustments to take place. Instead of simply stepping through the process, feedback loops allow interaction between virtually every step. For instance, the final step in the modeling process is traffic assignment. Congestion can affect a person's mode of travel, so a feedback loop of travel times is inserted into the mode-choice model that may predict that more people will take a transit mode. This loop can be repeated until the two steps reach a steady state. Likewise, travel times can affect trip distribution and the base socioeconomic makeup of the study area. Land use and household characteristics often reflect the condition of the transportation facilities that serve them. The model iteration process is described in the next section.

Model Iteration and Equilibrium

The components of travel-demand forecasting models are highly interrelated and require iterations back through the model chain to reach a stable or equilibrium state. The best example of the iterative nature of the models is the use of travel times in the trip-distribution model.

In the initial application of a model, interzonal travel times are not known until the highway and transit network impedances are calculated (skimmed). However, congested zone-to-zone travel times are not known until trip tables are assigned to the networks and a reasonable approximation of travel times that reflect traffic volumes is obtained. The accepted procedure is to make an initial estimate of zone-to-zone travel times (often taken as uncongested or free-flow travel times in the initial estimation of the trip tables) and then iterate the revised travel times produced after the trip tables are assigned to the networks. This procedure is repeated until there are few or no observed changes in the resultant trip tables. At this point the tables are considered to be in equilibrium with the travel times. A possible deficiency in the process is the assumption that actual trip ends (trip generation) do not change as travel times change.

In a paper, prepared for the National Association of Regional Councils by Harvey and Deakin[1], the lack of iteration of various travel-demand model components is identified as the most significant weakness in the application of traditional travel-demand models. The primary purpose of the paper was to evaluate the effects of improved travel-demand models on the estimation of environmental impacts of transportation systems, particularly on air quality evaluation.

There are several opportunities for iterations within the traditional travel-demand forecasting process. These fall into two groups: those that are commonly done today and those that are desirable and subject to further research.

Common iteration procedures are as follows:

- Congested highway travel times and costs resulting from traffic assignment iterated back into the trip-distribution and mode-choice models,
- Transit times (where transit is on the highway network) and costs iterated back into the mode-choice model, and
- Transit times and costs iterated back to the trip-distribution model in the case where travel times are a composite of highway and transit interzonal times and costs (composite impedance).

Desirable iteration procedures are as follows:

- Highway and transit interzonal travel times and costs iterated back to the zonal socioeconomic data—residential and employment location models,
- Automobile occupancy iterated back into time of day, and
- Highway and transit interzonal travel times and costs iterated back to the automobile-ownership models used to predict trip-generation rates.

Travel time linked to trip-generation and automobile-ownership models is the least understood. Residential and employment location models have been the subject of considerable research; however, the political realities of establishing regional forecasts of population and employment make the use of a model subordinate to regionally adopted forecasts.

This discussion of the evolution of travel-demand forecasting is presented with the intention that the transportation planner using the parameters contained in this report has some appreciation of the dynamic nature of travel-demand forecasting and understands that the process is as much a craft as it is a science.

SUMMARY OF TECHNIQUES AND PARAMETERS

As noted earlier, the parameters and techniques in this manual are presented in chapters that follow the traditional four-step travel-demand forecasting process. Supporting techniques (e.g., the treatment of external travel, time-of-day characteristics, and automobile-occupancy rates) are presented in the order in which they would typically be addressed in the process. For each chapter, an example of the application of the parameters and techniques accompanies a discussion of the basis for development of the parameters.

Trip Generation

Trip generation parameters are presented in two formats. The first format presents the vehicle-trip generation rates that are commonly used for site-impact analysis and for estimation of vehicle-trips from special generators. The source of these rates is the Institute of Transportation Engineers (ITE) *Trip Generation* report, 5th Edition (1991). Only a subset of the trip generation rates contained in the ITE manual are extracted for this report. The user should refer to the complete and most current manual for more detailed categories of vehicle-trip generation rates. These rates also include information on trip rates during peak periods of both the generator and the background traffic.

The second set of trip generation parameters is presented in the format of cross-classification trip production and attraction rates typically used in travel-demand models. These rates are daily person trips. As with *NCHRP Report 187,* trip purpose parameters are presented. The standard trip purposes used in this manual are: Home-Based-Work (HBW), Home-Based Non-Work or Home-Based Other (HBO), and Non-Home-Based (NHB).

Included in the trip generation chapter are the submodel parameters of automobile ownership and household income distributions. In addition to the trip generation parameters, balancing regional productions and attractions is discussed.

Trip Distribution

The trip distribution parameters presented are consistent with the standard gravity model input requirements. The

[1]Barton-Aschman Associates, Inc., *Development and Calibration of Travel-Demand Models for the New Orleans Area,* prepared for the Regional Planning Commission, Jefferson, Orleans, St. Bernard, ad St. Bernard Parishes, Louisiana (1981).

manual calculation techniques presented in *NCHRP Report 187* are not included in this report, since microcomputer-based procedures are assumed to be widely available. The new parameters may be used with the manual techniques when appropriate.

Average free-flow speeds for freeways, arterials, and collectors are presented for use in building travel times between zones. A more detailed discussion of speed, volume, and capacity relationships is included in the traffic assignment chapter. While highway travel time often is presented as the only method for measuring interzonal impedances, the inclusion of cost in the equation is becoming more widely accepted. Travel time factor (often referred to as friction factor) curves, look-up tables, and formulas are included.

External Trip Estimation

External trips are those trips that have at least one end outside a study area defined by an encircling cordon line. When both ends of a trip (origin and destination) are outside the cordon line, the trip is termed a through trip. The estimation of external travel requires a count of average daily traffic (ADT) at each of the highway crossings of the cordon line and classification of the ADT into percent automobiles and trucks. The technique first estimates the number of through trips. After these trips are removed from the total external trips, the remaining trips are distributed to the internal zones using a gravity model. The percent of through trips at external cordon stations has been found to be related to the functional classification of the roadway, the connectivity of each pair of external stations, the average daily volume at the station, the population of the study area, and the classification of vehicle at the external station. Procedures are included for estimating productions and attractions for internal zones before the distribution step.

Mode-Choice Analysis

The mode-choice procedure is based on the incremental application of a logit model. This is commonly referred to as the pivot point technique. A discussion of the application of various mode-choice model structures is presented, along with a discussion of HOV analysis and the estimation of travel changes resulting from TDM strategies.

Mode-choice modeling has been the most researched and advanced component of the travel-demand forecasting process in recent years. This has been largely driven by the analysis of major capital investments in mass transit, such as fixed-guideway systems. These include busways, HOV facilities, light rail, and heavy rail systems. The analysis of these systems requires the development of locally calibrated travel-demand models, a subject outside the scope of this manual. However, transferable parameters and techniques can be used to estimate marginal changes in HOV and transit demand resulting from level-of-service changes to existing systems. For medium and small urban area bus systems that wish to evaluate such changes, the techniques contained in this report are adequate. They are particularly appropriate for estimating changes in automobile demand resulting from HOV strategies.

Automobile-Occupancy Characteristics

Automobile-occupancy is usually a post-mode-choice process where average occupancy rates are applied for each trip purpose. In more complex model applications, occupancy may be incorporated into the mode-choice model. In either case, the result is the conversion of automobile person trips to vehicle trips. Automobile-occupancy rates are provided by urban area size, trip purpose, income, and facility type. Adjustments for occupancy by time of day and purpose also are presented.

Time-of-Day Characteristics

Time-of-day parameters allow the conversion of daily travel to hourly travel by direction. Two methodologies are presented for producing peak-hour traffic volumes:

- Post-assignment factoring of daily link volumes, using hourly and directional factors, and
- Post-distribution, preassignment factoring of trip tables by purpose to produce peak-hour, directional origin-destination trip tables.

This report outlines factors and procedures for both methods.

Traffic Assignment

The chapter on traffic assignment has three sections. The first section presents various traffic assignment techniques that can be applied within most travel-demand software packages. These techniques include "all or nothing" iterative capacity restraint, incremental capacity restraint, and equilibrium assignment. In addition to the assignment methodologies, the relationships of speed, volume, and capacity are discussed, and various equations and relationships are presented. These include the commonly used Bureau of Public Roads (BPR) formula and variations of the formula based on the 1985 *Highway Capacity Manual*. Also included is a discussion of incorporating intersection delay into the assignment process.

The second section presents a procedure for balancing or smoothing assigned traffic across a cutline or screenline. The third procedure is a sketch-planning process for estimating probable shifts in volumes between competing facilities in a corridor. This procedure is based on the stochastic assignment process but does not require the use of an origin-destination table. Rather, a diversion function is developed, based on known volumes and operating speeds. This function is used to estimate shifts between facilities based on improvements to one facility.

Capacity Analysis

Correct designation of link capacity is critical to producing a model that accurately reflects real-world situations. A link capacity regulates the volume of travel that can be carried over that link. Thus, for measuring current congestion levels as well as those forecast, it is necessary to reflect accurate capacities in the network database. Default link capacities are presented, as is the planning procedure for intersection capacity analysis.

Development Density/Highway Spacing Relationships

The basic purpose of including this manual technique is to permit the rapid development of a "first-cut" estimate of future highway needs, based on a desired level of highway service. Given a distribution within an area of land use, either in activities (people, households, jobs) or in acres by type of use, and given the presence of an existing highway system, future vehicle-trip ends are computed and adjusted for improved transit service. The average trip distance is then computed from counts or from trip-length frequency curves and adjusted for the future.

Average arterial volumes for a given spacing of freeways and arterials can be determined from the computation of vehicle miles of travel (VMT), and the level of service provided by each subarea can be computed. A comparison of the computed level of service with a desired level of service indicates a measure of highway needs for the study area. It is also possible to adjust land use inputs to revise the level of service or to compute the amount of additional land use that can be developed while still maintaining a given level of service.

Data Sources

Several sources of data were used to develop the trip generation, trip distribution, automobile occupancy, time of day, and other parameters in this volume. The primary data source was the 1990 *Nationwide Personal Transportation Survey* (NPTS). The NPTS is a periodic survey conducted to obtain travel behavior data from a large number of households (21,869). The project is sponsored by the U.S. Department of Transportation (US DOT), Federal Highway Administration (FHWA). More information on the NPTS can be found in US DOT report *FHWA-PL-92-007,* published December 1991.

The NPTS uses household interview techniques to collect data from each household over the telephone. The sample is drawn from listed and unlisted telephone numbers. Each sampled household is assigned a 24-hour travel day for which data on all travel by household members is collected. Each person older than 13 years is asked to report all trips taken during the designated travel day. The household members are interviewed within a 6-day period immediately following the travel day.

Data from travel surveys conducted in 11 cities around the country using home-interview techniques were also used. The trip rates derived from these surveys were used as a cross-check to the NPTS data. For more information on these data, see Appendix A.

CASE STUDY

A case study for the City of Asheville, North Carolina, has been developed in order to illustrate the application of the parameters and techniques described in this report. The application of the study parameters and techniques to this case study are presented throughout this report, at the conclusion of each chapter. This case study allows the user to follow the development and application of the travel forecasting model beginning with the data collection phase, where the highway networks and the socioeconomic data are presented. Subsequent chapters follow the model development through trip generation, where standardized trip generation rates are applied, and trip distribution, where standardized friction factors are applied. Ultimately, in Chapter 9, the final traffic assignment is presented, along with screenline comparisons of the existing traffic counts to the model results.

SUMMARY

Although the core of the modeling process has remained unchanged, many refinements to the process and technological advances have made the four-step traffic forecasting process a more intricate and comprehensive process. The computational power now available to virtually all planning departments is far superior to that in existence 20 years ago. The next chapter, Building a Transportation Database, describes some of the data sources available to the modeler and tells how to make use of them in modeling.

CHAPTER 2

BUILDING A TRANSPORTATION DATABASE

INTRODUCTION

The basic components of the forecasting model are the highway network, the transit network, and socioeconomic data. This chapter describes the network and socioeconomic data needed and some sources for such data but does not give significant detail on ways to build the needed databases. It reviews the types of information that will be necessary and the ways of obtaining it. The computer programs used to create the model will give the specific data formats needed.

NETWORK DATA[1]

Base Network

One of the most important aspects of travel-demand modeling is the method used to represent the transportation system. The estimation of travel demand requires an accurate representation of the transportation system serving the region. The most direct method is to develop an abstract model of the system elements. This is called a network. A network is developed for each travel mode (i.e., automobile and transit). The representation of the automobile system is called a highway network and includes those streets, roads, thoroughfares, and freeways that make up the regional highway system. The network is basically a map of these routes, defined in a manner that can be read, stored, and manipulated by standard transportation planning computer programs.

The highway network serves several purposes in transportation systems analysis. First, it is an inventory of the existing road system. It is an official record, for present and future years, of the physical status of the highway system. Second, the network is used in traffic modeling to estimate the highway travel impedance between zones in the region, which is the driving time and highway distance between different areas of the planning region. This information is critical in the trip-distribution and mode-choice portions of the analysis. Third, the roadway network is used to simulate automobile travel and estimate associated impacts, such as pollution, energy use, and accidents.

[1]Barton-Aschman Associates, Inc., *J.T. Dunkin Associates, Inc. Manual*, prepared for the Central Texas Council of Governments (October 1991).

Accurate transportation model calibration and validation requires that the transportation network represent the same time period (year) as the land-use data that will be used to estimate travel demand. For instance, if 1990 was specified as the base year to ensure consistency with the 1990 census data, roadway improvements completed after about April 1990 should be excluded from the base year network.

The process of translating the highway system into a digital format is called network coding. The various segments of the highway system are represented in transportation models using two basic data descriptors called *links* and *nodes*. Coding a network requires decisions regarding level of detail required, the type and amount of information to assemble, and the format and limitations of the link and node files in the software being used.

Source for Network Data

Selection and mapping of roadway links is the first major step in developing a network because links represent those facilities (highways, roads, and streets) that actually constitute the highway system. The two nodes that mark the end points define the link in the transportation network, and nodes are typically given x and y coordinates to permit the plotting of graphic displays. Nodes are locations in the highway system where vehicles are able to change direction (intersections, interchanges) or where level of service alters significantly (e.g., a road narrows from four lanes to two lanes). Base data for mapping the roadway network can be compiled from either census or commercially digitized map files or can be digitized from a good scaled map of the planning region.

Digitized Map Files

The Census Bureau compiles digital data for all 1990 census map features (such as roads, railroads, and rivers) and the associated collection geography (such as census tracts and blocks), political areas (such as cities and townships), and, within metropolitan areas, address ranges and zip codes for streets. Users can order a single-county file, a group of county files that make up a Metropolitan Statistical Area (MSA), or all files for a state.

If a highway network has not been prepared for a planning region, and an application software (GIS) is available, the basic data record (record type 1) of the Topologically Integrated Geographic Encoding and Referencing database (TIGER)/line can be used to create a roadway network. Each segment of the basic data record contains the geographic area code, latitude and longitude coordinates for all line segments, the name of the feature (such as highway name), and a class code (functional class). The geographic and cartographic data of a TIGER/line file can be combined with other statistical information (such as population, housing, or income) for planning purposes.

The census TIGER files are a comprehensive source of data. They can be used to produce area maps, such as census blocks or county boundaries, as well as a street system network. The TIGER files are available on CD-ROM from the Census Bureau, and most disks contain the data for two or three states, while some of the larger states are split onto two disks. The amount of detail available in these databases is more than is necessary to build the model network. Consequently, the user must take care to filter out unwanted detail, such as local streets. Even arterials and highways are described in significant detail in these databases. Great care was taken in their construction to create links that accurately reflect the true shape of the highway feature. The number of shape points used for this purpose, while useful in creating maps in GIS, is too much data for the models. Commercial digitized map files are also available from many vendors. The quality of census TIGER files may not be adequate for some study area's needs, and commercial vendors can be used as a source of digital maps.

With the use of GIS, many commercially produced networks are now available. Many of these are simply enhanced TIGER files, which save the user the time and effort of editing census TIGER files.

Scaled Maps

The base data to construct a computerized highway network file (location of links and nodes) can be digitized from scaled maps. That is, each facility selected for use in the network can be copied from the base map into digital form with an application software and a digitizer tablet. The digital input is scaled to either the latitude and longitude or a user-defined x, y coordinate system. There should be no dead-end links in the system. The links should be mapped with a node at every intersection and at each location where the number of lanes changes.

Figure 2 shows an example of a node and link plot with a zone centroid and connectors. Links connecting a centroid to the network (called centroid connectors) should be made roughly midlink, as shown. Care should be taken to suppress "backchannel" traffic on centroid links, although most modeling packages allow centroid control of this.

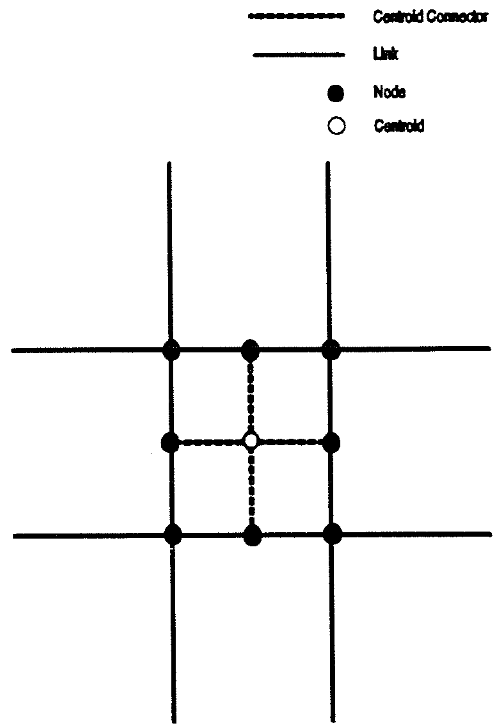


Figure 2. Example of network node and link plot with centroid connectors.

Network Coverage

The process used to select the links that will be included in the coded highway network requires the official functional classification of the roadways within the region, the average traffic volumes, street capacities, and a general knowledge of the area. Generally, all streets that carry a substantial volume of traffic should be included. The magnitude of volume considered to be substantial will vary by the population size of the area to be modeled, but it is reasonable to expect that all arterial streets and some collector streets will need to be represented. Local residential streets do not need to be included in the network, because they will be simulated using direct connections between traffic zone centroid nodes and the arterial street system via centroid connectors.

The kind of analysis for which the network will be used determines the level of detail required. For example, if a regional network is under analysis, all freeways and major arterials in the study area should be included as links. Additional links should be added when they: (1) create a contiguous network, connecting arterials and freeways together;

(2) represent several parallel streets that collectively carry arterial levels of traffic; or (3) interchange with the freeway system.

The boundary of the study area is usually drawn along a political boundary (county, census tract). A cordon line is drawn across streets where they enter or exit the study area. Such data as roadside surveys and traffic volume counts taken at the cordon line are useful in calibrating the model.

Network Attributes[2]

Highway links are assigned attributes representing level of service afforded by the segment and intersections of the highway system. Travel time, speed, and any delays attributable to travel time must therefore be assigned to the link, which may also designate energy consumption and air and noise pollutant emissions. The trend is toward greater detail of link-based data to allow intersection delay to be incorporated into the travel-demand model. However, three basic items are needed by a transportation model to determine impedance for the appropriate assignment of trips to the network: distance, speed, and capacity.

Because all three of these attributes can be estimated in various ways, it is useful to understand the alternative approaches and the possible implications of each approach.

Link Distance

Most software packages measure link length automatically. The length of each link also can be estimated from a properly scaled map. The accuracy of this approach is adequate, but the method is fairly labor intensive. The distances estimated in this manner also must be entered directly into the link records, and this provides an additional opportunity for errors to occur.

An alternative to hand measuring scaled distances is to use the *x* and *y* coordinates of the two nodes that define each link and computerize the process of estimating link distances. The accuracy of this method is related directly to the quality of the digitizing process; for instance, whether curved links are represented by straight lines. A significant advantage of this approach is the consistency of the estimates throughout the network.

Link Speeds

Link speeds are a major input within the modeling process because they are used to determine the fastest paths between areas of the planning region. This in turn is used in the trip distribution and mode-choice phases of the travel-demand process. A typical urban transportation model uses both peak-period travel speeds and off-peak travel speeds, depending on the analysis period being considered.

Link speeds obviously vary due to numerous factors, including

- Prevailing traffic volume on the link,
- Posted speed limits,
- Adjacent land use activity and its access control,
- Functional classification of the street, and
- Type of intersection control and spacing of intersection controls.

Transportation models can use any of several approaches to simulate appropriate speeds for the links included in the network.

A relatively simple approach uses the posted speed limit for each link included in the network. Because the transportation model will lower the initially coded link speeds in response to the traffic volumes assigned to the link, this simplified method works reasonably well in most cases. This approach requires a relatively complete knowledge of the posted speeds throughout the entire modeled region and may not be acceptable for air quality analysis.

An alternative approach is to use a free-flow speed look-up table like the one shown in Chapter 4. Such a table lists default speeds by area and facility type.

Link Capacity

Link capacities are a function of the number of lanes on a link. However, lane capacities can also be specified by facility and area type. Several factors are typically used to account for the variation in per-lane capacity in a highway network. These include

- Peak-hour factors,
- Type of intersection control,
- Percent trucks, and
- The green to cycle-length ratio at signalized intersections.

Determination of actual capacity for each link in a network is a time- and data-intensive process. If resources are not available, Chapter 10, Capacity Analysis, provides per-lane default capacities by area type, facility type, and default speed.

[2]Parsons Brinckerhoff Quade & Douglas, *Review of Best Practices*, prepared for the Metropolitan Washington Council of Governments (December 1992).

Area Type Considerations

Area type refers to a method of classifying small geographic areas by a rough measure of land use intensity, primarily based on population and employment density. A higher intensity of land use generally means more intersections, driveways, traffic signals, turning movements, and pedestrians, and, therefore, slower speeds.

Typically, roadway link speeds and capacities are adjusted slightly based on the area type where they are located. Many models use approximately five area type codes representing: CBD, CBD fringe (or outlying business district), urban, suburban, and rural.

Roadway link records include an area type field that computer software can use, in conjunction with facility type information and the number of lanes, to determine appropriate link capacities and speeds.

Final Network Database

This section describes procedures for establishing the network database. Among the attributes that should be included for each link are

- "A" and "B" node numbers and their associated *x, y* coordinates;
- Links defined by "A" and "B" nodes;
- Link length;
- Functional classification, including the divided or undivided status of the link's cross-section;
- Number of lanes;
- Controlled or uncontrolled access;
- One-way versus two-way status;
- Area type;
- Speed; and
- Capacity.

In addition, the coding of the traffic analysis zone in which each link is located on the link record facilitates the identification of area type for the link and is useful in producing assignment summaries. Base-year ground counts also may be coded for automatic screenline analysis.

Transit Networks

The transit network is developed after the highway network. Essentially, a route name is designated and the node-to-node path that makes up the transit line is coded. Additional information about the transit line includes

- Headway (typically, three different headways can be coded: AM, Midday, and PM),
- Route name/number, and
- An average speed, although this can be derived from the assignment process and fed back into the transit model.

In addition to the routes, the transit network will need to include walk links if they are not adequately covered by the centroid connectors. If park-and-ride lots are used, highway links are used to connect the zones to the park-and-ride lots.

SOCIOECONOMIC DATA

Socioeconomic data used in the planning process include household and employment data. Socioeconomic and land-use data are compiled and coded to units of geography to give the transportation planner an understanding of the way land is used in each section of the planning area. Most urban areas already have developed TAZs and collected land-use and socioeconomic base data within the zone geography. Where this is not the case or where the level of detail, comparability with census tract or block boundaries, or a specific project requires it, zones will need to be developed or modified.

Structure of the TAZs

Zones are geographic areas dividing the planning region into relatively similar areas of land use and land activity. Zones represent the origins and destinations of travel activity within the region. As it is not computationally feasible to represent every household, place of employment, shopping center, and other activity as a separate origin and destination, these entities are first aggregated into zones and then further simplified into a single node called a centroid.

A centroid is a point that represents all travel origins and destinations in a zone. Zone centroids can be placed in the center of activity of the zone, using land use maps, aerial photographs, and local knowledge. Unique special generators, especially when surrounded by a very different land use (such as a college campus in a predominantly residential area) should be isolated as separate zones. The center of activity is not necessarily the geographic center—it is the midpoint of activity. Often judgment is more useful than measurement technique in determining where the zone centroid should be located.

Each centroid, or loading point, must be connected to the highway and transit systems. Typically in the highway network, these centroids are connected to the highway system at several points to represent the many paths over which each of the discrete origins and destinations within a zone accesses the highway system. Multiple connections tend to smooth the traffic on the adjacent links—if only one connection is given, the point at which the centroid connects to the street system will show abrupt changes in traffic volume at that point. Special generators should have the actual load points coded, even if it is only one, for a realistic distribution of traffic on the network.

Once the zone system is developed and mapped, and a census equivalency table is constructed, zonal socioeconomic and land-use data can be assembled for the transportation planning process.

Relationship to Census Geography

Zone systems should follow available census data boundaries (either tracts, block groups, or blocks), so that data collected in the decennial census can be used with minimal manipulation. To implement a robust database collection and maintenance methodology, an equivalency table correlating census tracts and blocks to TAZs should be developed. The table below gives an example. An equivalency table will enable immediate cross reference and database aggregation to the TAZs and various planning or other study areas.

TAZ	Census Block
101	54039329104320
101	54039329104321
101	54039329104322
102	54039329104323
102	54039329104324

Zones should also be relatively homogeneous in character and consider major physical and transportation boundaries. Where possible, a zone should not contain various land uses, nor should it cross a river, freeway, or other major topographical barrier.

TAZ and Highway Network Comparability

The size of zones should reflect the purpose of the intended analyses. For systemwide planning, where volumes on individual transportation links are not of concern, zones can be larger than the arterial grid. If traffic volumes on the arterials are the subject of analysis, zones should not be so large that two or more arterials traverse the zone in any direction. When this happens, travel generated by the zone tends to be lumped together during the assignment process, to produce unrealistic travel patterns. If corridor analysis is the purpose of zone development or modification, zone sizes in the corridor or subarea should be more fine-grained.

Sources for Socioeconomic Data

The availability of various data sources, among other factors, will be one of the primary criteria in determining the suitability for collection and input to the master database for the transportation planning model. Another selection criterion is the accuracy of the data and ability to update the database periodically. Using these two criteria, the following data sources should be evaluated.

1. *U.S. Census*—The decennial census offers the best source for population and the required companion characteristics data. These data are available at block level and can be aggregated to traffic zones. Although the census documents employment in the form of labor force, it is a household-based count rather than a count of employment by location. Labor force statistics provide counts of employment in various areas where residential population is located, but do not specify employment by employer or location. The Census Transportation Planning Package (CTPP) provides sums of resident employment at the TAZ; therefore, the census can be used for some general cross-checks for employment, but cannot be used to compile employment data for small geographic areas.
2. *State Employment Commission (Employment Commission)*—The state employment commissions generally document all employees for tax purposes. Each employer is identified by a federal identification number, number of employees, and an address usually keyed to where the payroll is prepared for the specified number of employees. The state employment commission data are significant because the address can tie the employer, and therefore the number of employees, to a specific geographical area. One consideration with the employment commission data is that often up to half the employers list Post Office (P.O.) boxes as the address of record. In addition, employers with more than one location are not always disaggregated; that is, the headquarters of a firm may be listed with the total employment combined for all franchises.
3. *Market Research Listings*—Many market research firms offer commercial listings of all (or major) employers and number of employees by county and city. All the listings show business locations by street addresses, as well as P.O. boxes. Commercial listings offer these data on a subscriber basis with a range of access and purchase options.
4. *Local Area Population and Employment Data*—Many areas collect and record some type of population data. But few areas record employment data other than a broad listing of the employers with the highest number of employees locally. Chambers of Commerce often publish lists of member businesses.
5. *Aerial Photography and Existing Land Use*—Often aerial photographs can be used to update existing land use. The resolution of the photography is good enough to differentiate many residential and nonresidential

areas. When compared with the aerial photographs, each land use can be associated with a particular land use type (e.g., retail and industrial) for each building.

6. *Telephone Directory*—The telephone directory is a rich database that lists residential units and businesses by street address for any planning area; however, the rate of unlisted residential numbers is rising and may influence the use of telephone directories.
7. *Polk Directory*—The Polk Directory is a comprehensive list of household and employment data sorted by name and address. For households, such information as occupation and employer can be ascertained. For business establishments, type of business—including associations, libraries, and organizations that may not be on the tax file—can be determined.

Data Source Deficiencies

1. *Population.* The only data source acceptable to initially establish a residential database is the U.S. census. All of the other data sources identified above do not provide comparable population statistics by specific area (i.e., block level).
2. *Employment.* Each of the above data sources has some deficiency in accurately specifying employment for small geographic areas. The census provides total labor force by TAZ; however, this represents only employment location of residents and not total employment. The employment commission data provide accurate employment for each business but only partially list street addresses (with the remaining having P.O. box listings). Commercial listings have all employers by street address. Although these listings are extensive, the accuracy is controlled internally and often cannot be considered comprehensive (because of the lack of information regarding collection methodology), but it offers a check for other data sources. The aerial photography assists only in determining potential nonresidential areas. The land-use data obtained from aerial photography provide a geographic location of businesses but do not provide employment numbers. A similar condition exists with the telephone directory. The directory covers most businesses and provides addresses for most of them. Several multi-use areas, such as shopping centers, do not provide numbered street addresses.

In summary, none of the data sources offers a complete inventory of employment by geographic location.

Employment data are the most difficult data component to collect. The census data show labor force statistics by industry group but do not compile this by employer and specific geographic area (i.e., block). Therefore, the methodology for developing the employment database should be based on the most efficient and accurate method by which employment can be collected and organized into the database file.

Control Totals for the Database

The control totals for the database should be determined before the compilation of the data. The source of the control totals for population should be the U.S. census.

IMPACT AND USES OF GIS ON DATABASES

Geographic information systems are designed to capture, store, retrieve, analyze, and display data files referenced to detailed geographic location; for example, latitude and longitude, state plane coordinates, census tract or block, or a locally developed geographic scheme. GIS software enables the planner to process geographic-based information from a multitude of sources. For instance, the tax assessor's office collects and maintains a wealth of information organized by tax parcel and indexed by a complicated map reference system. Likewise, public utilities, school districts, police, and fire departments all collect information on the populations they serve and often have their own system of geographic reference. State departments of transportation have data on traffic accident locations, pavement condition, bridge locations, signs, and rights-of-way.

A GIS organizes and provides access to these data, allowing the user to overlay and analyze it using a common frame of reference (either address- or block-specific), and display it in an easily understood format. This allows otherwise unavailable or cumbersome data to be used in transportation planning. Increasingly, the major differences between traditional planning and GIS are becoming blurred.

Three typical applications of GIS in transportation planning are geocoding, processing socioeconomic data, and cartography.

Geocoding

One of the reasons that the compilation of transportation information is so expensive is that data gathered from surveys on trip origins and destinations must be related to specific physical location. This process, commonly referred to as geocoding, is usually a tedious and time-consuming manual process. Many GIS applications include a geocoding capability that automates this process, allowing a street address, place name, or intersection to be geographically referenced to latitude and longitude, census tract, or TAZ. Good geocoding software includes the ability to handle misspelled names; ambiguities caused by similar names given to avenues, streets, and boulevards; and incomplete addresses.

Socioeconomic Data

Socioeconomic data used in transportation planning include information on household characteristics, employment, and land development. These data are the common characteristics of each zone that affect the generation and attraction of trips (e.g., trips are generated by households and attracted by work or retail locations). Information can be obtained from various sources in addition to those listed above, such as tax assessment records, zoning maps, school enrollment files, and public utility records.

Cartography

A GIS in conjunction with digital cartographic information (such as U.S. Geological Survey [USGS] digital line graphs or the U.S. Bureau of the Census' Topologically Integrated Geographic Encoding and Referencing database [TIGER]/line files) and geocoded trip and socioeconomic data can be used to prepare maps to support technical analysis. The USGS and census TIGER maps show streets and railways; features such as schools, parks, and hospitals; census blocks and tracts; political boundaries; hydrographic features; and topographic relief. The difference that GIS makes to cartography is the ability to relate items spatially within the database.

Geographic systems co-relate point, line, and area data that describe the mapped region and attributes about those data. For example, a point-on-line analysis might be to identify the schools within 5 miles of a hazardous material route. A point-on-area inquiry could display building permits approved within the last 2 years in a TAZ. A line-on-area query could display all four-lane roadways within a metropolitan area. An area-on-line analysis could identify high-employment zones served by a proposed transit route.

CASE STUDY

At this point we will introduce the Asheville, North Carolina, test case. The Asheville MSA lies in the western quarter of the State of North Carolina, roughly 230 miles west of the state capital in Raleigh, and 110 miles east of Knoxville, Tennessee. As defined by the U.S. Census Bureau, the region consists of the City of Asheville and surrounding Buncombe County. In 1990, the entire MSA had a population of 174,821, and the City of Asheville had a population of 110,429.

Figure 3 displays a base map for the Asheville region. Asheville's transportation network consists primarily of its roadway system and the **City Coach** bus service, a 12-route system operated by the Asheville Transit Authority. Two U.S. Interstate routes meet just south of the City of Asheville: I-40, running east to west, and I-26, which connects Asheville to Atlanta. A belt-line, I-240, makes a half-circle around the City to its northern side. As of 1991, **City Coach** carried fewer than 4,000 daily passengers, approximately 1 percent of the daily person trips made in the Asheville area. The remainder of the mechanized person trips on the transportation network were made in private vehicles.

Socioeconomic Data

The trip generation equations introduced in this chapter use socioeconomic and land-use data to describe the quantity and type of travel activity in the region. Required data include the following: number of households by size; household income or automobile ownership; and employment by type. These data should be allocated throughout the region according to a TAZ structure that is appropriate for the level of analysis and the detail in the selected network.

The North Carolina Department of Transportation (NCDOT) originally developed the Asheville TAZs. Their zone system contains 353 internal zones and 36 external stations. NCDOT compiled household and employment data for the MSA at the 353 TAZ level of detail. A review of the NCDOT zone structure revealed that it provided more detail than was needed for the case study example, which is intended to forecast traffic volumes only on the major roadways. The 353 zones were aggregated into 107 internal zones and 16 external stations for the case study.

The socioeconomic data for this case study were extracted from the 1990 U.S. Census. Serial Tape File (STF) 3-A was downloaded from the North Carolina State Library. These data included the following summary information:

- Household income by household size,
- Median household income,
- Number of persons in household,
- Mode of travel to work,
- Time of departure from work, and
- Private vehicle occupancy for work trips.

The census data revealed that the study area contains a population of approximately 110,000 persons in 46,492 households. A listing of households by size for each of the 107 TAZs is provided as Appendix Table B-1.

The household and income data will be used in the trip generation equations to calculate the person-trip *productions*. Person-trip *attractions*, on the other hand, are based on employment data, stratified by type of employment. The NCDOT data provided for this study were divided into several different sectors according to the Standard Industrial Classification land use code. Total employment for the MSA is estimated at 59,037 by NCDOT's surveys. A listing of the employment in each of the 107 TAZs is provided as Appendix Table B-2.

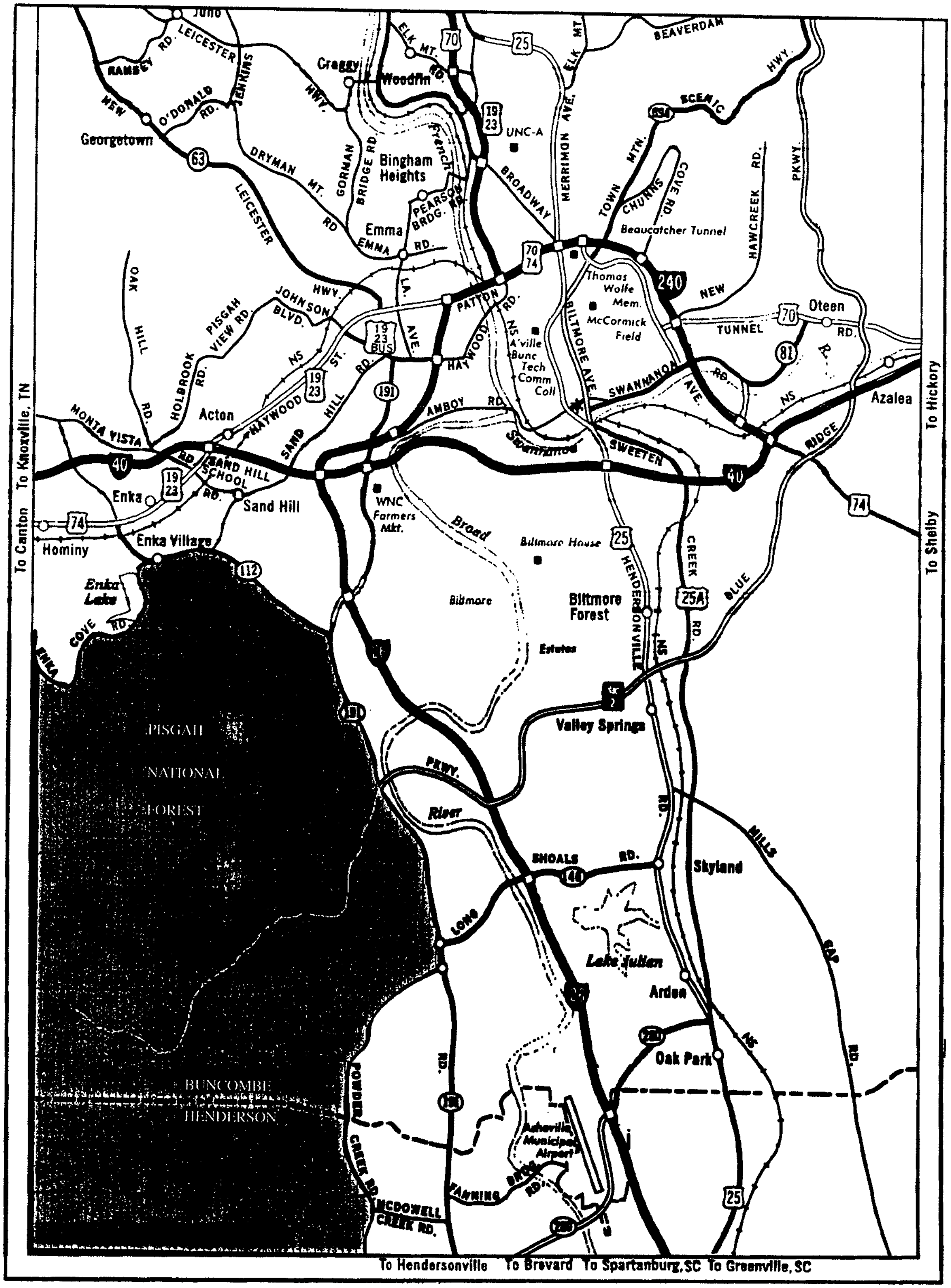


Figure 3. Asheville, North Carolina, highway map (courtesy of North Carolina Department of Transportation).

TABLE 1 Base network summary

Nodes	Quantity
Zone Centroids (Internal)	107
Zone Centroids (External)	16
Regular Nodes	1,156
Total Nodes	1,279

Link Type	Description	Quantity	Free-Flow Speed (mph)	Capacity Veh. per Hr.
1	Freeway	168	55	1350
2	Major Arterial	922	45	825
3	Minor Arterial	1,550	35	825
4	Centroid Collector	632	20	-
Total Links		3,272		

Network Description

The highway network for the region was acquired from NCDOT as a downloaded file on disk, which was then input directly into the transportation modeling software package. Each link in the network was then coded with a facility classification (freeway, major arterial, or minor arterial), number of exclusive lanes in the direction of travel, the free-flow speed, and the hourly per-lane capacity of the roadway.

As summarized in Table 1, the base highway network consists of 1,156 regular nodes connected by 168 freeway links, 922 major arterial links, and 1,550 minor arterial links. After the regular nodes were connected by links defined to represent actual highways, centroid connectors were added to allow the 107 internal centroids and the 16 external stations access to the highway network. (If we were planning to model the transit volumes on the local bus routes, we would have used the highway network as the base for building a transit network. However, given that only 1 percent of the person trips in the Asheville MSA use transit, that component of the transportation network was ignored.)

Figure 4 is a plot of the coded base highway network, including all link types except centroid connectors.

Traffic Count Data

NCDOT also provided a selected count map, which displayed total daily vehicle volumes for various intersections and cordon points. These counts, summarized in Table 2, were used to provide the traffic volumes at the 16 external stations (see Chapter 5) and to perform screenline comparisons of the actual versus modeled traffic counts within the network (see Chapter 9).

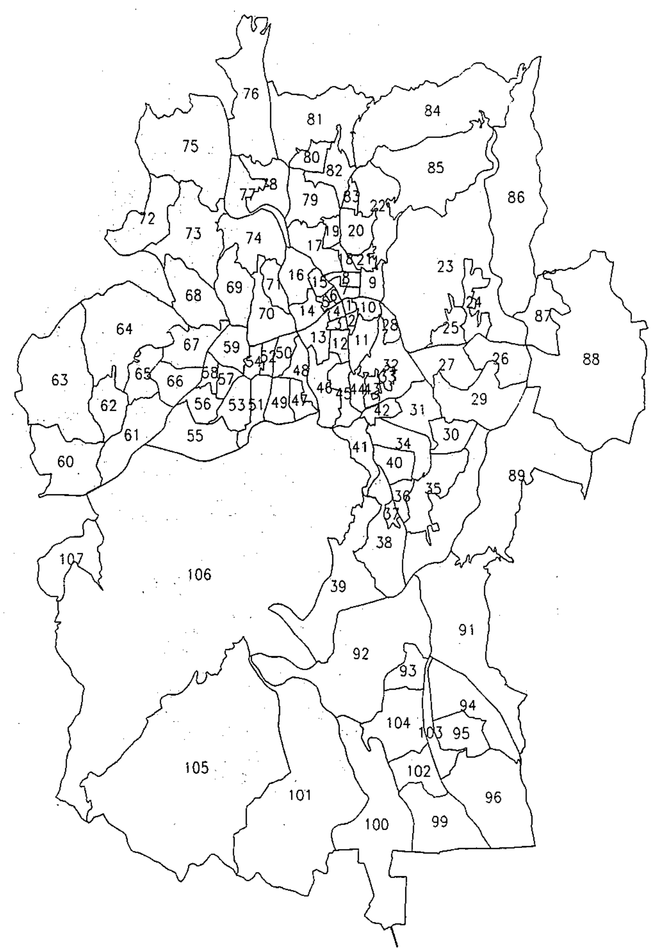


Figure 4. Asheville, North Carolina, TAZs.

TABLE 2 External stations

Station No.	Description	1989 ADT	Classification
108	Route 251	1,800	Minor
109	Routes 19 & 23 Bypass	27,700	Principal
110	Routes 19 & 23 Business	7,000	Minor
111	BRP (N)	2,850	Minor
112	Snope Creek Road	2,000	Minor
113	Route 70	16,100	Principal
114	I-40 (E)	24,700	Interstate
115	Route 74	11,000	Minor
116	Route 25	12,450	Minor
117	I-26	33,100	Interstate
118	Routes 191 & 280	7,400	Minor
119	BRP (S)	970	Minor
120	Route 151	1,550	Minor
121	I-40 (W)	27,500	Interstate
122	Leicester Highway	14,000	Principal
123	Bear Creek Road	3,940	Minor

SUMMARY

The range of electronic data now available to the modeler is substantial. These data are most useful in the creation of the socioeconomic inputs to the model as well as the development of the model network itself. This allows finer detail and greater accuracy than was available even a few years ago. While these advances are on the whole good for the modeler, one must be careful not to be overwhelmed by the amount of data available and to use only what is truly necessary to create the desired output.

With the use of GIS, many commercially produced networks are now available. Many of these are simply enhanced TIGER files.

The next chapter, Trip Generation, begins the four-step modeling process with a discussion of data needs and the process used to create a basic trip table that will be used as an input to the model.

CHAPTER 3

TRIP GENERATION

INTRODUCTION

The first step in travel forecasting is determination of the trips currently undertaken in a planning region. Trip generation, or the amount and type of travel in a region, is functionally related to the use of land. To estimate trip generation, land use is described in terms of the character, intensity, and location of activities. Factors influencing the amount of travel in a region include automobile ownership, income, household size, and density and type of development. The availability of public transportation and the quality of the transportation system also influence trip generation. The best travel-demand techniques make use of disaggregate socioeconomic data such as households classified by vehicle ownership, households classified by family size, or households classified by income group to determine the amount of travel generated in the region. The procedures presented in this report are not well suited to generating trips for nonmotorized modes, bicycle or pedestrian.

The purpose of trip generation estimation is to determine the number of person or vehicle trips to and from activities in an analysis area. Trip generation is important in a number of phases of transportation planning and traffic engineering studies. It is necessary for

- Regional studies that consider a range of land uses and related social and economic characteristics,
- Regional transportation alternatives studies and development of long-range transportation plans,
- Short- and long-range plans that evaluate transportation needs in a corridor or specific subarea, and
- Impact studies that assess the effect of new development such as a shopping center, residential development, or industrial park (site impact analysis).

These different requirements for trip generation information have resulted in various levels of trip generation data. Site-specific vehicle trip rates (Table 3) are presented for impact studies where land use is known for a small area, and vehicle rates are needed to assess the impact of development. For most other types of studies, the use of person trips is preferred.

In describing the direction for a trip, the term *origin* refers to the starting point and the term *destination* refers to the ending point. However, the trip ends at the household are called productions and the trip ends at nonresidential land uses are called attractions. The production-attraction format does not indicate the true direction of travel as opposed to the origin-destination format. The procedures for converting productions and attractions is discussed in the last section of Chapter 8.

Trip-generation models consist of two submodels including trip-production models and trip-attraction models. Trip productions are the trip ends associated with the traveler's home. Trip attractions are the trip ends associated with the non-home end of the trip, such as a workplace, shopping center, or school. For example, if a person went from home to work in the morning, and then went from work to home in the evening, the traveler would have generated two productions at the home zone and two attractions at the work zone. The household and employment data are used to estimate the total travel generated (produced and attracted) by each zone in the planning region.

In this chapter, trip-generation models are presented as person-trip productions based on household size, income and auto ownership (Tables 4 through 7), and auto ownership and income (Table 7). Table 8 presents trip-generation models for person-trip attractions.

BASIS FOR DEVELOPMENT

Site-Specific Vehicle Trip Rates

In Table 3, site-specific vehicle-trip generation rates were extracted from the Institute of Transportation Engineers' *Trip Generation,* 5th Edition. While the stated trip rates for many common land uses are provided here, the ITE *Trip Generation* report actually provides other methods for determining the trip generation rates for these land uses. The manual should be reviewed to determine the proper trip generation rate procedure to use and appropriate adjustments for factors such as transit use and multi-use projects. Consistent with the format of the ITE manual, the rates are presented as average daily vehicle trips and percent of vehicle trips during the a.m. and p.m. peak hours of the generator. Only a subset of the most commonly used rates are presented, and the user is referred to the most current version of the ITE manual for rates on generators not included or those which require more

TABLE 3 Site-specific vehicle trip generation rates

Land Use	Daily Vehicle-Trip Rate	per	Percent of Total Daily Vehicle Trips A.M. Peak	P.M. Peak	ITE Code
Residential					
Single-Family	9.55	DU	8.0%	10.7%	210
Apartment	6.47	DU	8.6	10.7	220
Condo/Townhouse	5.86	DU	7.5	9.2	230
Mobile Home Park	4.81	Occupied DU	8.9	12.1	240
Planned Unit Development	7.44	DU	7.8	9.7	270
Retail[1]					
Shopping Center					
Under 100,000 sq. ft.	70.7	1,000 sq. ft. GFA	2.3%	9.2%	820
100,000 to 1,000,000 sq. ft.	38.7	1,000 sq. ft. GFA	2.1	9.5	820
500,000 to 1,000,000 sq. ft.	32.1	1,000 sq. ft. GFA	2.0	9.3	820
More than 1,000,000 sq. ft.	28.6	1,000 sq. ft. GFA	1.8	9.1	820
Office					
General[2]	11.85	1,000 sq. ft. GFA	13.8%	13.1%	710
Medical	34.17	1,000 sq. ft. GFA	10.0	13.0	720
Office Park	11.42	1,000 sq. ft. GFA	16.1	13.2	750
Research and Development Center	7.70	1,000 sq. ft. GFA	16.0	13.9	760
Business Park	14.37	1,000 sq. ft. GFA	11.3	10.3	770
Restaurant[3]					
Quality Restaurant	96.51	1,000 sq. ft. GFA	6.6%	10.1%	831
High Turnover (Sit Down)	205.36	1,000 sq. ft. GFA	8.7	15.5	832
Fast Food without Drive-Through	786.22	1,000 sq. ft. GFA	9.7	13.7	833
Fast Food with Drive-Through	632.12	1,000 sq. ft. GFA	9.5	7.3	834
Bank					
Walk-In	140.61	1,000 sq. ft. GFA	13.7%	0.4%	911
Drive-Through	265.21	1,000 sq. ft. GFA	13.3	19.3	912
Hotel/Motel					
Hotel	8.7	Occ. Room	7.5%	8.7%	310
Motel	10.9	Occ. Room	6.7	7.0	320
Parks and Recreation					
Marina	2.96	Berth	5.7%	7.1%	420
Golf Course	37.59	Hole	8.6	8.9	430
City Park	2.23	Acre	NA	NA	411
County Park	2.99	Acre	NA	NA	412
State Park	0.50	Acre	NA	NA	413
Hospital					
General	11.77	Bed	10.0%	11.6%	610
Nursing Home	2.6	Occupied Bed	7.7	10.0	620
Clinic (one data point)	23.79	1,000 sq. ft. GFA	NA	NA	630

(continued on next page)

TABLE 3 *(Continued)*

Land Use	Daily Vehicle-Trip Rate	per	Percent of Total Daily Vehicle Trips A.M. Peak	P.M. Peak	ITE Code
Educational					
Elementary School	10.72	1,000 sq. ft. GFA	25.6%	23.2%	520
High School	10.90	1,000 sq. ft. GFA	21.5	17.8	530
Junior/Community College	12.57	1,000 sq. ft. GFA	17.2	8.2	540
University/College	2.37	Student	8.4	10.1	550
Airport					
Commercial	104.73	Average Flights/Day	7.8%	6.6%	021
General Aviation	2.59	Average Flights/Day	10.4	12.7	022
Industrial					
General Light Industry	6.97	1,000 sq. ft. GFA	14.5%	15.5%	110
General Heavy Industry	1.5	1,000 sq. ft. GFA	34.0	45.3	120
Warehouse	4.88	1,000 sq. ft. GFA	11.7	12.3	150
Manufacturing	3.85	1,000 sq. ft. GFA	20.3	19.5	140
Industrial Park	6.97	1,000 sq. ft. GFA	11.8	12.3	130

Note: Rates are often given for other factors, such as acres, employees, or sq. ft. of gross floor area. Weekend rates are also given for many uses. For some, like shopping centers, the weekend rates are higher than weekday rates.

1 Rates given are for high end of indicated range. ITE's *Trip Generation* details rates for 15 sizes. Weekend rates for shopping centers are significantly different from the weekday rates given here. *Trip Generation* also details rates by time of day, day of week, and month of year.

2 ITE details rate for 11 size categories, from 10,000 sq. ft. to 800,000 sq. ft. The rate given here is for a 200,000-sq. ft. general office.

3 Rates are given for the number of seats in the restaurant.

specific site characteristics. When appropriate, local data should be collected and rates developed as in Table 3.

Please note that the site-specific trip generation rates utilize the number of dwelling units as a key data input. This is because site-specific planning relies on the size and number of physical structures in a study area. Transportation modeling techniques, on the other hand, rely heavily on census information as a data source. Therefore, regional trip generation models use households, or the number of family units, as the primary data source for estimating home-based trip generation.

Model Trip Rates

The data presented in Tables 4 through 9 were derived from available home interview surveys taken since 1985 and from the 1990 NPTS. The data from both sources were stratified into the population subgroups listed. These subgroups are different from those used in *NCHRP Report 187* because of federally mandated planning requirements that specify population stratification groups. The small urban size is now consistent with requirements specified in ISTEA.

Population stratification groups are as follows:

- 50,000 to 199,999 persons,
- 200,000 to 499,999 persons,
- 500,000 to 999,999 persons, and
- More than 1,000,000 persons

Original home-interview surveys for the 50,000 to 199,999 category were limited. In addition, variations in survey design, definitions, collection methodologies, and the expansion of the data made it difficult to develop conclusive find-

TABLE 4 Percent of households by autos owned and income

	Autos Owned			
Income	0	1	2	3+
Urbanized Area Size = 50,000 - 199,999				
Low*	17	55	23	5
Medium	3	31	48	18
High	0	12	52	36
Weighted Average	8	32	40	20
Urbanized Area Size = 200,000 - 499,999				
Low	17	51	24	8
Medium	2	32	53	13
High	0	13	53	34
Weighted Average	7	32	42	19
Urbanized Area Size = 500,000 - 999,999				
Low	21	55	20	4
Medium	3	39	44	14
High	1	10	59	30
Weighted Average	7	33	42	18
Urbanized Area Size = 1,000,000 +				
Low	19	52	22	7
Medium	2	40	42	16
High	1	10	55	34
Weighted Average	7	31	41	21

* In actual 1990 dollars: Low = less than $20,000, Medium = $20,000 to 39,999, and High = $40,000 and up.

ings about variations in trip rates across urban area sizes and characteristics. The NPTS data provided the only consistent source of travel data throughout all ranges of urban area size and location; however, the NPTS rates were low compared with the rates collected by local areas. The lower rates can be attributed to the collection methodology of the NPTS. For generation data, the NPTS rates were factored in a normative distribution to match more closely the rates determined by the urban areas used as source data. A comparison of the actual rates is shown in Appendix Table A-2.

A major finding after reviewing the home-interview data and the NPTS data was that the difference between trip generation rates across urban areas of different sizes was not large, particularly when compared with the difference presented in *NCHRP Report 187.* The findings of the study resulted in trip generation rates closely grouped around an average of 9.0 daily person trips per household. A summary of the comparison of the average trip production rates contained in this report and those contained in *NCHRP Report 187* is presented below.

The impact of the revised trip rates should be reviewed by those who developed models using the earlier *NCHRP Report 187* rates. In many cases, it was acknowledged that the rates for small urban areas were high and the actual applied rates were adjusted downward. If the complete model set was calibrated and validated to match observed traffic count data, then any adjustments to the model should be reviewed in light of the revised rates.

Urbanized Area Population	Person Trips/ Household	Person Trips/Household *NCHRP Report 187* *
50,000 to 200,000	9.2	14.1
200,000 to 500,000	9.0	11.8
500,000 to 1,000,000	8.6	7.6
> 1,000,000	8.5	7.6

* Note: Because of different urban area size categories between *NCHRP Report 187* and this report, the rates shown were chosen from the closest matching category.

DATA REQUIRED FOR APPLICATION

Site-Specific Vehicle Trip Rates

For site-specific estimates, the following input is required:

Generator	Input Required
Residential locations	Type of residence and number of dwelling units or acres of development
Industrial/manufacturing, offices	Gross floor area (GFA), or employees, or acres of development
Restaurants	Gross floor area or acres of development
Banks	Gross floor area or employees
Parks and recreation sites	Acres (or employees for a few types)
Hospitals	Staff or beds
Educational locations	Students or staff
Airports	Take-offs and landings or employees or acres
Hotels/motels	Rooms or employees
Retail sites	Gross floor area or employees or acres
Military bases	Military personnel and civilian employees or total employees
Race tracks, stadiums	Seats or attendees
Service stations	Number of pumps

Model Trip Rates

The data presented in this section provide useful information for estimating trip rates based on differences in income and/or auto ownership. The data have been summarized into four urbanized area population groups. Income is in three income groups (low, medium, and high in 1990 tertiles).

To predict the number of trips produced in an area, the planner usually employs a set of household trip production rates stratified by at least two of the relevant variables that describe households, such as the number of persons in the household and income, or number of persons in the household and auto ownership. Most of these cross-classification models use household size as the independent variable to predict trips per household. The variation in trips between household sizes is so large that models without this variable are inferior in approximating the observed travel patterns in a region.[1] For the basic cross-classification model, the second independent variable is a measure of the wealth of the household, typically either directly as income or indirectly as auto ownership.

The data requirements for application of the information provided for trip generation include land-use and socioeconomic characteristics generally used for areawide planning and site-specific characteristics used in land development analysis. The material provided allows some variation in data requirements based on data availability, level of analysis required, and time available.

To use the material in Table 4 as input data for trip generation, estimates are required of the number of households by

[1]Parsons, Brinckerhoff Quade & Douglas, *Review of Best Practices,* prepared for the Metropolitan Washington Council of Governments (December 1992).

TABLE 5 Average daily person trips per household by persons per household and income

Income	Persons per Household 1	2	3	4	5+	Weighted Average
Urbanized Area Size = 50,000 - 199,999						
Low*	3.6	6.5	9.1	11.5	13.8	6.0
Medium	3.9	7.3	10.0	13.1	15.9	9.3
High	4.5	9.2	12.2	14.8	18.2	12.7
Weighted Average	3.7	7.6	10.6	13.6	16.6	9.2
Urbanized Area Size = 200,000 - 499,999						
Low	3.1	6.3	9.4	12.5	14.7	6.0
Medium	4.8	7.2	10.1	13.3	15.5	9.4
High	4.9	7.7	12.5	13.8	16.7	11.8
Weighted Average	3.7	7.1	10.8	13.4	15.9	9.0
Urbanized Area Size = 500,000 - 999,999						
Low	3.6	7.1	9.0	12.0	14.0	6.0
Medium	4.8	7.1	9.8	12.7	14.6	8.9
High	4.8	7.8	11.5	13.6	16.6	11.5
Weighted Average	4.0	7.3	10.2	13.0	15.4	8.7
Urbanized Area Size = 1,000,000+						
Low	3.7	6.3	8.1	10.0	11.8	5.7
Medium	4.9	7.6	9.1	12.3	15.1	9.0
High	5.4	7.9	10.3	12.4	15.3	10.8
Weighted Average	4.2	7.3	9.3	12.0	14.8	8.5

* In actual 1990 dollars: Low = less than $20,000, Medium = $20,000 to 39,999, and High = $40,000 and up.

income or auto ownership category. Such estimates can be developed from census data. Table 4 shows an estimate of the percent of households by autos owned in each income category. An estimate of the percent of households in each cell may be obtained by using either an income distribution or an auto-ownership distribution. Table 5 allows an estimate of average daily person trips given an income distribution and the number of persons per household. Table 6 estimates average daily person trips, given the number of autos owned and the number of persons in the household. In cases where the number of autos owned is greater than the number of persons in the household, the data are inconsistent; these cells were combined and weighted averages for combined cells are shown. Table 7 presents estimates of average daily person trips given an income distribution and the number of automobiles owned.

Estimation of trip attractions (Table 8) requires—for each analysis area—total employment, retail, service and other employment, and number of households.

After these trip attractions for CBD and non-CBD are computed, they are added together before proceeding to trip distribution.

Table 9 presents household data and can be used when detailed information is not available. Only the number of households is required, if the distribution by family size or income is not known, to use the weighted average by urban

TABLE 6 Average daily person trips per household by persons per household and auto ownership

Autos Owned	Persons per Household 1	2	3	4	5+	Weighted Average
Urbanized Area Size = 50,000 - 199,999						
Zero	2.6	4.8	7.4	9.2	11.2	3.9
One	4.0	6.7	9.2	11.5	13.7	6.3
Two	4.0	8.1	10.6	13.3	16.7	10.6
Three Plus	4.0	8.4	11.9	15.1	18.0	13.2
Weighted Average	3.7	7.6	10.6	13.6	16.6	9.2
Urbanized Area Size = 200,000 - 499,999						
Zero	2.1	4.0	6.0	7.0	8.0	3.1
One	4.3	6.3	8.8	11.2	13.2	6.2
Two	4.3	7.5	10.6	13.0	15.4	10.1
Three Plus	4.3	7.5	13.0	15.3	18.3	13.5
Weighted Average	3.7	7.1	10.8	13.4	15.9	9.0
Urbanized Area Size = 500,000 - 999,999						
Zero	2.5	4.4	5.6	6.9	8.2	3.4
One	4.6	6.7	8.8	11.0	12.8	6.4
Two	4.6	7.8	10.4	13.0	15.4	10.3
Three Plus	4.6	7.8	12.1	14.6	17.2	12.9
Weighted Average	4.0	7.3	10.2	13.0	15.4	8.7
Urbanized Area Size = 1,000,000+						
Zero	3.1	4.9	6.6	7.8	9.4	4.1
One	4.6	6.7	8.2	10.5	12.5	6.3
Two	4.6	7.8	9.3	11.8	14.7	9.7
Three Plus	4.6	7.8	10.5	13.3	16.2	11.8
Weighted Average	4.2	7.3	9.3	12.0	14.8	8.5

area size to estimate autos owned, average daily person trips and vehicle trips and the percent of person trips that are home-based-work (HBW), home-based-other (HBO), or non-home-based (NHB).

The trip-attraction model in *NCHRP Report 187* was based on rates included in the old Urban Transportation Planning System (UTPS) standard model set and presented as a function of employment by type (retail and non-retail) and the number of households in a zone. The *Report 187* rates were compared with rates from similar employment types used in other urban areas. For the most part, the *Report 187* rates are consistent but they may be a little high. This is particularly true for HBW and HBO trips per retail employee. It is also important to consider the employment types. The question of what constitutes retail trips has often led to a misclassification of employment data. Rather than dividing employment into simply retail and non-retail, the rates presented here are based on retail, service, and other. These would correspond to the following Standard Industrial Classification (SIC) codes:

- Retail: Major Groups 52 through 59 (5200–5999)
- Service: Major Groups 60 through 90 (6000–9000)
- Other: Major Groups 1 through 51 and 91 through 99 (100–5100 and 9100–9999)

"Other" includes both basic industries and government of the office type (rather than license bureaus, for example). The user should refer to the *SIC Manual,* Office of Management

TABLE 7 Average daily person trips by income and autos owned

Income	Autos Owned 0	1	2	3+	Weighted Average
Urbanized Area Size = 50,000 - 199,999					
Low*	3.4	5.3	8.7	10.6	6.0
Medium	5.3	7.0	10.1	12.1	9.3
High	7.1	8.9	12.4	14.6	12.7
Weighted Average	3.9	6.3	10.6	13.2	9.2
Urbanized Area Size = 200,000 - 499,999					
Low	2.8	4.9	8.6	11.5	6.0
Medium	4.0	7.1	10.0	13.4	9.4
High	5.2	8.4	11.2	14.0	11.8
Weighted Average	3.1	6.2	10.1	13.5	9.0
Urbanized Area Size = 500,000 - 999,999					
Low	3.2	5.5	9.2	11.8	6.0
Medium	4.0	7.0	10.0	11.9	8.9
High	4.9	8.1	11.0	13.8	11.5
Weighted Average	3.4	6.4	10.3	12.9	8.7
Urbanized Area Size = 1,000,000+					
Low	3.7	5.0	7.9	9.8	5.7
Medium	5.8	7.1	9.8	12.0	9.0
High	6.8	8.3	10.4	12.1	10.8
Weighted Average	4.1	6.3	9.7	11.8	8.5

* In actual 1990 dollars: Low = less than $20,000, Medium = $20,000 to 39,999, and High = $40,000 and up.

and Budget (OMB) 1987 for detailed descriptions of the industry classifications. The variation in HBO trip rates per retail employee was found to be significant between CBD and suburban zones; therefore, the rates presented are separated by CBD versus non-CBD zones.

TRIP GENERATION DATA AND EXAMPLES OF USE

Site-Specific Vehicle Trips

Table 3, Site-Specific Vehicle Trip Generation Rates, provides information on vehicle trip rates for a number of different generators. The basic information given for each generator is as follows:

1. *Daily Vehicle-Trip Rate.* This provides the trip rate based on the most appropriate land use measures for each type of site, such as trips per employee, acre, or household. A trip is defined as a one-way vehicle movement with either the origin or the destination in the study area. Therefore, the trip rates shown represent the sum of the vehicular trips to and from a site (or trip ends) divided by a measure of the land use such as number of households, acres, employees, and the like. Vehicles include automobiles, trucks, taxis, and buses.

TABLE 8 Person-trip attraction estimating relationships for all population groups

To estimate trip attractions for an analysis area, use[1]

HBW Attractions = 1.45 × *Total Employment*

HBO Attractions CBD = 2.00 × *CBD RE* + 1.7 × *SE* = 0.5 × *OE* + 0.9 × *HH*

HBO Attractions NBD = 9.00 × *NCBD RE* + 1.7 × *SE* + 0.5 × *OE* + 0.9 × *HH*

NHB Attractions CBD = 1.40 × *DBD RE* + 1.2 × *SE* + 0.5 × *OE* + 0.5 × *HH*

NHB Attractions NCBD = 4.10 × *NCBD RE* + 1.2 × SE + 0.5 × OE + 0.5 × *HH*

where

CBD RE	= Retail Employment in Central Business District Zones,
NCBD RE	= Retail Employment in Non-Central Business District Zones,
SE	= Service Employment,
OE	= Other Employment (Basic and Government), and
HH	= Households.

[1] Note: The coefficients for these equations were derived from a variety of trip attraction models for urban area studies and represent a consensus of these models.

2. *Percent of Total Daily Vehicle Trips in Peak Hour.* This provides percentages that can be applied to daily trip (or trip end) estimates based on the trip rates to obtain the traffic generated in the a.m. peak hour and the p.m. peak hour on the surrounding street system.

For example, a general hospital can be expected to generate 11.77 trips per bed (Table 3). For a hospital with 100 beds, one can expect 1,177 trips (or trip ends) per day (100 × 11.77). In the a.m. peak hour (normally occurring sometime between 7:00 a.m. and 9:00 a.m.), approximately 10 percent of total daily trips, or 118 vehicles (0.10 × 1,177), can be expected to enter or leave the facility. In the p.m. peak hour (normally occurring sometime between 4:00 p.m. and 6:00 p.m.), approximately 12 percent of total daily trips or 141 vehicles (0.12 × 1,177) can be expected to enter or leave the facility.

Model Trip Rates

The data in Tables 4 through 9 can be used in several ways. If an estimate of zonal average autos per household is available (for instance, from the census sample data), an estimate of average daily trips per household can be made directly using the data provided in Table 7. For example, in an urbanized area of 50,000 to 199,999 population, 9.2 average daily person trips per household can be expected to be produced where the average car ownership is 1.8 per household. This is an appropriate use where zonal averages are most easily developed or available. Where the number of households by income range is known, an estimate can be obtained of

- Percent of 0, 1, 2, and 3+ auto households (Table 4),
- Average daily person trips per household for low, medium, and high income (Table 5),
- Average daily person trips per household for 0, 1, 2, and 3+ auto households (Table 6),
- Percent of trips by purpose (Table 9), and
- Average autos per household (Table 9).

Some of these data are available from the decennial census, and the census tracts/blocks/urbanized areas (UAs) that make up the study area can be aggregated (a GIS makes this simple) to obtain control totals for the region. For instance, the 100 percent data will furnish the number of households by persons per household; the sample data will give number of households in each auto ownership or income category. Total trips for the region can be estimated from these aggregate data, thereby providing a basis for controlling estimates derived at the zone or household level.

To illustrate the use of the material presented here, assume an urbanized area with 150,000 population and 65,000 households. With 9.2 average daily person-trips per household (Table 9), a total of 598,000 internal-internal plus internal-external trips can be expected. A total of 20 percent of these (Table 9) would be home-based work (HBW) trips, or 119,600 daily person trips; 57 percent home-based non-work (HBO), or 340,860; and 23 percent non-home-based (NHB), or 137,540. To obtain auto vehicle trips, the total

TABLE 9 Trip estimation variables by urban size

	Average Autos per Household	Average Daily Person Trips per Household	Average Daily Vehicle Trips per Household	% Average Daily Person Trips by Purpose		
				HBW	HBO	NHB
Urban Area = 50,000 to 199,999						
Income						
Low*	1.2	6.0	4.8	16	60	24
Medium	1.9	9.3	8.1	21	56	23
High	2.4	12.7	11.7	20	55	25
Weighted Average	1.8	9.2	8.1	20	57	23
Household Size						
One Person	0.9	3.7	3.2	20	54	26
Two Person	1.8	7.6	6.5	22	54	24
Three Person	2.1	10.6	9.4	19	56	25
Four Person	2.4	13.6	11.8	19	58	23
Five Person Plus	2.4	16.6	14.0	17	62	21
Weighted Average	1.8	9.2	8.1	20	57	23
Urban Areas = 200,000 to 499,999						
Income						
Low*	1.3	6.0	4.8	17	60	23
Medium	1.8	9.4	8.2	20	56	24
High	2.4	11.8	10.7	23	52	25
Weighted Average	1.8	9.0	7.8	21	56	23
Household Size						
One Person	1.0	3.7	3.3	20	56	24
Two Person	9.9	7.1	6.4	23	53	24
Three Person	2.1	10.8	9.8	22	54	24
Four Person	2.2	13.4	11.2	18	61	21
Five Person Plus	2.4	15.9	12.8	19	59	22
Weighted Average	1.8	9.0	7.8	21	56	23

(continued on next page)

TABLE 9 *(Continued)*

	Average Autos per Household	Average Daily Person Trips per Household	Average Daily Vehicle Trips per Household	% Average Daily Person Trips by Purpose		
				HBW	HBO	NHB
Urban Area = 500,000 to 999,999						
Income						
Low*	1.1	6.0	4.8	18	59	23
Medium	1.7	8.9	7.5	23	55	22
High	2.3	11.5	10.3	22	54	24
Weighted Average	1.8	8.7	7.5	22	56	22
Household Size						
One Person	0.9	4.0	3.5	23	54	23
Two Person	1.8	7.3	6.7	24	53	23
Three Person	2.0	10.2	8.8	23	54	23
Four Person	2.3	13.0	10.6	21	57	22
Five Person plus	2.4	15.4	12.5	18	62	20
Weighted Average	1.8	8.7	7.5	22	56	22
Urban Area = 1,000,000 +						
Income						
Low*	1.2	5.7	3.8	16	62	22
Medium	1.8	9.0	6.9	21	56	23
High	2.4	10.8	8.9	24	51	25
Weighted Average	1.9	8.5	6.9	21	56	23
Household Size						
One Person	0.9	4.2	3.1	23	50	27
Two Person	1.7	7.3	5.9	25	52	23
Three Person	1.9	9.3	7.7	25	52	23
Four Person	2.2	12.0	9.9	21	59	20
Five Person plus	2.3	14.8	11.2	19	62	19
Weighted Average	1.7	8.5	6.9	22	56	22

* In actual 1990 dollars: Low = less than $20,000, Medium = $20,000 to 39,999, and High = $40,000 and up.

trips would be multiplied by 0.88 (average daily vehicle trips/average daily person trips, or $8.1 \div 9.2 = 0.88$). The results would be 526,240 vehicle trips for the region ($598{,}000 \times 0.88 = 526{,}240$).

Table 8, Person-Trip Attraction Estimating Relationships for All Population Groups, allows estimation of trip attractions by purpose and by two area groupings, CBD and non-CBD. For the example described previously, total area production controls were as follows:

Trip Purpose	*Trip Production Controls*
HBW	119,600
HBO	340,860
NHB	137,540
Total	598,000

Assume also that the analysis area for the example has the following employment/residential mix:

Employment Type	*CBD*	*Non-CBD*
Total Employment	55,000	20,000
Retail Employment	16,000	10,000
Service Employment	18,000	7,000
Other Employment	21,000	3,000
Dwelling Units	10,000	55,000

Trip attractions for the analysis area can be developed using the relationships presented in Table 8 as follows:

Trip Attractions for CBD

HBW Attractions $= 1.45 \times 55{,}000 = 79{,}750$

HBO Attractions $= (2.0 \times 16{,}000) + (1.7 \times 18{,}000) + (0.5 \times 21{,}000) + (0.9 \times 10{,}000) = 82{,}100$

NHB Attractions $= (1.4 \times 16{,}000) + (1.2 \times 18{,}000) + (0.5 \times 21{,}000) + (0.5 \times 10{,}000) = 59{,}500$

Trip Attractions for Non-CBD

HBW Attractions $= 1.45 \times 20{,}000 = 29{,}000$

HBO Attractions $= (9.0 \times 10{,}000) + (1.7 \times 7{,}000) + (0.5 \times 3{,}000) + (0.9 \times 55{,}000) = 152{,}900$

NHB Attractions $= (4.1 \times 10{,}000) + (1.2 \times 7{,}000) + (0.5 \times 3{,}000) + (0.5 \times 55{,}000) = 78{,}400$

Note that the calculated attractions do not equal the production control totals. A procedure for balancing these numbers will be discussed later in this chapter.

It is possible to use the material provided in Table 3 for specific activity sites to develop trip-end estimates through aggregation for an entire urbanized area, corridor, or small area. With a generalized land-use map providing land allocated to various uses and with more specific details on certain generators (e.g., educational facilities and hospitals), total trip ends by analysis unit (e.g., block, zone, and district) can be developed for residential and nonresidential uses. The data in Table 4 or Table 5 can be used to develop a control total for the entire study area, as well as to adjust the total trip ends developed from Table 3.

To calculate trips produced in a study area (e.g., region, zone, district, and corridor), an estimate is required of the number of households by household size and one of the two "wealth" variables—either income range (tertiles in 1990 dollar base) or autos owned. With this estimate, the user can obtain from the tables for a particular urbanized area size the

- Average autos per household,
- Average daily person trips per household,
- Percent households by autos owned,
- Average daily person trips per household by number of autos per household, and
- Percent average daily person trips by purpose.

For example, if 1,000 households are in the low-income range in an urbanized area of 200,000 to 499,999 population, two methods can be used to compute the trip generation for these households. The first method is the aggregate method, which shows that 1,000 low-income households in an urbanized area of 200,000 to 499,999 population should produce 6.0 trips per household (Table 7). Therefore, a total of 6,000 trips would be produced by these households.

The second method for computing the trip generation for these 1,000 households is the disaggregate method. In this method, the households are first disaggregated into the expected number of households by auto ownership level. The trip generation is calculated for these households and then aggregated to estimate the total trip generation. This method is summarized as follows:

Trip Generation Data for Low-Income Households—Disaggregate Method (example)

• Households with 0 cars	=	17% or 170 HHs (Table 4)
• Households with 1 car	=	51% or 510 HHs
• Households with 2 cars	=	24% or 240 HHs
• Households with 3+ cars	=	8% or 80 HHs
• Trips by 0 car households	=	2.8/HH or 476 (Table 7)
• Trips by 1 car households	=	4.9/HH or 2,499
• Trips by 2 car households	=	8.6/HH or 2,062
• Trips by 3+ car households	=	11.5/HH or 920
• Total trips by all households:	=	5,957
• Trips generated: HBW	=	17% or 1,013 (Table 9)
• Trips generated: HBO	=	60% or 3,574
• Trips generated: NHB	=	23% or 1,370

These two methods result in trip generation rates for the study area that vary by less than 1 percent.

The HBW and HBO trips are generated at the household, whereas the NHB trips are generated elsewhere.

At the end of the application of the trip generation data presented here, the user will have a matrix of zones with the necessary information—that is, the total productions (person trips by purpose) and the attractions for each zone—to move on to the next step, balancing production and attractions.

BALANCING PRODUCTIONS AND ATTRACTIONS

The last step in trip generation modeling is the balancing of regional trip productions and attractions. Because of the nature of the survey data used in this chapter to derive trip generation rates, the resulting productions and attractions include both internal-internal (I-I) and internal-external (I-E) trips by residents of the study area. In Chapter 5, definitions of I-E, external-internal (E-I), and through trips made by both residents and nonresidents of the study area are presented. That chapter also presents parameters and a technique for estimating external travel. Because the distribution of I-E and E-I trips is accomplished by using the gravity model structure presented in the next chapter, the regional total of trip productions (including trips produced at the external cordon) must be equal to the total of trip attractions (again, including the trips attracted at the external cordon).

The estimated total trips produced at the household level should be equal to the total trips attracted at the activity centers. Each trip must have two ends—a production and an attraction. In reality, the estimation of trip productions and attractions will not be exactly equal. While trip production and attraction rates may contribute to the imbalance, the majority of the difference can be explained by the estimation of the number of households, the socioeconomic characteristics of the households, and the estimation of the number of employees by type. To bring the regional totals in balance, either the zonal productions or the attractions are scaled to equal regional control totals. In the majority of cases, the control totals of trips are the regional totals of trip productions by purpose. This is because we generally have a greater degree of confidence in household data than we do in employment data. This is particularly true when the 100 percent decennial census data are used to develop the number of households by zone. The employment data from which the attractions are computed are less certain, not only on a regional basis but, more critically, at the TAZ level of geography. There are cases where trip attractions are used as the control total and productions are scaled to match attraction totals. Special generators and subarea studies with detailed information about employment and trip attractions are examples of instances where attractions would be the control for the balancing process.

Regional control totals must be calculated to balance productions and attractions. This is done for each purpose—HBW, HBO, and NHB. In this procedure, zonal attractions will be balanced to match regional productions. Regional productions and attractions consist of productions and attractions from TAZs, and productions and attractions from external stations.

Productions and attractions at external stations are a function of observed and forecast traffic counts at the stations and, therefore, are fixed and not factored. Productions and attractions at external stations, however, will not be in balance, and the difference must be balanced across zonal trips. As noted earlier, zonal trips include I-I, I-E, and E-I trip ends. The following equation is used to obtain the control total of trip productions:

$$CT_p = \sum P_z + \sum P_e - \sum A_e \qquad (3\text{-}1)$$

where

CT_p = the control total of productions,
P_z = trip productions for each zone,
P_e = trip productions at each external station, and
A_e = trip attractions at each external station.

Control totals are computed for each trip purpose. The next step is to compute the balancing factor for each trip purpose, using the following equation:

$$Factor = \frac{CT_p}{\sum A_z} \qquad (3\text{-}2)$$

where

$Factor$ = balancing factor (computed for each trip purpose), and
A_z = trip attractions at each zone (by purpose).

Each zone's trip attractions are then multiplied by the balancing factor (by purpose) to arrive at the final balanced trip attractions. The equation to use is

$$A_z' = Factor \times A_z \qquad (3\text{-}3)$$

where

A_z' = balanced trip attractions for each zone.

External station attractions are not factored. A final summation of productions and attractions by purpose for all zones and external stations should be made, and they should be equal. Any special generators should be handled in the same manner as external stations in the matrix balancing process. The last step is to replace the zonal NHB productions with zonal NHB attractions.

By definition, home-based trips (HBW and HBO) have one end of the trip in the zone in which the household is located. For non-home-based trips, we know how many NHB trips are made by the household; however, we do not know where they take place. The regional total of NHB trips produced by the households is judged to be the best estimate of the control total of NHB trips, but the NHB attractions are judged to be the best estimate of where these trips take place. Therefore, the zonal NHB productions are replaced by the balanced NHB attractions. While home-based trips do not have to be equal by zone, NHB productions will be equal to NHB attractions for each zone.

The following example illustrates the balancing process. Note that there are fewer trips for the external stations than would be typically found in order to have the proper ratio of zonal and external station trips for this example. Any special generators would be treated the same as an external station in the balancing process.

Zone	Unbalanced Work Trips		Balanced Work Trips	
	Productions	Attractions	Productions	Attractions*
1	100	4,000	100	4,540
2	300	3,000	300	3,405
3	500	5,000	500	5,675
4	1,000	1,000	1,000	1,135
5	1,500	1,200	1,500	1,362
6	1,000	1,500	1,000	1,703
7	5,000	500	5,000	568
8	7,500	100	7,500	114
9	3,000	1,500	3,000	1,703
10	1,000	2,000	1,000	2,270
Subtotal	20,900	19,800	20,900	22,475
External Station				
11	500	50	500	50
12	1,000	100	1,000	100
13	250	25	250	25
Subtotal	1,750	175	1,750	175
Total	22,650	19,975	22,650	22,650

*Calculated by multiplying unbalanced attractions by 1.1351 (see below).

The balancing factor for the above example is computed as

$$Factor = \frac{20{,}900 + 1{,}750 - 175}{19{,}800}$$

$$Factor = 1.1351$$

The balanced trip productions and attractions are now ready to be used as input to the trip distribution model presented in the next chapter.

LIMITATION OF DATA

In using the information in Table 3, the user must keep in mind that the values given are averages and that they may vary by location in an urbanized area, by size of urbanized area, and by location within the United States (e.g., East Coast versus West Coast). However, the material does provide estimates that are useful for many applications.

The trip data and car ownership data in Tables 4 through 7 and Table 9 have been summarized from a number of urbanized areas and grouped by population. Consideration must be given to the fact that trip rates for a specific area may vary significantly based on special characteristics (e.g., high proportion of retired persons and high tourism). Local data will provide more specific information for the area in question than the material presented in this chapter.

Although the data used for developing the parameters presented here showed little difference across regions or between urban sizes, it is clear that the urban form has an immense impact on the transportation system and that the transportation system has an immense impact on urban development. The shape individual cities assume as they grow affects the transportation system by influencing travel demand and the provision of transportation infrastructure and services. In turn, the provision of services and infrastructure determines the relative accessibility of various land parcels and thereby affects land use decisions and urban form.

Disaggregate analysis, such as the cross-classification at the household level reflected by the material presented here, produces results that can be applied at any level for which land use and related characteristics can be developed. Likewise, at the nonresidential end, sufficient disaggregation is desirable to allow a detailed accounting for any specialized land uses in the area of study.

CASE STUDY

The Asheville, North Carolina, case study was introduced in Chapter 2 along with a presentation of the transportation networks and the socioeconomic data for that region. The techniques described in this chapter have been followed to obtain trip productions and attractions and to balance productions and attractions.

Trip Productions

The estimation of trip productions using disaggregate travel-demand models typically uses a cross-classification of household size data with a measure of wealth, such as income or the number of automobiles available to the household. For this case study, however, no cross-tabulations were yet available from the *Census Transportation Planning Package* for the Asheville region. As a result, trip production rates were calculated by using the average values for the region, stratified only by household size. The average daily vehicle trips per household are taken from Tables 5, 6, and 9.

Since the trip productions are classified according to trip purpose, the information regarding trip purpose by household size was also used. These data can be found in Table 9.

The calculation of trip productions is performed easily with a computer spreadsheet. The input data can be arranged in five columns reflecting the household size groupings from one-person households through five-plus-person households. The output data are the three columns reflecting the trip purposes—home-based work, home-based other, and non-home-based. The person trip calculations are expressed by the following formulas:

$$\textit{Home-Based Work Productions} = 0.20 \times 3.7 \times HH(1) + 0.22 \times 7.6 \times HH(2) + 0.19 \times 10.6 \times HH(3) + 0.19 \times 13.6 \times HH(4) + 0.17 \times 16.6 \times HH(5)$$

$$\textit{Home-Based Other Productions} = 0.54 \times 3.7 \times HH(1) + 0.54 \times 7.6 \times HH(2) + 0.56 \times 10.6 \times HH(3) + 0.58 \times 13.6 \times HH(4) + 0.62 \times 16.6 \times HH(5)$$

$$\textit{Non-Home-Based Productions} = 0.26 \times 3.7 \times HH(1) + 0.24 \times 7.6 \times HH(2) + 0.25 \times 10.6 \times HH(3) + 0.23 \times 13.6 \times HH(4) + 0.21 \times 16.6 \times HH(5+)$$

where

$HH(n)$ = the number of households with n occupants.

These equations were used to calculate the trip productions for each of the 107 internal zones in the Asheville MSA. The total number of trip productions for the region is 383,006, which includes 76,033 HBW productions, 215,407 HBO productions, and 91,566 NHB productions.

Trip Attractions

Trip attractions were also calculated on a spreadsheet using the parameters from Table 8. The input data for these calculations include the employment by type—specifically retail, service, and other employment—and the total households for each of the 107 TAZs.

The home-based-work trip attractions for all 107 internal zones are calculated using the following equation:

$$\textit{Home-Based Work Attractions} = 1.45 \times \textit{Total Employment}$$

For the other two trip purposes, home-based other and non-home based, two different equations are used for calculating the number of attractions for each TAZ, depending on whether the zone is located within the CBD. In the City of Asheville, zones 1 through 15 are considered to be within the CBD, and the remaining zones, 16 through 107, are considered to be in the non-CBD category. The trip attraction rates for CBD zones 1 through 15 are calculated using the following equations:

$$\textit{Home-Based Other Attractions} = 2.0 \times \textit{Retail Employment} + 1.7 \times \textit{Service Employment} + 0.5 \times \textit{Other Employment} + 0.9 \times \textit{Total Households}$$

$$\textit{Non-Home-Based Attractions} = 1.4 \times \textit{Retail Employment} + 1.2 \times \textit{Service Employment} + 0.5 \times \textit{Other Employment} + 0.5 \times \textit{Total Households}$$

The trip attraction rates for non-CBD zones 16 through 107 are calculated using the following equations:

$$\textit{Home-Based Other Attractions} = 9.0 \times \textit{Retail Employment} + 1.7 \times \textit{Service Employment} + 0.5 \times \textit{Other Employment} + 0.9 \times \textit{Total Households}$$

$$\textit{Non-Home-Based Attractions} = 4.1 \times \textit{Retail Employment} + 1.2 \times \textit{Service Employment} + 0.5 \times \textit{Other Employment} + 0.5 \times \textit{Total Households}$$

For all internal zones, the trip attractions in the region totaled 383,741, of which 85,604 were HBW trips, 188,806 were HBO trips, and 109,331 were NHB trips. These totals reflect the unbalanced attractions before they are matched to the productions in the region. Appendix B-3 lists the productions and attractions for the three trip purposes for each of the 107 internal TAZs.

TABLE 10 Unbalanced trips

	Productions			Attractions		
	HBW	HBO	NHB	NBW	HBO	NHB
Internal	76,033	215,407	91,566	85,604	188,806	109,331
External	48,842	62,986	26,087	20,932	41,990	26,087
Total	124,875	278,393	117,652	106,536	230,796	135,418

TABLE 11 Balanced trips

	Productions			Attractions		
	HBW	HBO	NHB	NBW	HBO	NHB
Internal	76,033	215,407	91,566	103,943	236,402	91,566
External	48,842	62,986	26,087	20,932	41,990	26,087
Total	124,875	278,393	117,652	124,875	278,393	117,652

Balancing Productions and Attractions

The final step in the trip generation phase of travel-demand forecasting is the balancing of regional trip productions and attractions. The next step of the model, trip distribution, requires that the total number of regional trip productions equal the total number of regional trip attractions for each of the trip purposes. Table 10 summarizes the internal trip and external trip totals (see Chapter 5) before balancing.

The regional control totals for all three trip purposes are set to equal the combined internal plus external trip productions. For example, the control total for home-based work trips is set at 124,875 trips. The balancing process is accomplished by applying a balancing factor to the attraction trips for all internal TAZs. The balancing factor is designed to change the total number of internal attractions so that the total number of attractions, including external stations, equals the total number of productions. Following the same example for home-based work trips, the goal is to factor the 85,604 internal HBW attractions so that the total number of attractions equals the total number of productions. In order to factor the 106,536 total HBW attractions to equal the 124,875 productions, the internal HBW attractions must be factored to equal the total number of attractions, minus the number of external HBW trips (since external trips are based on existing traffic volumes, they are not factored). The balancing factor for HBW trips is therefore calculated as

$$\textit{HBW Factor} = (124{,}875 - 20{,}932) + 85{,}604 = 1.2142$$

Similarly, balancing factors are calculated for the other trip purposes as follows:

$$\textit{HBO Factor} = (278{,}393 - 41{,}990) + 188{,}806 = 1.2521$$

$$\textit{NHB Factor} = (117{,}652 - 26{,}087) + 109{,}331 = 0.8375$$

After the balancing factors are applied, the total numbers of productions are as summarized in Table 11. The total number of attractions for the internal and external zones is then 520,920, which matches the total productions for the region.

The final step in trip balancing is updating the non-home-based trips. Although the zonal estimates for NHB trip production are useful for determining the total number of NHB trips, they are not useful for determining where the trip is located because neither trip end for an NHB trip is at the household. After the NHB trip attractions are scaled so that the total attractions equal the total productions, the NHB trip productions in each zone are set equal to the NHB trip attractions.

The balanced productions and attractions for the three trip purposes are listed in Appendix B-5. These values for the productions and attractions are ready to be used in the trip distribution phase of model development in order to prepare the person trip tables. Therefore, the production and attraction data have been imported into the travel-demand forecasting software and saved in three origin vectors for the production data for the three trip purposes and three destination vectors for the attraction data for those same trip purposes.

CHAPTER **4**

TRIP DISTRIBUTION

INTRODUCTION

Trip distribution is the second major step in the travel modeling process. The first major step, Trip Generation (Chapter 3) provides a methodology for estimating trip productions and trip attractions or, in other words, how many trips have their start in each zone and how many trips have their end in each zone.

Trip distribution is the step that links the trip productions to the trip attractions for each zonal pair. Productions and attractions are not the same as origins and destinations. The tables that are produced by the gravity model must be converted to origin-destination (O-D) format, after mode split, before being assigned to the network. A method for converting these tables is presented in Chapter 8.

Trip distribution is a vital part of the planning process because it is the trip interchanges between each zone pair that eventually have to be accommodated by the transportation system. Figure 5 provides schematic representation of the trip generation and trip distribution process. In the schematic, the upper left-hand sphere represents a zone with 300 productions and 700 attractions. The 300 trips produced in the zone are distributed based on attractions in all three zones and distance between the zones. At the same time, the zone is attracting 700 trips from all three zones.

The critical factors of trip distribution are trip length and travel orientation (e.g., suburb to CBD and CBD to suburb) and the resulting magnitude of traffic and passenger volumes. In summary, the trip distribution models are designed to convert the trip production and attraction input data into trip tables that represent movements between the TAZs that constitute the region being modeled. The results of trip distribution are assigned to the highway and/or public transportation systems to determine the travel demand as related to the carrying capacity of the facilities in question.

BASIS FOR DEVELOPMENT

Trip-distribution models estimate trip interchanges between zones based on characteristics of the land-use pattern and the transportation system. Most distribution models have similar characteristics; trip interchange between areas is a function of the amount and type of land development and the spatial separation between zones.

The most common form of model used for trip distribution is the gravity model. The gravity model is used to distribute the trip productions and attractions estimated by the trip-generation model component. Gravity models are implemented as mathematical procedures designed to preserve the observed frequency distribution of trip lengths for each modeled trip purpose.

The gravity model structure can be calibrated and implemented using conventional transportation planning programs. Although the basic model structure is standard from area to area, there are differences in the methods of estimating calibration parameters and in the definition of the measure of separation between zones. The procedure to calibrate the gravity model is an iterative process in which travel time or impedance factors are developed for each trip purpose and a mathematical function, such as an inverse exponential function or a gamma function, is used to describe spatial separation.

Gravity model procedures produce a trip table for each trip purpose. The trip tables produced by these procedures can be factored to represent the proportion of travel projected to occur over an entire day, or any specific time period that needs to be investigated (see Chapter 8).

In some areas, growth factor techniques are used to develop future values for a known trip distribution by multiplying interchange values by adjustment factors calculated at the origins and destinations of the trips. Such adjustments are based on changes in land-use and socioeconomic characteristics, such as new development or a decline in family size in the zones of origin and destination.

In this chapter, the gravity model concept is reviewed, along with its mathematical definition. This overview is followed by a discussion of the parameters required for trip distribution, such as freeway and arterial travel speeds and terminal times, and default friction factor curves, look-up tables, and gamma functions by trip purpose. A method for splitting trip tables for corridor and subarea applications and an example application is included.

THEORY OF THE GRAVITY MODEL

The most widely used trip distribution procedure is the gravity model. As its name suggests, the gravity model for

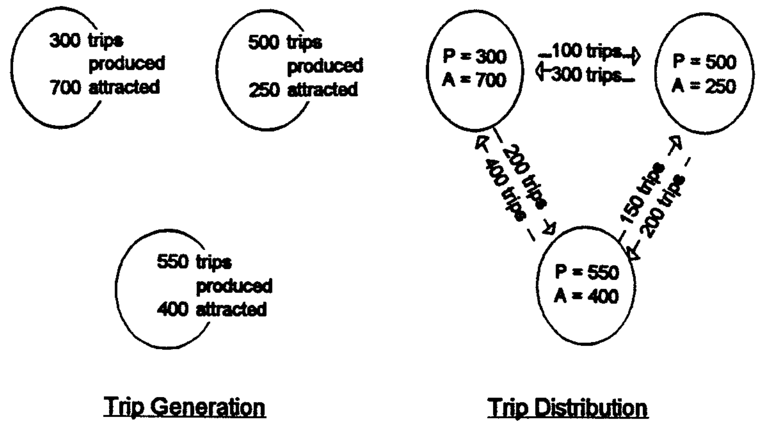


Figure 5. Diagrammatic representation of the trip generation and trip distribution process.

transportation planning is based on the gravitational theory of Newtonian physics. The Newtonian theory predicts that the force or attraction between bodies is directly proportional to the mass of the bodies and inversely proportional to the square of the distance between the bodies. Similarly, the gravity model of transportation planning predicts that the relative number of trips made between two geographical areas or TAZs, is directly proportional to the number of trip ends (productions or attractions) in each TAZ and inversely proportional to a function of the spatial separation (or travel time) between those two areas.

Therefore, zones with large amounts of activity tend to exchange more trips, and zones farther from each other tend to exchange fewer trips. Most modeling processes develop trip-distribution models for three to six trip purposes. Typically, the number of purposes is defined by resource constraints (i.e., each additional purpose requires added computer time and disk space to model) and the ability to project trip ends. One common set of purposes is HBW, HBO, and NHB.

Trip distribution can be improved by additional stratification. For example, HBO includes all home-based and non-work trip purposes including shopping, school, social-recreational, personal, and other trips. Shopping trips are attracted to retail locations and school trips are attracted to educational institutions. If retail employment and school locations can be forecast, the HBO distribution can be improved by stratifying the purpose into HBShop, HBSchool, and HBOther (including home-based personal and social-recreational trips).

The gravity model trip distribution technique is an adaptation of the basic theory of gravitational force.[1] As applied in transportation planning, the gravity model theory states that the number of trips between two TAZs will be directly proportional to the number of productions in the production zone and attractions in the attraction zone. In addition, the number of interchanges will be inversely proportional to the spatial separation between the zones. For example, suppose that from all of the zones in a region, four zones with the following characteristics were considered:

Zone	*Productions*	*Attractions*	*Distance from Zone A*
A	1,000	0	—
B	0	200	10
C	0	200	20
D	0	400	10

In the above example, the interchange between zones A and D would be greater than the interchange between zones A and B because the number of attractions in zone D is greater than the number of attractions in zone B and the distance between the two pairs of zones are equal. This demonstrates the direct relationship of trip attractions in the gravity model. Likewise, even though the attractions in zones B and C are the same, the interchange between zones A and B would be greater than the interchange between zones A and C because the distance between zones A and B is less than the distance between zones A and C. This demonstrates the inverse relationship of spatial separation in the gravity model.

Mathematically, the gravity model for trip distribution is defined as follows:

$$T_{ij} = P_i \left(\frac{A_j F_{ij} K_{ij}}{\sum_{k=1}^{zones} A_k F_{ik} K_{ik}} \right) \qquad (4\text{-}1)$$

where

T_{ij} = the number of trips from zone i to zone j,
P_i = the number of trip productions in zone i,

[1] Barton-Aschman Associates, Inc., *Plan Regional De Transportation San Juan*, San Juan, Puerto Rico (October 1992).

A_j = the number of trip attractions in zone j,
F_{ij} = the friction factor relating the spatial separation between zone i and zone j, and
K_{ij} = an optional trip-distribution adjustment factor for interchanges between zone i and zone j.

The friction factor is the primary independent variable and quantifies the impedance or measure of separation between two zones. Friction factors are inversely related to spatial separation of the zones—as the travel time increases, the friction factor decreases. It attempts to represent the behavior of the traveler in terms of the perception of distance. The willingness of the traveler to spend time or distance on a trip varies by trip purpose.

A number of different functional forms have been used for friction factors. In fact, early gravity models used hand-fitted friction factors. More recently, however, it has been discovered that the gamma function does a very good job for trip distribution. Using such a function produces a smooth, continuous curve. The gamma function can be stated as follows:

$$F_{ij} = a \times t_{ij}^{b} \times e^{c \times t_{ij}} \quad (4\text{-}2)$$

where

F_{ij} = the friction factor between zones i and j,
a, b, and c = model coefficients; both b and c should, in most cases, be negative; a is a scaling factor and can be varied without changing the distribution,
t_{ij} = the travel time between zones i and j, and
e = the base of the natural logarithms.

Some distribution models use k-factors, or socioeconomic factors, to modify the results of the gravity model to more closely match real trip characteristics. For example, river crossings tend to require a "barrier" effect—that is, the movement between zones separated by a bridge may not be as great as would be expected from using only quantifiable measures. The planner can use either k-factors or artificial times on the bridge links to match the actual interchange of travel.

TRIP DISTRIBUTION PROCESS

The trip-distribution process is usually implemented in two steps. The first step is the estimation of friction factors based on estimated or existing travel times. The second step uses the gravity model to distribute the trip productions and attractions estimated by trip generation.

The following information is necessary to proceed with the trip-distribution process:

1. Production and attraction trip ends by analysis area or TAZ for each trip purpose. These estimates are the result of the trip-generation analysis performed in Chapter 3.
2. A coded network. The basic network coding procedure is to first digitize the node coordinates, then to record the a-node and b-node combinations that are used to define each roadway network link. Network coding is outlined in Chapter 2.
3. Coded-link attributes such as link distance, functional classification, and posted speeds for each link in the network.

The development of travel impedance represented by friction factors and the implementation of the gravity model to create trip tables is discussed in the following sections.

TRAVEL IMPEDANCES

One of the major inputs to a gravity model trip distribution method is the creation of highway impedances. In areas with extensive transit systems, some modelers use composite impedances that incorporate both highway and transit times. Composite impedances should be calculated with care because the relationships of the composite's components are specific to the transit system being modeled. The weighing of each component must be carefully developed. In determining the travel impedance (path of least resistance between each pair of zones), travel times, distances, and/or tolls are summed for the links between each zone pair and the results are stored in a zone-to-zone travel impedance matrix. In order to calculate zone-to-zone travel impedance, the components that define impedance for the path-building must be defined. Time and distance estimates require link length and link speeds to be identified.

Link length may be part of the network definition (TIGER/line files carry link length, for instance) or it may be calculated using the x and y coordinates of the a-node and b-node that define the link (see Chapter 2, Building a Transportation Database). The value of including distance in the impedance calculation is that, if faced with two paths of equal or near-equal time, travelers will choose the path of lesser distance. In many urban areas free-flow travel times are used for creating the travel impedances, although an emerging trend is toward the use of congested speeds to build shortest-time paths for both distribution and mode-choice modeling.[2]

Link-specific speeds can be first estimated by simply carrying posted speeds on the links or using Table 12 to estimate link speeds by facility type and area type.

Once each link is defined with a length and a speed in the attribute file, shortest travel time paths can be built, and zone-to-zone travel impedance can be calculated.

[2]Parsons Brinkerhoff Quade & Douglas, Inc., *Review of Best Practices,* prepared for Metropolitan Washington Council of Governments, (December 1992) p.2-15.

TABLE 12 Link speeds by facility type and area type

Facility Type		Area Type: CBD Free Flow	Suburban Free Flow	Rural Free Flow
Freeway		60	60	60
Expressway		45	45	55
Principal Arterial	Divided	35	45	50
	Undivided	35	35	45
Major Arterial	Divided	35	45	40
	Undivided	25	35	35
Minor Arterial		30	35	35
Collector		15	30	30

Source: Various urban transportation studies.

INTRAZONAL TRAVEL TIMES

The matrix of travel times produced by most software packages will result in times for each zone pair but will not include the travel time within the zone. This travel time within the zone is called the intrazonal travel time. The trip-distribution model will not only distribute trips between zones but will also determine the number of trips that stay within the zone. Therefore, the average travel time for trips that stay within a given zone must be estimated. The intrazonal trips largely take place on the local street network that are not coded. An approximation of the intrazonal time can be made by a number of techniques. One popular technique is the nearest neighbor technique.

The nearest neighbor technique assumes that the travel time within a zone is equal to one-half the average travel time to the nearest adjacent zones. Many software packages have specific modules that apply this technique. The user may be asked to input either a list of neighboring zones for each zone, or parameters for the program to find the nearest neighbors (using the centroid coordinates) and compute the average travel time.

Another technique assumes that intrazonal travel times can be expressed as a function of the area of the zone and the intrazonal speed. When this method is employed, the intrazonal time for a TAZ may be calculated using the following equation:

$$\textit{Intrazonal Time} = 0.5 \times \sqrt{(\textit{Zonal Area})} \times 60 \\ + \textit{Intrazonal Speed}\,(\textit{Area Type})$$

where the intrazonal time is expressed in minutes, the zonal area is expressed in square miles, and the intrazonal speed in miles per hour varies by the area type of the zone. For example, the intrazonal speed for a CBD zone could be set at 15 miles per hour, and the intrazonal speed for a rural zone could be set at 30 miles per hour.

TERMINAL TIMES

Building the matrices of zone-to-zone travel times or travel impedances (skims) also involves adding terminal times to the over-the-network travel times. The nearest neighbor technique should be applied to the travel times before the terminal times are added. This is due to the fact that the terminal times are a function of area type and the neighboring zones may have different area types. The terminal times for the zones should be added after the nearest neighbor procedure is applied.

Terminal times represent impedances at both ends of a trip such as the amount of time and the time value of money required to walk to and from a transit mode, to park or access a parked car, to pay parking cost, and so forth. As such, terminal impedances vary by area type. Terminal times are added to the initial impedance times at both the origin and the destination end of a trip. Terminal times are typically estimated as a function of population and employment density within a traffic zone or district. If terminal impedances have not been estimated for an analysis region, the default values presented in Table 13 may be used.

CHOICE OF FRICTION FACTORS

Once the zone-to-zone travel times have been estimated, the gamma function can be applied to calculate friction factors for each zone pair. Friction factors from several calibrated models for smaller urban areas were used to produce Figure 6. These curves correlate to the gamma function coefficients presented in Table 14. If these coefficients are used

TABLE 13 Terminal times for different area types

Area Type	Terminal Time (minutes)
CBD	5
CBD Fringe	4
Urban	3
Suburban	2
Rural	1

in the gamma function presented in Equation 4-2, with travel times (impedances) of 1 to 60 minutes, the friction factors shown in Table 15 result.

The friction factors in Table 15 should cover the range of travel times for most small urban areas. If travel times exceed 60 minutes, the table should be expanded. It is not wise simply to assume the 60-minute friction factor for all times greater than 60 minutes. This would imply that travelers are insensitive to increases in travel times greater than 60 minutes. Friction factors should not be rounded to zero, as this would imply that no trips are interchanged for the given time factor.

Two goals should be considered when choosing or calibrating friction factors for use in a travel-demand model: (1) the average trip length should be reasonable; and (2) the trip-length frequency distribution should be reasonable.

Average Trip Lengths

The most desirable source with which to calibrate trip-length data is derived from a home interview survey conducted in the study area. If no home interview survey data are available, census journey-to-work data can be used as a source of average trip-length data for work trips in every Metropolitan Statistical Area (MSA) in the country. Average trip lengths for home-based work trips generally range from 15 to 20 minutes in smaller communities, up to as much as 25 to 30 minutes in large metropolitan areas.

The closest correlation that we have found between average trip length and urban area size relates the average trip length to the land area of the urbanized area. This correlation between trip length and land area is slightly stronger than the correlation between trip length and population. The average trip length for home-based work trips can be estimated using the following equation:

$$\textit{Average HBW Trip Length (minutes)} = 5.0 + 0.10 \times \sqrt{\textit{Land Area}}$$

Average trip length data for other trip purposes are not as readily available as for home-based work trips. One problem that we encountered with respect to home interview data is that other trip purposes are subject to a great deal of variation. Specifically, the number of home-based non-work trip purposes varies from one to five categories including school, college, shopping, personal, social-recreational, and other trip purposes. Also, analysis of home interview survey data collected for various urban areas has shown that the average trip lengths for other trip purposes are much less predictable than for work trips. For example, in some communities, school or college trips are relatively short, indicating the presence of a centralized campus, while in other communities school or college trips are relatively long, resulting either from a commuter type campus or a school busing program. In fact, the correlation between the different data sources is so shaky that it is difficult to say whether home-based non-work or non-home-based trips are longer or shorter than the other, in general.

The best correlation that we were able to find regarding trip lengths for other trip purposes relates the average trip length for home-based work trips to the average trip length for all other trip purposes combined, which we will refer to as non-HBW trips. For urbanized areas with populations of less than 500,000, the average trip length for the non-HBW trip purposes is typically 75 percent to 85 percent of the

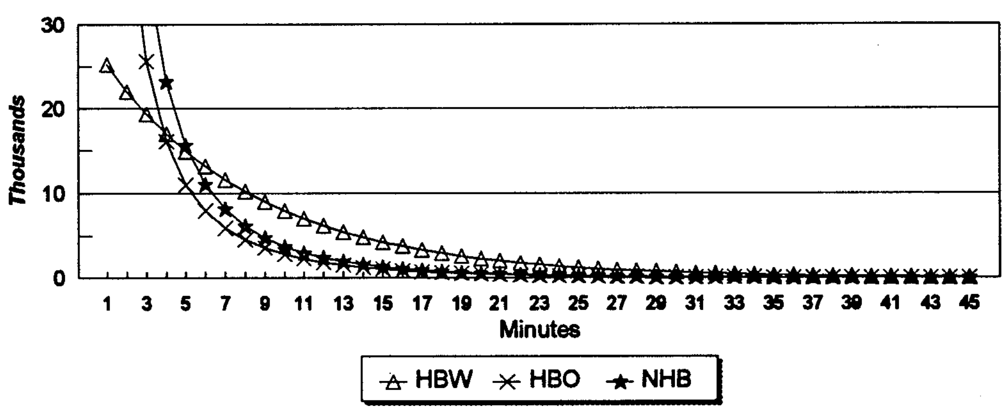


Figure 6. Synthetic friction factor curves by purpose.

TABLE 14 Gamma function coefficients for friction factors

Trip Purpose	a	b	c
HBW	28,507	-0.020	-0.123
HBO	139,173	-1.285	-0.094
NHB	219,113	-1.332	-0.100

Note: for use in the following formula, the "a" is a constant scaling factor which may be omitted.

$$F_{ij} = a \times t_{ij}^{b} \times e^{c \times t_{ij}}$$

average trip length for HBW trips. (For larger metropolitan areas of over 1,000,000 population, the ratio ranges from 60 to 70 percent of the HBW trip length.)

Trip-Length Frequency Distribution

Along with the average trip length, another indicator of the distribution of trips in trip tables is the trip-length frequency distribution (TLFD), which describes the shape of the curve that is summarized by the average trip length. For example, Figure 7 displays the TLFDs for HBW and non-HBW trips made in the San Francisco MSA. These curves display the distribution of trip lengths that, in combination, average 24 minutes per home-based work trip and 14 minutes per trip for other purposes.

Figure 8 displays a similar set of trip distribution curves for a much smaller urbanized area—Santa Barbara, California. Comparison of the two figures shows that the relationship between the HBW and non-HBW curves for the two regions is remarkably similar. For both areas, the distribution of non-HBW trips peaks at between 5 and 10 minutes per trip and then falls sharply, with very few trips over 30 minutes in length. The home-based work curves, on the other hand, peak between 10 and 15 minutes and fall more gradually, with tails approximately twice as thick as in the non-HBW curves.

The most striking difference between the HBW and non-HBW curves is the presence of very short trips in the non-HBW trip purposes and the lack of these very short trips in the HBW curves. Notice that the non-HBW curve for San Francisco is quite different from the HBW curve for Santa Barbara, even though they both represent an average trip length of 14 minutes per trip.

Look-Up Tables Versus Formulas

The application of the friction factors in the trip-distribution model depends on the required format of the software package. Many packages require the friction factors to be input as a look-up table with a corresponding factor for each travel time increment (usually 1 minute). The data in Table 15 can be used for these cases. Other programs allow for the input of a friction factor equation. In these cases, the gamma function can be input using the coefficients presented in Table 14.

If trip-length frequency distribution data are available (from a home interview survey, an existing model, or census data), an iterative process can be used to calibrate the friction factors to match the observed trip-length frequency. Each iteration of the calibration consists of the following steps:

1. Determine the number of observed trips in each time period for each purpose: HBW, HBO, and NHB. This is called the observed trip-length frequency.
2. Calculate an initial friction factor for each time period. A spreadsheet software package makes this relatively easy by filling one column with numbers from 1 to 60 (minutes) and applying the log-linear form of the gamma function to each time increment. Initially the coefficients presented in Table 15 may be used.

   The transformation of the gamma function to a log-linear function is:

   $$\ln(f) = \ln(a) + b \times \ln(t) + c \times t \tag{4-3}$$

3. Current iteration friction factors for each time interval (usually 1 minute) included in the trip-length frequency distribution are factored by the ratio of the observed number of trips in the time interval (from the observed trip-length frequency distribution) divided by the current number of trips in the time interval:

   $$F_t^{i+1} = F_t^i \times \frac{T_t^{obs}}{T_t^i} \tag{4-4}$$

   where

   F_t^{i+1} = the friction factor for time interval t for iteration $i + 1$,
   F_t^i = the friction factor for time interval t for iteration i,

TABLE 15 Synthetic friction factors

Minutes (impedance)	HBW	HBO	NHB
1	25,214	126,632	198,293
2	21,990	47,295	71,303
3	19,291	25,562	37,607
4	16,963	16,072	23,203
5	14,936	10,979	15,601
6	13,161	7,904	11,075
7	11,605	5,900	8,163
8	10,236	4,522	6,184
9	9,032	3,537	4,784
10	7,972	2,811	3,763
11	7,037	2,263	2,999
12	6,213	1,841	2,417
13	5,486	1,511	1,966
14	4,845	1,250	1,612
15	4,280	1,041	1,331
16	3,780	872	1,105
17	3,339	734	923
18	2,950	620	774
19	2,607	527	652
20	2,303	449	551
21	2,035	383	467
22	1,798	329	397
23	1,589	282	339
24	1,404	243	290
25	1,241	210	248
26	1,097	182	213
27	969	158	184
28	857	137	158
29	757	119	137
30	669	104	118
31	592	90	102
32	523	79	89
33	462	69	77
34	409	60	67
35	361	53	58
36	319	47	51
37	282	41	44
38	249	36	39
39	221	32	34
40	195	28	30
41	172	25	26
42	152	22	23
43	135	19	20
44	119	17	18
45	105	15	15
46	93	13	14
47	82	12	12
48	73	10	10
49	64	9	9
50	57	8	8
51	50	7	7
52	44	6	6
53	39	6	6
54	35	5	5
55	31	4	4
56	27	4	4
57	24	4	3
58	21	3	3
59	19	3	3
60	17	3	2

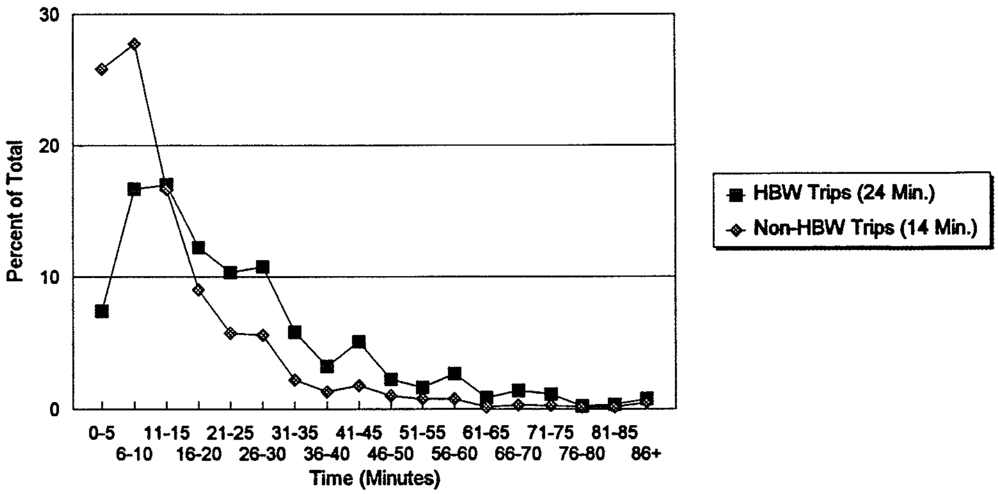


Figure 7. Trip-length frequency distribution for San Francisco, California.

T_t^{obs} = the observed number of trips in time interval t, and

T_t^i = the estimated number of trips in time interval t for iteration i.

4. The revised friction factors are used as independent variables in a linear regression to estimate revised gamma function model coefficients for the next iteration. (The natural log of the revised friction factor is the dependent variable. The time increment and the natural log of the time are the independent variables.) The coefficients of the converted log-linear regression model can be taken directly from the regression output or estimated with a statistical analysis program.

The iterative calibration process stops when the model coefficients become stable. This normally takes four or five iterations, depending on the choice of values for the initial iteration.

The friction factors directly influence trip length (in minutes). Therefore, the reasonableness of the friction factor is reflected in the forecasted average trip lengths. The faster the friction factor decreases (see Figure 4), the shorter the average trip length. The average trip length for home-to-work trips is available for urbanized areas as part of the census journey-to-work data.

CREATION OF TRIP TABLES

With an estimate of the impedance (friction factors) between zones, and the attractions and the productions within each zone, the trips can be distributed from all zones to all other zones. This process includes iterations to balance the matrices to ensure that the total attractions and productions

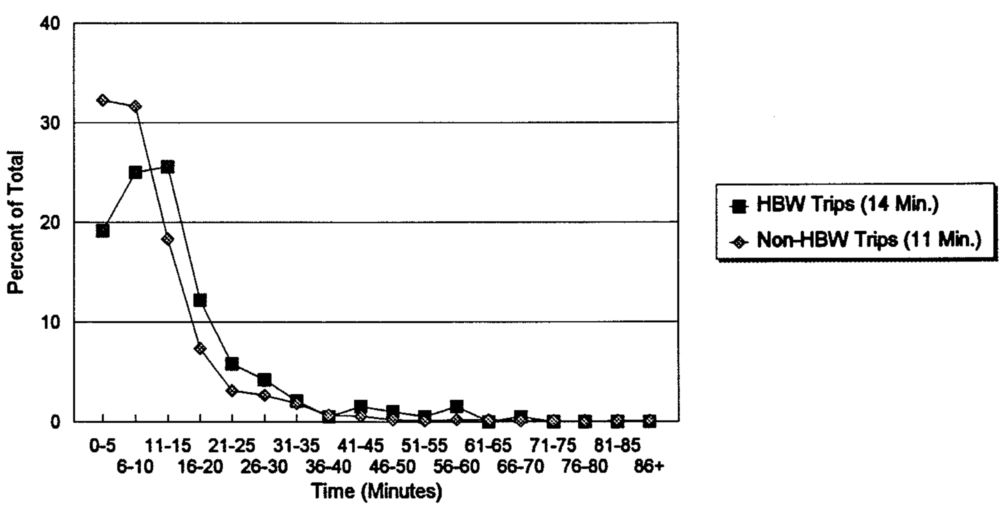


Figure 8. Trip-length frequency distribution for Santa Barbara, California.

(row and column totals) match the total productions and attractions in each zone. The most common way to balance the zonal productions and attractions is the Fratar method.

The trip tables that are produced by the gravity model are in the production-attraction format. Before these trips can be assigned to the network they normally are converted to origin-destination format. Chapter 8 outlines a procedure to create an origin-destination format from a production-attraction trip table. Production-attraction format trip tables are used as an input to the mode-choice model, primarily because for non-auto modes the production and attraction ends often have different access modes. For example: at the home end of a work trip, the traveler might drive to the bus stop or rail station, but at the work end, the traveler must walk because he or she does not have access to a car.

If a subarea analysis is being performed, then the following section will be useful.

METHOD FOR SPLITTING TRIP TABLES FOR CORRIDOR AND SUBAREA APPLICATIONS

A smaller sized zone structure is required in corridor or subarea studies that use the travel-demand model. This produces traffic assignment for a finer level of roadway analysis. The first step in this type of analysis is to modify the trip table for the desired new zone system. This requires the splitting of zones within the study area and aggregating zones outside the study area to districts. The aggregation of zones to districts is done by simply adding the zones' trips within the new district together. Historically this aggregation was done to reduce the run time on the mainframe computer. With the power of the microcomputer application of the travel-demand model, this aggregation may not be necessary. The splitting of the trip table to smaller zones and a procedure for splitting the zones are presented below.

The splitting of a zone into smaller zones is the splitting of trip productions and attractions of the old zone. The splitting of the trip table should always be done by purpose. The following steps can be followed to split a trip table:

1. Compute productions and attractions for new zones, by purpose, using the new zones' socioeconomic data. The total productions and attractions for the new zones must match those for the old zone.
2. Compute percent of old zone's productions and attractions for each new zone.
3. Compute trip interchange percentages for the new zones by multiplying the percent productions times the percent attractions for each of the zone pairs. The sum of all percentages should equal 100 percent.
4. Multiply the percentages obtained in Step 3 by the old zone trips to obtain new zone trip interchanges. Check the sum of new zones' trips to see if it matches the old zone's total.

The following example illustrates this procedure

Trips from Zone 1 to Zone 2	Old Zone	New Zones	
	$P_1 = 1{,}000$	$P_{11} = 700$	70%
		$P_{12} = 300$	30%
200		$A_{21} = 500$	25%
	$A_2 = 2{,}000$	$A_{22} = 1{,}500$	75%

	New Zone Percentages		New Zone Trips	
	Attraction Zone		Attraction Zone	
Production Zone	21	22	21	22
11	17.5%	52.5%	35	105
12	7.5%	22.5%	15	45

where

P_1 = Productions in old zone 1,
A_2 = Attractions in old zone 2,
P_{1j} = Productions in new zone j of old zone 1, and
A_{2j} = Attractions in new zone j of old zone 2.

Using a spreadsheet or database program, the user can create a table of equivalency of new zones to old zones and the percentage of old zone productions and attractions in each new zone. Then the new zone structure trip table can be created. Some transportation planning packages include modules to split trip tables.

CASE STUDY

The distribution process for the Asheville, North Carolina, case study was implemented in two parts. First, a matrix of zone-to-zone travel times was estimated, and then the gravity model was used to produce a full trip table for each trip purpose.

This distribution process was repeated in order to use congested travel times as the measure of impedance for the ultimate traffic assignments. The free-flow times were used to perform the first distribution of trips for each trip purpose. These trip tables were converted into a daily trip table and assigned to the highway network with an equilibrium assignment. The result of this assignment was a set of traffic volumes and congested speeds for each link in the highway network. These congested speeds were used to produce a second matrix of congested travel times, which were used to perform a second application of the trip-distribution model, which resulted in the ultimate trip distribution.

Estimation of Travel Times

The free-flow zone-to-zone travel matrix was constructed using the default speeds posted on each link in the Asheville highway network. Speeds were set at 55 mph on freeways, 45 mph on major arterials, and 35 mph on minor arterials. Travel time was calculated using the simple relationship:

$$\textit{Travel Time (in minutes)} = \frac{\textit{Link Length (in Miles)} \times 60}{\textit{Speed (in mph)}}$$

The transportation planning software was used to produce the matrix of travel times, or travel skims, based on the minimum time path between each pair of zones. These free-flow travel times were based on speed and distance only; no volume delay was included.

Intrazonal Times

The free-flow matrix did not contain any intrazonal travel times, which represents the travel time required to make a trip wholly within a single TAZ. An intrazonal travel time matrix, which is essentially the diagonal of the 107 by 107 matrix of internal zones, was produced using the nearest neighbor method. This consisted of identifying the zones adjacent to each of the 107 internal zones, taking the free-flow travel time from the zone of interest to all adjacent zones, calculating a mean for that set of times, and halving that value to arrive at the assumed intrazonal travel time. These steps resulted in intrazonal times ranging from 0.54 minute to 4.33 minutes, with an average value of 1.85 minutes.

Terminal Times

Terminal times represent impedances at both ends of a trip, such as the time required to park or access a car, parking cost, etc. For the Asheville case study, the study area was assumed to have three kinds of area types: CBD, suburban, and rural. Zones 1 through 15 are designated as CBD zones and all trip-ends at those zones have a terminal time of 5 minutes. Zones 16-59, 61, 62, 65-71, 74, 77-80, 82, and 83 are designated as suburban zones and have terminal times of 2 minutes for each trip-end. The remainder of the internal zones are designated as rural zones and have a 1-minute terminal time associated with all trip-ends. The average terminal time for the 107 internal TAZs is 2.2 minutes.

The total travel time was calculated for each zone-to-zone pair by adding the terminal times at both the origin and destination ends of the trip to the free-flow travel time or to the intrazonal travel time in the case of intrazonal zone pairs.

Choice of Friction Factors

The gamma function was used to estimate the travel impedances between zones in the Asheville region. The calculation of friction factors for each zone pair was performed within the travel-demand model software by using a matrix calculator. The preliminary friction factors used in this case study were produced by using the gamma function coefficients listed previously in this chapter.

The coefficients listed below for the three trip purposes were used for the first application of the gamma function:

Trip Purpose	a	b	c
Home-Based Work	100	-0.020	-0.125
Home-Based Non-Work	100	-1.300	-0.100
Non-Home-Based	100	-1.350	-0.100

For example, the home-based work friction factors were calculated using the equation:

$$HBW\ Friction\ Factor_{i,j} = 100 \times Time_{i,j}^{-0.020} \times e^{Time_{i,j} \times (-0.125)}$$

for all interchanges between origin zone i (from 1 to 123) and destination zone j (from 1 to 123).

The final step in the calculation of the friction factors was to set the values for the external-external zone pairs to zero. This adjustment was performed in order to prevent the gravity model from distributing any trips to external-external zone pairs. (Otherwise, the distribution model and the through traffic model would combine to overestimate the number of through trips made in the region.) A friction factor value of zero was used to replace the calculated value for trips with both origin and destination zones between 108 and 123.

Creation and Assignment of Free-Flow Trip Tables

After the friction factor matrices were created for the three trip purposes, the trips were distributed using the gravity model component of the travel-demand modeling software. The balanced productions and attractions by trip purpose were set as the row and column control totals. The Fratar method was then applied to the trip ends so that the row and column totals matched the total productions and attractions in each zone.

The output of the distribution process was a set of three person-trip tables. These matrices contain the same number of trips as the trip-generation control totals: 124,875 home-based work trips, 278,393 home-based other trips, and 117,652 non-home-based trips. However, unlike the production and attraction vectors, the person-trip tables are two-dimensional and reflect the movement of trips between zones.

Since the distribution of trips is calibrated to the trip length in minutes for each trip purpose, it is useful to review the trip lengths after applying the gravity model. Average trip length was obtained by weighting the free-flow travel time matrix, including intrazonal times and terminal times, with the person-trip tables. The trip lengths for the first application of the gravity model are as follows: home-based work—16.9 minutes; home-based other—14.4 minutes; and non-home-based—14.8 minutes.

Two reasonableness checks should be performed on these results. First, the average trip length for home-based work trips resulting from the gravity model should be compared to the average home-based work trip length derived from the 1990 census data. The 1990 journey-to-work statistics show that residents of the Asheville MSA reported an average home-based work trips length of 18.7 minutes. The average trip length produced by the gravity model, using free-flow speeds to build the impedances, should be slightly less than the average trip length reported by actual commuters, who tend to experience congested traffic during their home-based work trips. The average modeled travel time of 16.9 minutes, achieved with the use of the default parameters, passes this reasonableness check.

The second reasonableness check suggests that the average trip length for home-based other trips and non-home-based trips should be approximately 80 percent of the average home-based work trip length. For the Asheville MSA, this corresponds to 15.0 for home-based non-work and non-home-based trips. The modeled results, using the default coefficients for the gamma function, produce average trip lengths of 14.4 minutes and 14.8 minutes for home-based non-work and non-home-based trips, respectively. Since these values are based on free-flow speeds, they are well within the range of reasonableness.

Aside from trip lengths, another way to check the reasonableness of the trip-distribution results is by comparing the trip table data to any data regarding observed travel patterns. Such data, if they existed, would usually come in the form of trip movements between districts or groups of zones, which could be compared to the model estimated interchanges. Unfortunately, such data do not exist for the Asheville MSA.

Creation and Assignment of Congested Trip Tables

The estimation of congested travel times is similar to the process used to estimate the free-flow travel times. The major difference between the two processes is that the travel time function used to build the congested travel times assumes that the link speeds are subject to volume delay. The person trips resulting from the free-flow trip distribution were converted to vehicle trips, and the production-attraction format was changed to origin-destination format. An equilibrium assignment was performed and the congested travel times between zones were saved in a matrix. The congested trip time matrices were completed by calculating the congested intrazonal times and adding the terminal times to the congested travel times. The revised friction factors were calculated and the gravity model was applied to create new person-trip tables based on the congested times.

Average trip lengths were also calculated for the revised person-trip tables based on the congested travel time. Once again the travel-time matrices were weighted by the person trip tables. Model-produced congested trip lengths were: home-based work—17.7 minutes; home-based other—14.9 minutes; and non-home-based—15.4 minutes.

The estimated travel time increased slightly for all three trip purposes as the result of the congested travel times. The Asheville region probably does not experience a great deal of congestion, which can help explain the relatively small degree by which the average trip lengths changed.

Since the average trip length for home-based work trips was approximately 1 minute less than the target value, the researchers performed two more iterations of the trip-distribution model to achieve a more acceptable average travel time for this trip purpose. The coefficients listed below were the ultimate coefficients used to apply the gamma function for the three trip purposes:

The resulting trip tables had average trip lengths of 18.7 minutes for HBW, 15.0 minutes for HBNW, and 15.4 minutes for NHB trips. The trip-length frequency distribution curves for these three trip purposes are displayed in Figure 9.

Trip Purpose	a	b	c
Home-Based Work	100	-0.300	-0.070
Home-Based Non-Work	100	-1.250	-0.100
Non-Home-Based	100	-1.350	-0.100

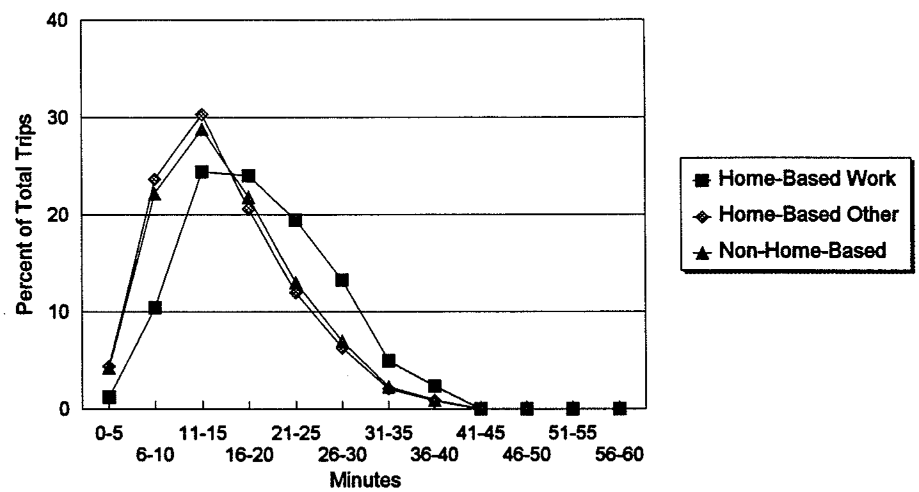


Figure 9. Model-generated trip length distribution—by trip purpose.

CHAPTER 5

EXTERNAL TRAVEL ESTIMATION

INTRODUCTION

External trips are trips that have at least one end outside the study area defined by an encircling cordon line. When both the origin and destination of a trip are outside the cordon line, the trip is termed a through trip or external-external trip. When one trip end is outside the study area, the trip is classified as an external-internal or internal-external trip. The point on the roadway where the area cordon is crossed is referred to as an external station. Figure 10 displays the various types of external travel.

Because of the small proportion of external travel relative to total travel, the effort on measuring and modeling external travel has been less intensive than for internal travel. However, while the percentage of total travel that is external may be small, decisions regarding improvements to facilities that carry high percentages of external trips must be made with some degree of confidence in the estimate of external travel behavior. Very little is known about the population and employment characteristics at the end of the trip that is outside the internal study area. Travel is measured in vehicle trips instead of person trips, and transit trips from outside the region are often ignored. Future-year external travel is typically growth factored, using an average annual growth rate.

Historically, the most popular method for collecting external travel data is to conduct a roadside intercept survey at the regional cordon. Very few roadside surveys have been conducted in recent years, primarily because of the concern that stopping vehicles on the highway would be perceived as an unacceptable intrusion on the motorist. Poorly conducted roadside surveys have resulted in unnecessary delays and extended queues of vehicles. Alternative, nonintrusive survey methods have been used to collect external survey data. These include the following:

- The recording of license plate numbers (either through the use of video tape, direct reading of the plates into a tape recorder, or direct entry into a notebook computer by a survey recorder) and matching plate numbers at the cordon to obtain through trip tables; or
- The recording of license plate numbers (using one of the above methods), matching the number with Department of Motor Vehicle registration, and mailing out a survey form to the registered owner of the vehicle.

The first method provides data only on through travel and does not allow for the estimation of observed external-internal or internal-external travel. The second method, although providing data on all external travel, has the disadvantage of a definite time lag between the time the trip is actually made and the time the survey form is received by the driver. Even with direct entry of the plate number into a computer and overnight matching of numbers to registrant, it is at least 3 days (and more likely 4 to 5) before the registrant receives the survey forms. The registrant may not recall exactly where the trip was made or in some cases was not the driver of the vehicle. For these reasons, the roadside intercept is still the most cost-effective method for obtaining external travel data.

Techniques for estimating the number of trips generated within an area were discussed in Chapter 3. Depending on the size and geography of the study area, a majority of these trips will take place completely within the study area. The larger the study area's geographic limits, the less impact that external travel has on total travel.

This chapter presents a method for estimating external travel in a study area where an external survey is not available or possible. This step is typically done before trip distribution because the external-internal trips are distributed using the same procedure as internal trips. Through trips are needed before a traffic assignment can be performed. As will be noted in the next section, the procedure for estimating external travel is applicable only to smaller sized urban areas.

BASIS FOR DEVELOPMENT

In most regional or large-area studies, an external cordon survey is a required input to the travel modeling process. An external survey can provide accurate information on trip interchanges, particularly for through trips. In addition to the trip origin and destination, a number of other variables are needed to model external travel. The following information is typically asked during a roadside survey of vehicles entering the study area:

1. *Vehicle Class.* Vehicle class is important from several points of view. The vehicle's impact on the highway varies by size and weight, as does its impact on capacity and air quality. The minimum number of categories

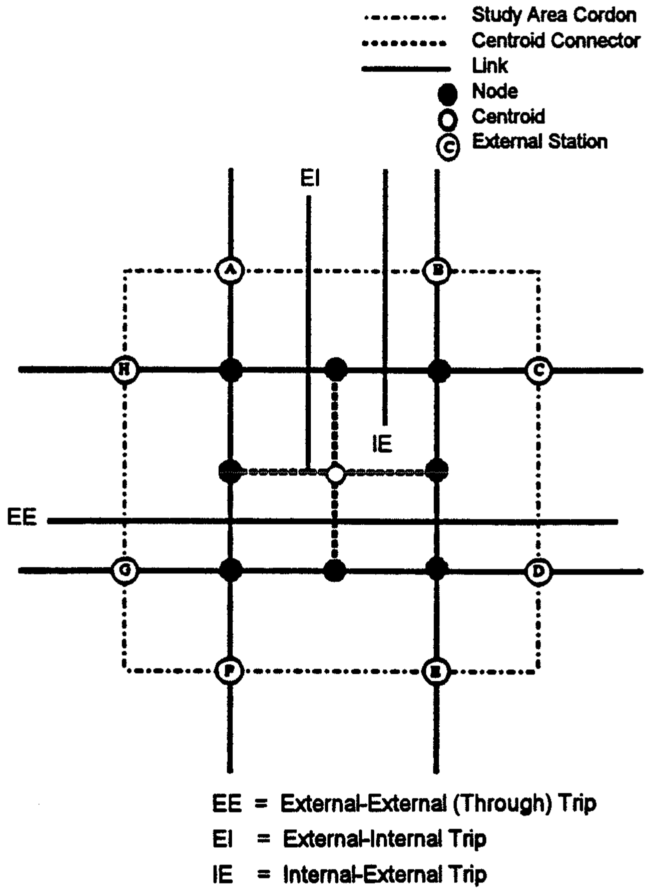


Figure 10. External travel diagram.

would seem to be cars, vans, and pickups as a group and trucks as a group. Some argument might be made for dividing trucks into light, medium, and heavy, and combining light trucks with automobiles, vans, and pickups to yield three strata. Of course, each added stratum imposes additional base year data requirements and methodological requirements.

2. *Trip Purpose.* The major person-trip purposes are work, shop, and school. The work trips typically have a longer trip length than do the shop trips. A minimum stratification probably should include work and other. No stratification of truck trips by trip purposes seems necessary.
3. *Resident Status.* The resident status for persons is simply whether they reside in the region, and for trucks, where they are garaged; i.e., if a truck is garaged in the study area normally, it is considered a resident.

The smaller area- and sketch-planning studies for which this report has been designed may not have the resources to conduct a survey of external travel. An alternative method for estimating external travel is required and presented in this chapter.

The trip rates presented in Chapter 3 represent all trips made by residents, including trips in which one end of the trip is outside the study area. These internal-external trips are part of the total productions for a zone. To create a trip table of internal-external movements, the relative attractiveness of each exit route or external station is needed.

The estimation of external trips assumes that counts of the average daily traffic (ADT) on each of the major highways entering the study area at the cordon line are available. The sum of the counts for all stations, representing total cordon crossings, is greater than the total number of external trips because through trips cross the cordon twice. If possible, classification counts should be conducted to determine the split between autos and trucks.

The following steps are required for developing internal-external, external-internal, and external-external volumes:

- Estimation of through trips at each station,
- Distribution of through trips between stations,
- Estimation of external-internal trip productions and attractions, and
- Distribution of internal-external and external-internal trips between internal zones and external stations.

The procedure presented below produces reasonable results for small urban areas, particularly those with populations of 50,000 or less. For interstates and principal arterials, the rates appear to be reasonable for areas with a population up to about 100,000. For areas with populations greater than 100,000, the method produces through trip percentages that are less than zero, an illogical conclusion. The research conducted in this project yielded very little in the treatment of external travel behavior. The characteristics of external travel are much more a function of the unique geographic location and character of each urban area and, as such, the opportunity for transferring external travel characteristics between urban areas is limited. The procedures presented below should be applied with extreme caution and the reasonableness of the results must be thoroughly reviewed.

ESTIMATION OF THROUGH TRIPS AT EXTERNAL STATIONS

The first step in the process will be to estimate through trips at the external stations. Previous research has shown that the percent of through trips at and between stations is related to the functional classification of the external highway, the connectivity of each external station pair, the average daily volume at the station, the relative size of the station, the size of the population of the study area, and the vehicle composition at the external station.

Through trips as a percent of all external trips vary from place to place. Data for selected cities are shown in Table 16.

TABLE 16 Through trips as a percent of external trips

Place	1990 Population	External - Internal Internal - External	External - External (Through)	Total
Chicago	6,070,000	95%	5%	100%
Twin Cities	2,464,000	93	7	100
San Diego	2,498,000	88	12	100
Phoenix	2,122,000	86	14	100
Reno	255,000	87	13	100
Wausau	37,000	80	20	100

Through trips as a percent of total external trips range from 5 percent in the largest region, Chicago, to 20 percent in the smallest region, Wausau.

D.G. Modlin, Jr., working with the State of North Carolina,[1,2] developed a model for estimating through trip ends at a station on the cordon of a study area. The model used functional classification of the highway, the ADT at the external station, the percentage of trucks (excluding vans and pickups), the percentage of vans and pickups, and the population of the study area.

The equation for estimating the percent through trips at an external station is

$$Y_i = 76.76 + 11.22 \times I - 25.74 \times PA - 042.18 \times MA + 0.00012 \times ADT_i + 0.59 \times PTKS_i - 0.48 \times PPS_i - 0.000417 \times POP \quad (5\text{-}1)$$

where

- Y_i = percentage of the ADT at external station i, that are through trips,
- I = interstate (0 or 1),
- PA = principal arterial (0 or 1),
- MA = minor arterial (0 or 1),
- ADT_i = average daily traffic at external station i,
- $PTKS_i$ = percentage of trucks excluding vans and pickups at external station i,
- PPS_i = percentage of vans and pickups at external station i, and
- POP = population inside the cordon area.

In equation 5-1, an external station can be only one of the three functional classifications. For that classification, the value of the variable is 1; for the other two, the value will be 0 (i.e., functional class is a dummy variable).

For illustration, given a route with ADT of 7,000, 6 percent heavy and medium trucks (excluding vans and pickups), and 10 percent vans and pickups, the following through trips percentages shown in Table 17 would be predicted by functional class using equation 5-1.

Because total through-trip percentages can vary substantially, it is important that the overall through trips be reasonable and the total should be checked after application of the equation. Regression models are particularly susceptible to error when used outside of the range of data used for the initial fitting or calibration.

If classification counts are not available at the cordon, the percentage of trucks at the external stations must be estimated. In *NCHRP Report 187,* total areawide truck trips were presented as a percent of areawide vehicle trips. At the time that report was released, truck traffic represented anywhere from 27 percent of total trips in areas with less than 100,000 population to 16 percent of total trips in the largest urbanized areas. Recent studies suggest that trucks are a smaller portion of the total vehicles on the road now, because of the increase in personal nonwork trips. A truck percentage between 5 percent and 15 percent of the total trips might be more realistic.

Once the percent of through trips crossing the cordon is estimated, the number of through trips can be calculated by station.

Using the example problem from Table 17, assume that an area with a population of 25,000 had a minor arterial with counts of 3,600 inbound and 3,400 outbound for a total of 7,000 ADT. The total through trips at the station would equal 24 percent of 7,000 or 1,680 crossings. This would be split into 864 through trips entering the area and 816 through trips leaving the area. The remaining 5,320 crossings have a trip end in the study area.

DISTRIBUTION OF THROUGH TRIPS BETWEEN STATIONS

The distribution of the estimated through-trip ends from an external station to each of the other external stations is the next step in obtaining a matrix of through trips among sta-

[1] David G. Modlin, Jr. *Synthesis of Through Trip Patterns in Small Urban Areas,* Department of Civil Engineering, North Carolina State University, Raleigh (1971).

[2] David G. Modlin, Jr., "Synthesized Through-Trip Table for Small Urban Areas," *Transportation Research Record 842,* Transportation Research Board, National Research Council, Washington, DC (1982).

TABLE 17 Alternative through-trip percentages

Functional Class	Population 25,000	50,000	100,000
Interstate	77%	67%	46%
Principal Arterial	40	30	9
Minor Arterial	24	13	0 [2]

[1] Example problem assumes the following:

ADT = 7,000
Heavy and Medium Trucks = 6%
Vans and Pickup Trucks = 10%

[2] Computed value less than 0%, therefore use 0%

tions. If an area had 10 external stations, then the resulting vehicle trip table would be a matrix with 10 origins and 10 destinations.

Modlin developed equations, one for each functional class, to estimate the distribution of through trips that enter the analysis area at an origin external station (i) to each of the destination stations (j). For estimation of each interchange, the functional class of the destination station dictates which equation is to be used.

Interstate:

$$Y_{ij} = -2.70 + 0.21 \times PTTDES_j + 67.86 \times RTECON_{ij} \quad (5\text{-}2)$$

Principal Arterial:

$$Y_{ij} = -7.40 + 0.55 \times PTTDES_j + 24.68 \times RTECON_{ij} + 45.62 \times \frac{ADT_j}{\sum_{j=1}^{n} ADT_j} \quad (5\text{-}3)$$

Minor Arterial:

$$Y_{ij} = -0.63 + 86.68 \times \frac{ADT_j}{\sum_{j=1}^{n} ADT_j} + 30.04 \times RTECON_{ij} \quad (5\text{-}4)$$

where

Y_{ij} = percentage distribution of through-trip ends from origin station i to destination station j,

$PTTDES_j$ = percentage through-trip ends at destination station j,

$RTECON_{ij}$ = route continuity between stations i and j: 1 = Yes, 0 = No, and

ADT_j = average daily traffic at the destination station j.

Station-to-station trip movements also can be estimated using a simple factoring procedure which uses an external station's portion of the total through trips. However, because the geographic characteristics of the study area often determine the likely connections between stations, some effort should be made to ascertain the existing through movement patterns either by reference to earlier studies of the area or by general observations. The likely movements can be set using control totals.

Example of Through-Trip Table Estimation

To illustrate the application of through-trip procedures, a simple five-station external example is presented. Assume that the data in Table 18 have been observed at the external stations.

In this example, stations 101 and 103 are two points on a continuous route, and stations 102 and 104 are two points on another continuous route.

The estimated through trips for each station are computed using the equation:

$$Y_i = 76.76 + 11.22 \times I - 25.74 \times PA - 42.18 \times MA + 0.00012 \times ADT_i + 0.59 \times PTKS_i - 0.48 \times PPS_i - 0.000417 \times POP$$

For example, the percent through trips for station 101 would be:

TABLE 18 Example data for through-trip estimation

Station	Functional Classification	ADT	Percent Trucks	Percent Vans and Pickups
101	Principal Arterial	15,000	5	10
102	Interstate	25,000	10	10
103	Principal Arterial	10,000	7	10
104	Interstate	20,000	10	10
105	Minor Arterial	5,000	3	10
Total		75,000		

$$Y_{101} = 76.76 + 11.22 \times 0 - 25.74 \times 1 - 42.18 \times 0 + 0.00012 \times 15{,}000 + 0.59 \times 5 - 0.48 \times 10 - 0.000417 \times 50{,}000 = 30$$

The resulting through trips are presented in Table 19. The trips have been rounded to the nearest 100 trips.

The next step is to estimate the distribution of the through trips between the external stations. The equations presented previously are used and the results are normalized in order for the sum of the distribution percentages to be equal to 100 percent. For example, the distribution of trips from station 101 to the other four stations is presented in Table 20.

The through-trip distributions are computed for each of the four remaining external stations. Table 21 contains the normalized percentages of through trip distributions among the five stations. The percentages sum to 100 percent down each column.

TABLE 19 Through trips

Station	ADT	Percent Through	Through Trips	E-I and I-E Trips
101	15,000	30	4,500	10,500
102	25,000	71	17,800	7,200
103	10,000	31	3,100	6,900
104	20,000	71	14,100	5,900
105	5,000	11	600	4,400
Total	75,000		40,100	34,900

TABLE 20 Distribution of through trips for external station 101

Origin Station	Destination Station	Calculated Percent	Normalized Percent
101	102	12%	18%
	103	40	58
	104	12	17
	105	5	7
	Total	70	100

TABLE 21 **Through-trip distribution percentages**

Destination Station	Origin Station 101	102	103	104	105
101	—	15	59	16	31
102	18	—	17	67	21
103	58	13	—	13	27
104	17	67	17	—	21
105	7	4	7	4	—
Total	100	100	100	100	100

The percentages presented in Table 21 are applied to the through trips presented in Table 19 for each external station. Table 22 contains the initial through-trip table.

Note that the row totals of trips do not equal the desired number of trips for each external station and that the table is not symmetrical about the intrastation diagonal. For example, the trips from 101 to 102 equal 2,736 trips while the trips from 102 to 101 equal 790. Because the trips represent average daily trips, the table should be symmetrical. The trip table is averaged to produce a table symmetrical about the diagonal. This symmetrical trip table is presented in Table 23.

At this step in the process, the row and column totals are equal; however, they are not equal to the desired number of through trips at each external station. This difference is presented in Table 24.

The most common procedure for adjusting a trip table to match desired row and column totals is the matrix balancing or Fratar technique. Many of the travel demand software packages have programs for applying this technique. The major use of the technique is to produce future-year trip tables that are growth factored. Table 25 contains the balanced or "Fratared" external through-trip table.

The resulting through-trip table is saved for later use in traffic assignment. The station-to-station vehicles are added to the total vehicle trips and assigned using the standard highway assignment procedures. Although the through trips are a minor portion of total vehicle trips in a region, the external-external volumes have a significant impact on facilities crossing the cordon line and passing entirely through the study area.

ESTIMATION OF EXTERNAL-INTERNAL TRIP PRODUCTIONS AND ATTRACTIONS

The estimation of external-internal trip productions and attractions is needed as part of the trip generation process. In Chapter 3, the section on balancing productions and attractions specified the need for external travel information in developing regional control totals by purpose. In fact, the approach for developing external productions and attractions is determined by whether or not the external trips made by

TABLE 22 **Initial through-trip table**

Destination Station	Origin Station 101	102	103	104	105	Total
101	—	2,736	1,837	2,165	188	6,926
102	790	—	524	9,483	126	10,924
103	2,595	2,329	—	1,843	160	6,927
104	782	11,965	519	—	125	13,391
105	332	770	220	609	—	1,932
Total	4,500	17,800	3,100	14,100	600	40,100

TABLE 23 Averaged through-trip table

Destination Station	Origin Station 101	102	103	104	105	Total
101	—	1,763	2,216	1,474	260	5,713
102	1,763	—	1,426	10,724	448	14,362
103	2,216	1,426	—	1,181	190	5,013
104	1,474	10,724	1,181	—	367	17,746
105	260	448	190	367	—	1,266
Total	5,713	14,362	5,013	13,746	1,266	40,100

residents of the region are included in the trip generation rates by trip purpose. If external trips are not included with the home-based work, home-based other, or non-home-based trips, the external trips could be treated as a separate purpose. The approach outlined in this report assumes that external trips are included in the trip rates by purpose.

The first part of this step will be to summarize the through-trip matrix by direction and station and subtract these totals from the station counts. The remainders represent the overall control totals by station for external-internal trips. While the counts conducted at the external stations might show differences in the number of vehicles traveling into and out of the study area on a particular route, the directional differences are ignored. This assumption, that the total trips entering the study area equals the total trips leaving the study area on a typical day, simplifies the process used to estimate external-internal travel.

The next step involves separating the external trips by purpose and resident status. The resident totals by purpose become the attractions at each station. Nonresident totals by purpose become the productions at each station.

If an external survey has been conducted, information on the purpose and residency status of trips could be used directly to estimate productions and attractions. External truck trips could be treated separately in determining the residency status based on the garage location. However, when basic information on external travel is not available, it will be necessary to apply typical factors by station. These factors are applied to the two-way ADT by station.

While the external travel characteristics of cities and metropolitan areas can vary significantly, a few common variables exist. Earlier it was stated that the size of the study area affects the percentage of through trips. The size of a region (in area), its socioeconomic characteristics, and proximity to other urbanized and suburban areas are other factors that affect the purpose and residency status of external-internal trips. The existence of a strong employment center within the study area will tend to pull more nonresidents into the region to seek employment. In areas where trip attractions such as employment and shopping are distributed more evenly between the areas inside and outside the cordon, the split between resident and nonresident trips at the cordon becomes relatively equal. Alternatively, a region that is mostly suburban may have a shortage of overall employment opportunities and a surplus of service and retail employment. In such a community, the flow of trips across the cordon could reflect a net export of work trips and a net import of other trips.

TABLE 24 Difference between calculated and desired external station through trips

External Station	Calculated Trips	Desired Trips	Ratio Desired/ Calculated
101	5,713	4,500	0.79
102	14,342	17,800	1.24
103	5,013	3,100	.63
104	13,746	14,100	1.03
105	1,266	600	.47
Total	40,100	40,100	

TABLE 25 **Balanced through-trip table**

Destination Station	Origin Station 101	102	103	104	105	Total
101	—	2,781	974	662	83	4,500
102	2,781	—	1,684	12,952	383	17,800
103	974	1,684	—	397	45	3,100
104	662	12,952	397	—	89	14,100
105	83	383	45	89	—	600
Total	4,500	17,800	3,100	14,100	600	40,100

Tables 26 and 27 show the split of internal-external trip totals by purpose and resident status for an area with a centralized activity center—San Juan, Puerto Rico—and an area with a more even distribution of activities on either side of the cordon—San Diego, California. These are presented to show the variation possible when planning regions have strong central activity centers or more diffuse employment.

These examples also demonstrate another characteristic of traffic across cordons: the number of work trips across the cordons is greater than the regional share of work trips. Two obvious reasons can be used to explain this phenomenon: (1) auto occupancy for work trips is generally lower than for all other purposes, so the share of vehicle trips that are carrying work trips is higher than the share of person trips that are work trips; and (2) average trip lengths for work trips are generally longer than average trip lengths for other trip purposes so work trips tend to be more likely to pass between regions than trips made for other purposes. If no data are available to estimate the distribution of interregional vehicle trips, local knowledge should be used to estimate the values from the following ranges: home-based work—25 to 50 percent of total vehicle trips across the cordon; home-based other—30 to 50 percent; non-home-based—15 to 25 percent. These default values for external travel should be used cautiously, however, and external surveys are highly recommended.

Returning to the example in Table 19 in which through trips were estimated, the external-internal trip productions and attractions also can be estimated. It was noted that 34,900 of the crossings represented external-internal or internal-external trips. The 10,500 external-internal trips for station 101 could be split as follows: 3,675 home-based work (35%); 4,200 home-based other (40%); and 2,625 non-home based (25%).

The next step in the process is to translate the vehicle trips into productions and attractions. External station productions are trips whose home base is outside of the region, and external station attractions are trips whose home is within the region. The task of splitting the vehicle trips is therefore dependent on a basic level of knowledge of the general land use and travel patterns in and around the study area. Suppose that the study area in the preceding example is primarily a suburban area 20 miles away from a major urban area. Suppose also that the primary attractions in the study area are a major university and several regional shopping centers. If local knowledge tells us that the

TABLE 26 **External trip purpose/residency factors for centralized areas[1]**

Trip Purpose	Resident	Non-Resident	Total
Home-Based Work	12%	34%	46%
Home-Based Other	9	23	32
Non-Home-Based	11	11	22
Total	32	68	100

[1] San Juan, Puerto Rico 1990 External Cordon Survey.

TABLE 27 External trip purpose/residency factors for evenly distributed areas[1]

Trip Purpose	Resident	Non-Resident	Total
Home-Based Work	15%	10%	25%
Home-Based Other	27	23	50
Non-Home-Based	8	17	25
Total	50	50	100

[1] San Diego Region.

predominant flow of traffic during the a.m. peak period flows from out of the study area at the ratio of 3 to 1, we could make the following assumptions: 75 percent of external-internal home-based work trips have productions within the study area; 40 percent of the home-based other trips have productions within the study area; and (by definition) 50 percent of the non-home based trips have productions within the study area. The following table would summarize the 10,500 external-internal trips associated with station 101:

Trip Purpose	Productions	Attractions	Total
Home-Based Work	919	2,756	3,675
Home-Based Other	2,520	1,680	4,200
Non-Home Based	1,312	1,313	2,625
Total	4,751	5,749	10,500

The trip attractions would equal 5,749 vehicles and the trip productions would equal 4,751 vehicles at external station number 101. These vehicle trips need to be converted to person trips using the automobile occupancy rates presented in Chapter 7 before they can be included in the final steps of the trip generation process.

DISTRIBUTION OF INTERNAL-EXTERNAL AND EXTERNAL-INTERNAL TRIPS

After the external productions (nonresident trips) and attractions (resident trips) have been estimated for each station and purpose, they are used in the standard modeling process to reflect trips between internal zones and external stations. In trip generation, control totals of trip productions can be calculated using the external totals to balance productions and attractions. While attractions should be normalized to productions for internal trips, the external station attractions should be held constant, because they represent actual counts of the base year. This was shown in Equation 3-1 in Chapter 3. Trip distribution of internal-external and external-internal trips follows the conventional gravity model approach described in Chapter 4, Trip Distribution.

CASE STUDY

As has been discussed previously, external trips can be divided into two categories: external-external trips, which pass completely through the region without having a trip-end within the region, and external-internal trips, which have one trip-end within the region and one trip-end outside of the region. The external-internal trips are converted to person trip-ends and incorporated into the regional trip generation model, while the external-external trips are expressed as a separate trip table that is added to the other vehicle-trip tables before assignment.

The procedures used to estimate external travel for the Asheville case study are listed below. All of the calculations were performed with the aid of a computer spreadsheet program.

Classification of External Stations

Average daily traffic (ADT) counts were collected for 16 facilities crossing the external cordon around the Asheville region. These ADT counts were collected at each location where significant traffic volumes flow into or out of the Asheville region. Each of these external stations was classified as either a minor arterial, a principal arterial, or an interstate facility. In addition, external station pairs that were linked by a continuous facility were noted because they would be expected to carry a statistically significant share of external-external traffic. The most notable of these pairs in the Asheville region are stations 109 and 117, which are connected by the Route 19/23 bypass and Interstate 26, and stations 114 and 121, which are connected by Interstate 40.

Estimation of Through-Trip Percentages

The synthetic procedures outlined previously in this chapter for estimating the share of external cordon trips that are likely to be through trips are only appropriate for urbanized areas with less than 50,000 in population. Therefore, local experience must be relied upon to estimate the through-trip-making potential for the Asheville region. This experience was used to classify four facilities, those carrying ADT volumes of greater than 20,000, as interstates, each of which was estimated to contribute 30 percent of its traffic to the external-external trip table. Another two facilities, designated as principal arterials, were estimated to have a 10 percent through-trip share each. The remainder of the external stations were designated as minor arterials and were assumed to contribute a negligible share of their ADT volumes to the through-trip table.

Table 28 displays the external station volumes including the estimated number of through trips and internal-external trips. All of the data in this table reflect vehicle trips, because the data are based upon existing traffic count data.

Distribution of Through Trips to External-External Trip Table

The distribution of through trips between stations is estimated using Equations 5-2, 5-3, and 5-4. The relative shares were first calculated as in the following example for the interchange between external stations 109 and 117, which represent the eastern and western extremities of I-40 within the study area:

$$Y_{ij} = -2.70 + 0.21 \times PTTDES_j + 67.86 \times RTECON_{ij}$$
$$= -0.70 + 0.21 \times 30 + 67.86 \times 1 = 71.46$$

TABLE 28 External station through-trip summary

Station Number	Description	1989 ADT	Classification	Percent Through	External-External	Internal-External
108	Route 251	1,800	Minor	0	0	1,800
109	Routes 19 & 23 Bypass	27,700	Interstate	30	8,310	19,390
110	Routes 19 & 23 Business	7,000	Minor	0	0	7,000
111	BRP (N)	2,850	Minor	0	0	2,850
112	Snope Creek Road	2,000	Minor	0	0	2,000
113	Route 70	16,100	Principal	10	1,610	14,490
114	I-40 (E)	24,700	Interstate	30	7,410	17,290
115	Route 74	11,000	Minor	0	0	11,000
116	Route 25	12,450	Minor	0	0	12,450
117	I-26	33,100	Interstate	30	9,930	23,170
118	Routes 191 & 280	7,400	Minor	0	0	7,400
119	BRP (S)	970	Minor	0	0	970
120	Route 151	1,550	Minor	0	0	1,550
121	I-40 (W)	27,500	Interstate	30	8,250	19,250
122	Leicester Highway	14,000	Principal	10	1,400	12,600
123	Bear Creek Road	3,940	Minor	0	0	3,940

where

Y_{iy} = percentage distribution of through-trip ends from origin station i to destination station j,
i = 109,
j = 117,
$PTTDES_j$ = percentage through trip ends at destination station j, and
$RTECON_{ij}$ = 1 = route continuity flag for stations i and j.

The calculations for the other external station pairs are displayed in Appendix Table B-4.

The relative shares for each of the possible destinations from a cordon station are added together and the result is used to normalize the raw data. Table 29 displays the raw shares and the normalized shares for each of the potential destinations for through trips entering the region at each of the six external stations.

Next, the normalized shares were used to distribute the through trips originating at those stations to the other five external stations expected to contribute a significant number of through trips to the external-external trip table. For station 109, the adjusted shares were used to distribute the 8,310 through trips originating at that station to the other five stations. The same procedure was used to distribute the through trips associated with the other five interstate and principal external stations. The results of this process are displayed in Table 30. Note that, for intuitive reasons, there are no *intrazonal* trips within the external zones, and that there are no trips allowed between stations 113 and 114, which are proximate, parallel facilities unlikely to attract trips from one another.

Given that the values arrived at in Table 26 are not symmetrical (i.e., the number of trips from station i to j is not equal to the number of trips from j to i) the next step is to average the ij and ji values to produce a symmetrical trip table. For example, given that the estimated value from station 109 to station 117 is 7,031, and the value from station 117 to 109 is 8,402, the average value between stations 109

TABLE 29 Through-trip distribution—raw and normalized percentages

	Origin Station					
Destination Station	109	113	114	117	121	122
Raw Percentages						
109	—	3.60	3.60	71.46	3.60	3.60
113	3.23	—	—	3.23	3.23	3.23
114	3.60	—	—	3.60	71.46	3.60
117	71.46	3.60	3.60	—	3.60	3.60
121	3.60	3.60	71.46	3.60	—	3.60
122	2.56	2.56	2.56	2.56	2.56	—
Total	84.46	13.36	81.22	84.46	84.46	17.63
Norm. Factor	1.184	7.483	1.231	1.184	1.184	5.671
Normalized Percentages						
109	—	26.94	4.43	84.61	4.26	20.42
113	3.83	—	—	3.83	3.83	18.33
114	4.26	—	—	4.26	84.61	20.42
117	84.61	26.94	4.43	—	4.26	20.42
121	4.26	26.94	87.98	4.26	—	20.42
122	3.03	19.18	3.16	3.03	3.03	—
Total	100	100	100	100	100	100

TABLE 30 Through-trip table—asymmetrical

Destination Station	Origin Station 109	113	114	117	121	122	Total
109	—	434	328	8,402	352	286	9,802
113	318	—	—	380	316	257	1,271
114	354	—	—	423	6,981	286	8,044
117	7,031	434	328	—	352	286	8,431
121	354	434	6,519	423	—	286	8,016
122	252	309	234	301	250	—	1,347
Total	8,310	1,610	7,410	9,930	8,250	1,400	36,910

and 117 is 7,717. The results of this exercise are displayed in Table 31, the symmetrical trip table.

The result of this latest maneuver, however, is a trip table in which the row totals and column totals are not equal to the through volumes estimated in Table 28. The recommended solution to this problem is to apply the Fratar technique to the symmetric trip table, using the through trip volumes in Table 28 as the row and column targets. The ultimate result of the Fratar process is the final external-external vehicle trip table, as displayed in Table 32.

Conversion of Internal-External Trips to Person-Trip Productions and Attractions

In order to estimate the internal-external vehicle trip totals, the through-trip totals were subtracted from the external station totals as shown in Table 28. Next the external trip purpose factors were applied to the external-internal totals. Local knowledge of the region is used to estimate that the traffic crossing the external cordon is composed of 40 percent home-based work trips, 40 percent home-based other trips, and 20 percent non-home-based trips. Local experience is then used to further estimate that the Asheville area is a net importer of work trips, by a ratio of 70 to 30, and that the region is a net importer of other home-based trips by a ratio of 60 to 40. The non-home-based trips are assumed to be balanced between productions and attractions. Finally, auto-occupancy factors (from Chapter 7) of 1.11 persons per vehicle for home-based work trips, 1.67 persons per vehicle for home-based other trips, and 1.66 persons per vehicle for non-home-based trips were used to convert the vehicle trips to person trips. The resulting estimates of trip productions and attractions for external stations in the Asheville region are

TABLE 31 Through-trip table—symmetrical

Destination Station	Origin Station 109	113	114	117	121	122	Total
109	—	376	341	7,717	353	269	9,056
113	376	—	—	407	375	283	1,440
114	341	—	—	376	6,750	260	7,727
117	7,717	407	376	—	387	294	9,180
121	353	375	6,750	387	—	268	8,133
122	269	283	260	294	268	—	1,373
Total	9,056	1,440	7,727	9,180	8,133	1,373	36,910
Target	8,310	1,610	7,410	9,930	8,250	1,400	36,910
Adj. Factor	0.918	1.118	0.959	1.082	1.014	1.020	

TABLE 32 Through-trip table—after the Fratar adjustment

Destination Station	Origin Station 109	113	114	117	121	122	Total
109	—	222	167	7,526	243	152	8,310
113	222	—	—	676	439	273	1,610
114	167	—	—	515	6,521	207	7,410
117	7,526	676	515	—	746	467	9,930
121	243	439	6,521	746	—	301	8,250
122	152	273	207	467	301	—	1,400
Total	8,310	1,610	7,410	9,930	8,250	1,400	36,910

summarized in Table 33. This table shows that the estimated 157,150 external-internal vehicle trips crossing the cordon around the Asheville region carried 226,925 person trips, including 137,915 productions (from locations outside the region) and 89,010 attractions (to locations outside the region).

SUMMARY

This is a review of steps required to estimate external travel. The key is knowing the ADT by direction for trucks and autos at each external station.

TABLE 33 External-internal person-trip productions and attractions

Station Number	Productions			Attractions		
	HBW	HBO	NHB	HBW	HBO	NHB
108	559	721	298	239	480	298
109	6,026	7,771	3,218	2,582	5,181	3,218
110	2,175	2,805	1,162	932	1,870	1,162
111	885	1,142	473	379	761	473
112	621	801	332	266	534	332
113	4,503	5,807	2,405	1,930	3,871	2,405
114	5,373	6,929	2,870	2,303	4,619	2,870
115	3,418	4,408	1,826	1,465	2,939	1,826
116	3,869	4,989	2,066	1,658	3,326	2,066
117	7,201	9,286	3,846	3,086	6,191	3,846
118	2,299	2,965	1,228	985	1,977	1,228
119	301	388	161	129	259	161
120	481	621	257	206	414	257
121	5,982	7,715	3,195	2,564	5,143	3,195
122	3,916	5,050	2,091	1,678	3,366	2,091
123	1,224	1,579	654	524	1,052	654
Total Person Trips	48,842	62,985	26,086	20,932	41,990	26,086

1. Collect classification counts at each cordon station.
2. Estimate percentage of through trips (E-E) at each cordon station.
3. Take through trips and distribute to create the E-E trip table. This vehicle trip table will be used in the traffic assignment step.
4. Subtract through trips from total ADT at each station to get E-I/I-E totals.
5. Apply the trip purpose and residence (direction) factors to two-way ADT by station. Resident totals by purpose correspond to attractions at each external station. Nonresident totals by purpose correspond to productions at each external station.
6. Convert external-internal vehicle-trip productions and attractions to person trips (Chapter 7) and complete balancing of Ps and As by purpose as shown in Chapter 3.
7. Distribute the E-I and I-E trips using the gravity model by trip purpose (i.e., HBW, HBO, and NHB) as shown in Chapter 4.

CHAPTER 6

MODE-CHOICE ANALYSIS

INTRODUCTION

Mode-choice analysis is the third step in the traditional four-step travel-demand forecasting process. It is the most complex of the modeling steps and in the last decade most of the research and advancement in travel-demand models has related to this step. The focus on mode-choice models has been generated by the analysis of major new proposed and constructed fixed-guideway systems throughout the United States. Mode-choice modeling is also used to evaluate improvements in bus systems and for analysis of HOV strategies. In mode-choice analysis, the total zone-to-zone person trips resulting from the trip-distribution model are split into trips using each available mode between each zone pair. By incorporating various levels of auto occupancy into the mode-choice model, the vehicle-trip tables are produced directly by the model and the need for further auto-occupancy factors is eliminated. Similarly, transit trips by submode (e.g., local bus, express bus, and rail) and access mode (e.g., walk to transit or drive to transit) are produced and ready for the last step—assignment.

Most mode-choice models are based on the logit formulation. The following mode-choice model formulations will be discussed:

- Simple multinomial logit,
- Incremental logit (pivot point), and
- Nested logit.

The third form of the logit model, the nested logit model, is gaining use by larger urban areas where there are competing modes of public transportation (e.g., local bus, express bus, rail, and HOV) and multiple access modes. For the small- to medium-sized urban areas that are primarily evaluating local bus service as a competition for the auto mode, the multinomial logit model is usually adequate. However, if mode of access and/or auto occupancy (HOV) is desired in the mode-choice model, the use of a nested model should be considered.

The multinomial logit and nested logit formulations are used to estimate mode shares for most transit strategies, including the introduction of a new transit mode (e.g., rail) or for introduction of transit service into an area that currently has no service. These formulations require a complete description of all modes of available or proposed highway, HOV, and transit and are extremely data-intensive. The incremental logit or pivot-point formulation allows for analysis of transit improvement strategies or policies without the complete simulation of the entire transit system and its alternatives. A limitation of this formulation is that it cannot be used to estimate transit use in an area that does have existing transit service and patronage. This incremental logit structure is, however, the most transferable of the three among different urban areas and will therefore receive the most discussion.

The use of incremental logit often is used for the evaluation of Travel Demand Management (TDM) strategies directed at reducing vehicle travel during peak periods. The application of the incremental logit model to evaluate example TDM strategies is presented in this chapter.

BASIS FOR DEVELOPMENT

A brief discussion of the multinomial and incremental formulations of the logit model is presented below. The following discussion is presented as background for the development of the incremental logit model; full application of either a multinomial or nested logit model requires, as a minimum, a calibration and validation of the mode-specific model constants to reflect localized transit and mode-choice characteristics.

LOGIT FORMULATION

The generalized logit model formulation is a mathematical relationship that estimates the probability of choosing a specific mode by using the following equation

$$P_i = \frac{e^{u_i}}{\sum_{i=1}^{k} e^{u_i}} \tag{6-1}$$

where

P_i = the probability of a traveler choosing mode i,
u_i = a linear function of the attributes of mode i that describe its attractiveness, also known as the utility of mode i, and

$\sum_{i=1}^{k} e^{u_i}$ = the summation of the linear functions of the attributes of all the alternatives, k, for which a choice is available.

The linear function of the attributes, or utility function u_i, is composed of

$$u_i = a_i + b_i \times IVTT_i + c_i \times OVTT_i + d_i \times COST_i \quad (6\text{-}2)$$

where

$IVTT_i$ = the in-vehicle travel times for mode i,
$OVTT_i$ = set of variables measuring the out-of-vehicle travel times for mode i—walk, wait, and transfer times—may all be kept separate or combined, depending on the calibrated structure of the model,
$COST_i$ = the cost of mode i,
a_i = mode-specific coefficient (constant) to account for mode bias not measurable with the level-of-service variables,
b_i = coefficient for the *IVTT* variables of mode i,
c_i = a set of coefficients for *OVTT* variables of mode i, and
d_i = coefficient for *COST* variable of mode i.

The level-of-service variables may be aggregated to total *IVTT, OVTT,* and *COST,* or they may be kept separate with specific coefficients. For example, out-of-vehicle variables such as walk time, first wait, and second wait times are often kept separate with different estimated coefficients. In most simple applications, a single total is computed each for *IVTT, OVTT,* and *COST.*

Examples of the structures of the simple multinomial and nested logit models are presented in Figure 11.

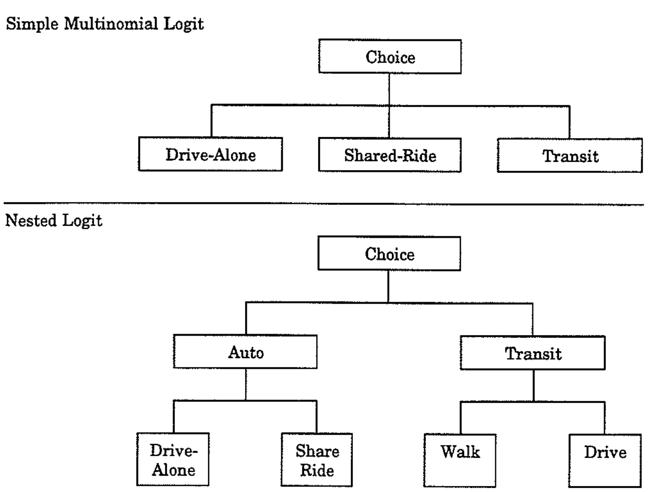


Figure 11. Mode-choice model structures.

Figure 11 presents the multinomial logit model with three modes: drive-alone, shared-ride, and transit. This structure allows for the analysis of network and policy alternatives that are designed to increase the shared-ride, or HOV, mode. These alternatives can include dedicated HOV lanes and preferential parking for HOV that result in a quantifiable difference in the level of service for each mode. In many urban areas, there are no significant level-of-service differences for drive-alone and shared-ride modes (other than the sharing of operating costs) that can by measured by a model. In these cases, a simple binary or two-mode model is appropriate. The modes would be transit and auto. The resulting auto person trips are converted to vehicle trips using auto occupancy ratios presented in Chapter 7. The level-of-service coefficients, in-vehicle travel time, out-of-vehicle travel time, and costs, that are presented in this chapter are the same for the total auto mode as they are for the drive-alone and shared-ride.

INCREMENTAL LOGIT FORMULATION

The multinomial mode-choice model is estimated on the basis of the complete characteristics of the transit system and the potential users. An alternative method of applying these models is in an incremental formulation that begins with existing mode shares and modifies these baseline values based on changes in the characteristics of the transit or auto networks.[1] The following are the principal advantages of the incremental formulation:

- Uses observed, measured mode shares
- Requires a description only of the changes to the transit service
- Highly transferable among urban areas because mode-specific and socioeconomic bias is accounted for in the observed, measured shares of travel by each mode.

The incremental form is a derivation of the standard multinomial logit formulation presented earlier. The formulation is

$$P_i' = \frac{P_i \times e^{\Delta u_i}}{\sum_{i=1}^{k} (P_i \times e^{\Delta u_i})} \quad (6\text{-}3)$$

where

P_i = the baseline probability (share) of using mode i,
P_i = the revised probability of using mode i, and
Δu_i = the change in utility for mode i.

The change in utility expression can be derived from the utility formula presented earlier as

[1]Barton-Aschman Associates, Inc., and Parsons Brinckerhoff Quade & Douglas, Inc., *Task 3.03 Service and Patronage Forecasting Methodology-Honolulu Rapid Transit Program,* Honolulu, Hawaii (March 1992).

$$\Delta u_i = (a_i + b_i \times IVTT_i' + c_i \times OVTT_i' + d_i \times COST_i) - (a_i + b_i \times IVTT_i + c_i \times OVTT_i + d_i \times COST_i)$$

$$\Delta u_i = b_i(IVTT_i' - IVTT_i) + c_i(OVTT_i - OVTT_i') + d_i(COST_i' - COST_i) \quad (6\text{-}4)$$

$$\Delta u_i = b_i \times \Delta IVTT_i + c_i \times \Delta OVTT_i + d_i \times \Delta COST_i$$

where

$IVTT'_i$, $OVTT'_i$, $COST'_i$ = level-of-service variables after proposed change for mode i, and
$\Delta IVTT_i$, $\Delta OVTT_i$, $\Delta COST_i$ = the change in level-of-service variables for mode i.

The mode-specific constants, a_i, fall out of the computations. The only terms entering the equation are those that change. The lack of mode-specific constants is a particularly attractive feature of the incremental logit structure. These constants capture the effects of such unmeasurable attributes as transit reliability, image, and other characteristics that can vary substantially from one urban area to another. In fact, the level-of-service coefficients of a mode-choice model are often transferred from one urban area to another, and the model is calibrated to fit observed transit shares by adjusting the mode-specific constants or coefficients. Because they drop out of the incremental form, differences in these unmeasurable attributes also drop out, to produce a model that is more likely to be transferable between urban areas.[2]

MODEL COEFFICIENTS

Table 34 summarizes a review of several mode-choice models used around the country and forms the basis for establishing suggested default coefficient values to be used in the application of the incremental model discussed in the Basis of Development section. Most of the models presented are of the multinomial logit formulation, but there is some experience with the nested logit structure. Table 35 summarizes the values of time coefficients for home-based work mode-choice models.

A review of Table 34 reveals that although there are differences in the coefficients, the major independent variables of in-vehicle time, out-of-vehicle time, and cost have coefficients within a similar range. The in-vehicle time coefficients range from −0.015 to −0.040, with most being in the −0.017 to −0.028 range. The New Orleans, Seattle, and Dallas models have separate coefficients for normal in-vehicle time and drive-to-transit in-vehicle time. Although the New Orleans and Seattle models use coefficients for drive-to-transit times approximately 7 times as great as the "normal" in-vehicle times, the Dallas model uses a drive-to-transit coefficient that is the same as used for out-of-vehicle time.[3] This variation in coefficients is related to network coding conventions and market segmentation.

A default coefficient for in-vehicle travel time of −0.025 is recommended for use in the incremental logit model.

The out-of-vehicle time coefficients, some of which are stratified by walk, initial wait, and transfer time, are larger than the in-vehicle time coefficients by a factor of 1.5 to 2.3. The coefficients range from −0.114 to −0.028, with the majority being between −0.077 and −0.030. A default coefficient of out-of-vehicle time equal to 2 times the in-vehicle coefficient, −0.050, is recommended. The IVTT and OVTT default coefficients are summarized in Table 36.

The coefficient for cost is a function of the average income of the urban area and the relative value the trip maker places on time and cost. As a general rule, for higher income trip makers, cost has less importance and minimizing time has more importance in the decision-making process. Table 35 presents the values of time in dollars per hour and as a percentage of income for a sample of urban area models. Most of the cost coefficients range between 20 and 30 percent of regional average income. Table 36 presents a set of default cost coefficients. Users should enter the table with the average income for their region and the desired value of time as a percentage of income. If this percentage cannot be determined, then an average value of 25 percent may be used. A plot of the cost coefficients as a function of income and value of time is presented in Figure 12.

The cost coefficients in Table 36 can be derived using the formula

$$d_i = \frac{1,248 \times b_i}{Income \times TVP} \quad (6\text{-}5)$$

where

d_i = coefficient for $COST$,
b_i = coefficient for $IVTT$ (−0.025 used for Table 36),
$Income$ = average regional household income,
TVP = value of time percentage (expressed as decimal), and
1,248 = factor to convert income in \$/year to ¢/minute.

Table 36, Part B, shows the results of this derivation for various income levels.

INCREMENTAL MODEL APPLICATION

The application of the incremental mode-choice model can be done in any spreadsheet program or by using simple

[2]Parsons Brinckerhoff Quade & Douglas, *Review of Best Practices*, prepared for the Metropolitan Washington council of Governments (December 1992).

[3]Ibid.

TABLE 34 Review of home-based work mode-choice coefficients

City	In-Vehicle Time	Transit Drive-Access Time	Out-of-Vehicle Time	Auto Terminal Time	Transit Walk Time	Initial Transit Wait Time	Transit Transfer Time	Total Cost	Auto Operating Cost	Transit Fare	Parking Cost
Coefficients on Service-Level Variables from a Sample of Home-Based-Work Mode-Choice Models											
New Orleans	-.015	-.100			-.033	-.077	-.032	-.008			
Minn/St. Paul	-.031				-.044	-.030	-.044	-.014			
Chicago	-.028			-.030	-.114	-.023	-.114	-.0121			
Los Angeles	-.020		-.112					-.0144			
Seattle	-.040	-.286			-.044	-.030	-.044	-.014			
Cincinnati	-.019		-.028					-.0045			
Washington	-.017		-.058						-.004	-.004	-.009
San Francisco	-.025		-.058					-.0039			
Dallas	-.030			-.055	-.055	-.055	-.059		-.005	-.005	-.012
Shirley (low)	-.022	-.055	-.035					-.0037			
Shirley (high)	-.034		-.044					-.0046			
Salt Lake City	-.019		-.037					-.0059			
Portland	-.034		-.072					-.01384			

Sources: Parsons Brinckerhoff Quade & Douglas, Inc., *Review of Best Practices,* Washington, D.C. (1992).
KPMG Peat Marwick, *Compendium of Travel Demand Forecasting Methodologies,* prepared for Federal Transit Administration, Washington, D.C. (February 1992).

TABLE 35 Review of mode-choice coefficients—values of time

City	Values of Time for Home-Based Work [1]				Values of Time as Percent of Median Income for Home-Based Work Models [2]				Relative Importance of Travel Time Coefficients of Home-Based Work Models			
	C(ivt)/C(cost)	C(ivt)/C(oper)	C(ivt)/C(fare)	C(ivt)/C(park)	C(ivt)/C(cost)	C(ivt)/C(oper)	C(ivt)/C(fare)	C(ivt)/C(park)	C(ovt)/C(ivt)	C(Walk)/C(ivt)	C(wait)/C(ivt)	C(xfer)/C(ivt)
New Orleans	2.76				30.3					2.200	5.133	2.133
Minn/St. Paul	2.48				20.8					1.419	.968	1.419
Chicago	2.56				21.9					4.127	.844	4.127
Los Angeles	1.12				10.6				5.600			
Seattle	2.09				20.3					1.100	.750	1.100
Cincinnati	2.98				27.4				1.456			
Washington		2.61	2.08	0.97		19.5	15.5	7.26	3.381			
San Francisco	3.47				29.4				2.3			
Dallas		2.68	2.68	1.07		25.3	25.3	10.1		1.862	1.851	1.992
Shirley (low)	2.29				16.8				1.018			
Shirley (high)	3.74				27.4				2.00			
Salt Lake City[3]	1.90				na				2.00			
Portland[3]	1.48				na				2.112			

Note: Income values for 1979.

[1] Expressed as $/hour.
[2] Expressed as percentage of hourly income.
[3] Income for years other than 1979.

ivt = In-Vehicle Time
cost = Total Cost
oper = Auto Operating Cost
fare = Transit Fare
park = Parking Cost
ovt = Out-of-Vehicle Time
walk = Transit Walk Time
wait = Initial Transit Wait Time
xfer = Transit Transfer Time

TABLE 36 Default home-based work mode-choice model coefficients

Part A: In-Vehicle and Out-of-Vehicle Coefficients

Level-of-Service Variable	Coefficient
In-Vehicle Travel Time *(b_i)*	-0.025
Out-of-Vehicle Travel Time *(c_i)*	-0.050

Part B: Cost Coefficients *(d_i)*

Average Income	Value of Time as Percentage of Income					
	10.0%	15.0%	20.0%	25.0%	30.0%	35.0%
$10,000	-0.031%	-0.021%	-0.016%	-0.012%	-0.010%	-0.009%
12,500	-0.025	-0.017	-0.012	-0.010	-0.008	-0.007
15,000	-0.021	-0.014	-0.010	-0.008	-0.007	-0.006
17,500	-0.018	-0.012	-0.009	-0.007	-0.006	-0.005
20,000	-0.016	-0.010	-0.008	-0.006	-0.005	-0.004
22,500	-0.014	-0.009	-0.007	-0.006	-0.005	-0.004
25,000	-0.012	-0.008	-0.006	-0.005	-0.004	-0.004
27,500	-0.011	-0.008	-0.006	-0.005	-0.004	-0.003
30,000	-0.010	-0.007	-0.005	-0.004	-0.003	-0.003
32,500	-0.010	-0.006	-0.005	-0.004	-0.003	-0.003
35,000	-0.009	-0.006	-0.004	-0.004	-0.003	-0.003
37,500	-0.008	-0.006	-0.004	-0.003	-0.003	-0.002
40,000	-0.008	-0.005	-0.004	-0.003	-0.003	-0.002

Note: Assumes 2,080 working hours/year for conversion from annual income to $/hr. and ¢/min.
Source: Derived from formula 6-5.

worksheets. Included in this section are sample worksheets that can be used to apply the model for a specific corridor or interchange. The major steps to applying the model are as follows:

1. Estimate initial mode shares (Figure 13, Worksheet 1),
2. Estimate the incremental change in level of service (Figure 14, Worksheet 2),
3. Apply model to compute revised mode shares (Figure 15, Worksheet 3), and
4. Compute vehicle trips (Figure 16, Worksheet 4).

The method for estimating existing or base mode shares depends on the transit or HOV strategy being analyzed. The two basic sources for the base mode shares are (1) observed traffic counts and occupancy level for the corridor being studied, or (2) base shares for trip interchange from existing regional travel-demand model. Information on base mode shares may also be available from Census journey to work data (for work trips only) and travel survey data (if the sample size is large enough to represent the use of transit adequately).

The best way to illustrate the application of the incremental mode-choice model is through the use of an example.

EXAMPLE APPLICATION OF INCREMENTAL MODE-CHOICE MODEL

One of the most common applications of the incremental mode-choice model is the analysis of HOV strategies. Of particular concern is the analysis of HOV lanes on existing freeways. HOV lanes can be created either by adding one or more lanes or by taking an existing lane and converting it to HOV only. The other consideration in the analysis is the number of persons per vehicle that defines an allowed HOV on the lane. The process of analysis becomes iterative with the objective being stable shifts in mode shares and travel times. The following example illustrates this iterative analysis procedure.

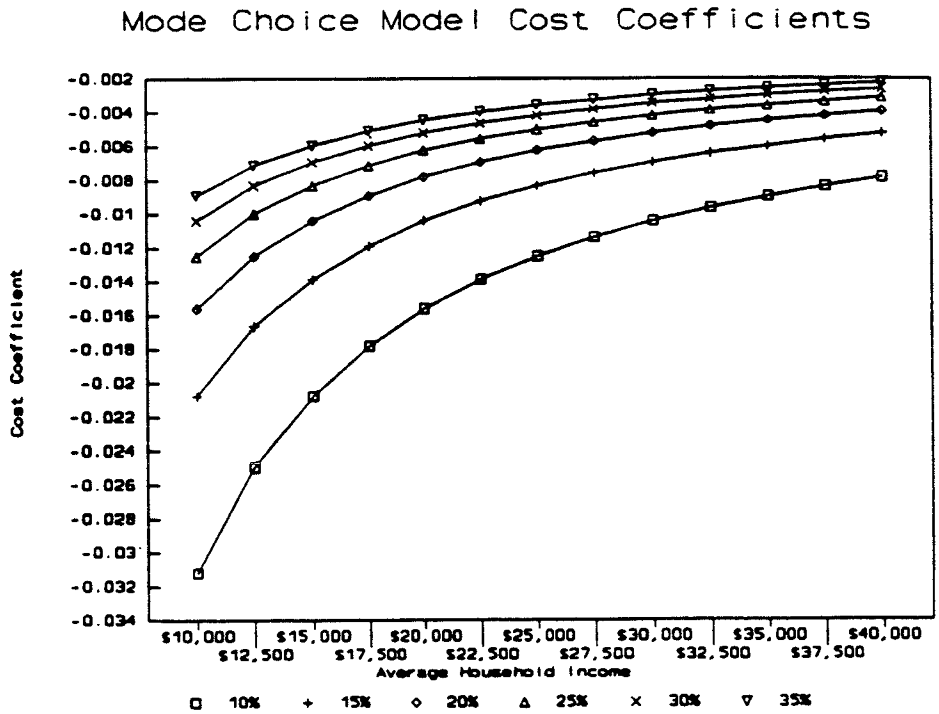


Figure 12. Cost coefficients as a function of income.

Problem

An urban area has a major six-lane freeway oriented radially to the CBD. A major section with a length of 10 miles is operating under congested conditions both now and into the future. An alternative to the standard widening of the freeway is the use of HOV lanes. An alternative that would be examined is the taking away of one of the lanes in each direction during the peak periods and converting these lanes to HOV only. Allowable vehicles for the HOV lane would be buses and vehicles with two or more persons per vehicle. Observed PM peak-hour counts revealed the following mix of vehicles throughout the 10-mile corridor:

Vehicle Classification	P.M. Peak-Hour Count (Vehicles)
Drive-Alone	4,182
2 persons/vehicle	356
3 persons/vehicle	231
4+-persons/vehicle	126
Vanpools	25
Trucks	540
Total	5,460

In addition to the above vehicles, the count program counted 100 person trips using buses in the corridor during the PM peak hour. The following steps will be used to analyze this alternative:

Step 1: Compute the base modal shares (Worksheet 1).

Using the existing count data, Worksheet 1 (displayed as Figure 17) can be used to compute the base shares for each level of vehicle occupancy and transit.

Step 2: Compute the existing HOV and non-HOV travel times.

From Chapter 10, the freeway capacity per hour, per lane is 1,800 vehicles. Directional capacity is therefore 5,400 vehicles/hr. Free-flow speed would be 55 mph. This results in an uncongested travel time of 11 minutes (10 miles at 55 mph) in the corridor. From Chapter 9, the following formula is used to compute existing congested travel time:

$$T_f = T_c \times \left[1 + 0.83 \times \left(\frac{v}{c}\right)^{5.5}\right]$$

The existing volume-to-capacity ratio is 1.01 (5,460/5,400) and the resulting congested travel time for the corridor is

$$T_f = 11 \times \left[1 + 0.83 \times (1.01)^{5.5}\right] = 21$$

For the HOV lane, the initial assumption will be made that it operates at free-flow conditions and the travel time will be 11

	Vehicle Count	Factor	Person Trips	Base Shares (%)
Auto				
Drive-Alone		× 1 =		
2-person carpool		× 2 =		
3-person carpool		× 3 =		
4+-person carpool*		× 4 =		
Shared-Ride		× 2.5 =		
Vanpool		× 7 =		
Bus				
Total				100%

* Note: This assumes that 4+-person carpools have 4 people in them. If there are more than 4 persons, this process will underestimate the number of person trips.

Figure 13. Worksheet 1: computation of base shares.

		ΔIVTT		ΔOVTT		ΔCOST		Cost Coef		Δu_i
Auto										
Drive-Alone	(		× (-0.025)) + (		× (-0.050)) + (		×		) =	
2-person carpool	(		× (-0.025)) + (		× (-0.050)) + (		×		) =	
3-person carpool	(		× (-0.025)) + (		× (-0.050)) + (		×		) =	
4+-person carpool	(		× (-0.025)) + (		× (-0.050)) + (		×		) =	
Shared-Ride	(		× (-0.025)) + (		× (-0.050)) + (		×		) =	
Vanpool	(		× (-0.025))+ (		× (-0.050)) + (		×		) =	
Bus	(		× (-0.025)) + (		× (-0.050)) + (		×		) =	
Total										

Figure 14. Worksheet 2: computation of change in utilities.

	Δu_i	$e^{\Delta u_i}$	$P_i x e^{\Delta u_i}$	Revised Shares (%)
Auto				
Drive-Alone				
2-person carpool				
3-person carpool				
4+-person carpool				
Shared-Ride				
Vanpool				
Bus				
Total				100%

Figure 15. Worksheet 3: computation of revised shares.

	Revised Shares P_i'(%)		Total Person Trips		Revised Person Trips		Revised Vehicle Trips
Auto							
Drive-Alone						÷ 1 =	
2-person carpool						÷ 2 =	
3-person carpool						÷ 3 =	
4+-person carpool		×		=		÷ 4 =	
Shared-Ride						÷ 2.5=	
Vanpool						÷ 7 =	
Bus							
Total	100%						

Figure 16. Worksheet 4: revised vehicle trips.

	Vehicle Count	Factor	Person Trips	Base Shares (%)
Auto				
Drive-Alone	4,182	x 1 =	4,182	65.69%
2-person carpool	356	x 2 =	712	11.18
3-person carpool	231	x 3 =	693	10.9
4+-person carpool	126	x 4 =	504	7.92
Vanpool	25	x 7 =	175	2.75
Bus			100	1.57
Total			6,366	100.00%

Figure 17. Worksheet 1: computation of base shares—example HOV problem.

minutes. Therefore, the change in in-vehicle travel time for the HOV vehicles and buses will be −10 minutes. The non-HOV vehicles will have to use the remaining two unrestricted lanes. For this initial iteration, the time for these vehicles will be assumed not to change. After the new shares and number of drive-alone vehicles are estimated, the congested speed on the unrestricted lanes will be computed.

Step 3: Compute change in modal utilities, shares, and vehicle trips.

The revised vehicle trips are calculated using Worksheets 2 through 4 (displayed as Figures 18 through 20). A summary of the revised shares and vehicle trips follows:

The average vehicle occupancy excluding the buses is computed as

$$\textit{Average Vehicle Occupancy} = \frac{6{,}366 - 117}{4{,}674} = 1.34$$

Step 4: Check volume-to-capacity ratios for HOV and regular lanes.

The volume-to-capacity (v/c) ratio for the HOV lane is equal to the two-person and above vehicles divided by the single-lane capacity of 1,800. The result is

$$\frac{V_{HOV}}{C_{HOV}} = \frac{417 + 270 + 147 + 29}{1{,}800} = 0.48$$

Mode	Revised Shares	Revised Person Trips	Revised Vehicle Trips	ΔIVTT
Drive-Alone	59.84%	3,809	3,809	
2-person carpool	13.08%	833	417	-10
3-person carpool	12.75%	812	271	-10
4+-person carpool	9.26%	590	148	-10
Vanpool	3.23%	205	29	-10
Bus	1.84%	117	—	-10
Total		6,366	4,674	

	ΔIVTT		ΔOVTT		ΔCOST		Cost Coef		Δu_i
Auto									
Drive-Alone	(0	×(-0.025) + (	0	×(-0.050)) + (	0	×	0	) =	0
2-person carpool	(-10	× (-0.025)) + (	0	× (-0.050)) + (	0	×	0	) =	.25
3-person carpool	(-10	× (-0.025)) + (	0	× (-0.050)) + (	0	×	0	) =	.25
4+-person carpool	(-10	× (-0.025)) + (	0	× (-0.050)) + (	0	×	0	) =	.25
Vanpool	(-10	× (-0.025)) + (	0	× (-0.050)) + (	0	×	0	) =	.25
Bus	(-10	× (-0.025)) + (	0	× (-0.050)) + (	0	×	0	) =	.25
Total									

Figure 18. Worksheet 2: computation of change in utilities—example HOV problem.

The *v/c* ratio is low enough that it can be determined that the HOV lane will operate at free-flow conditions. The *v/c* ratio of the non-HOV or regular lanes is equal to the drive-alone vehicles plus the trucks divided by the remaining two-lane capacity. The result is

$$\frac{V_{non-HOV}}{C_{non-HOV}} = \frac{3{,}811 + 540}{1{,}800 \times 2} = 1.21$$

The *v/c* ratio of the regular lanes is higher than the initial value of 1.01 for all three lanes. The new congested travel time for the regular lanes is computed as

$$t_f = 11 \times \left[1 + 0.83 \times (1.21)^{5.5}\right] = 37 \ minutes$$

Step 5: Compare ΔIVTT *and iterate as necessary.*

This congested travel time is 16 minutes longer than the existing conditions. Therefore, the drive-alone Δ*IVTT* should reflect the increased travel times for the drive-alone mode. This increase in congestion for the drive-alone mode makes the HOV modes even more attractive. However, if the entire 16 minutes is added to the drive-alone mode then the resulting *v/c* ratio will probably be less than 1.21 and the travel time will be less than 37 minutes. The process can be iterated until the resulting shares for drive-alone produce a *v/c* ratio that is in balance with the time used for input to the change in *IVTT* for drive-alone. For this example, a Δ*IVTT* of +8 minutes for the drive-alone mode will be tested. The following is a summary of those results:

Mode	Revised Shares (%)	Revised Person Trips	Revised Vehicle Trips	ΔIVTT
Drive-Alone	54.97%	3,500	3,500	+8
2-person carpool	14.68%	934	467	-10
3-person carpool	14.29%	910	303	-10
4+-person carpool	10.39%	661	165	-10
Vanpool	3.61%	230	33	-10
Bus	2.06%	131	—	-10
Total		6,366	4,468	

	Δu_i	$e^{\Delta u_i}$	$P_i x e^{\Delta u_i}$	Revised Shares (%)
Auto				
Drive-Alone	0	1.0	65.69	59.84%
2-person carpool	.25	1.284	14.36	13.08%
3-person carpool	.25	1.284	14.00	12.75%
4+-person carpool	.25	1.284	10.17	9.26%
Vanpool	.25	1.284	3.53	3.23%
Bus	.25	1.284	2.02	1.84%
Total			109.77	100.00%

Figure 19. Worksheet 3: computation of revised shares—example HOV problem.

	Revised Shares P_i'(%)		Total Person Trips	Revised Person Trips				Revised Vehicle Trips
Auto								
Drive-Alone	59.84%			3,809	÷	1	=	3,809
2-person carpool	13.08			833	÷	2	=	417
3-person carpool	12.75			812	÷	3	=	271
		×	6,366					
4+-person carpool	9.26			590	÷	4	=	148
Vanpool	3.23			205	÷	7	=	29
Bus	1.84			117				
Total	100.00%			6,366				4,674

Figure 20. Worksheet 4: revised vehicle trips—example HOV problem.

Average vehicle occupancy is now 1.40 versus the existing value of 1.27, or an increase of more than 9 percent. The resulting *v/c* ratios are

$$HOV\ Lane\ v/c = \frac{467 + 303 + 165 + 33}{1{,}800} = 0.53$$

$$Regular\ Lanes\ v/c = \frac{3{,}500 + 545}{3{,}600} = 1.12$$

The resulting travel time for the regular lanes is

$$t_f = 11 \times \left[1 + 0.83 \times (1.12)^{5.5}\right] = 28\ minutes$$

The $\Delta IVTT$ for drive-alone mode is +7 minutes as compared with the input value of +8 minutes. An additional iteration could be made and the actual $\Delta IVTT$ would be about +7.5 minutes; however, a difference of 1 minute is acceptable.

Summary of Example Problem Results

The following table summarizes the results of the take-a-lane HOV alternative for the existing traffic conditions:

	Existing Conditions	Take-a-Lane HOV Alternative	Change
Vehicle Trips *	4,929	4,668	-252
Person Trips *	6,366	6,366	0
Vehicle-Miles of Travel (VMT)	49,200 miles	46,680 miles	-2,520
Vehicle-Hours of Travel (VHT)	1,722 hours	1,811 hours	89
Person-Miles of Travel (PMT)	63,660 miles	63,660 miles	0
Person-Hours of Travel (PHT)	2,228 hours	2,159 hours	-69
HOV Lane Travel Time	21 minutes	11 minutes	-10
Reg. Lanes Travel Time	21 minutes	28 minutes	+7
HOV *v/c*	n/a	0.53	n/a
Regular *v/c*	1.01	1.12	+0.11
Average Vehicle Occupancy	1.27	1.40	+0.13

* Excludes truck volumes

The results of this analysis show that although the HOV lane will reduce total vehicle traffic in the corridor, it will increase congestion in the remaining two regular lanes, thereby increasing overall corridor vehicle hours of travel. There is, however, some saving in corridor person-hours of travel. The example is for existing conditions; a more complete analysis should be done for future years. Future-year volumes can be obtained either from a regional travel-demand model or by factoring growth into the existing count data. To complete the analysis, a second alternative in which the HOV lane is added to the existing regular lanes could be examined. The same analysis process would be used.

ANALYSIS OF TRAVEL DEMAND MANAGEMENT (TDM) STRATEGIES

Travel-demand management is a set of strategies designed to encourage the use of alternatives to driving alone, particularly during the peak periods. The analysis of supply-side TDM strategies that can be expressed as time and cost changes can be accomplished through the application of the incremental mode-choice model presented earlier in this chapter. This includes transit improvements, priority treatments such as HOV lanes, and financial incentives/disincentives. The financial strategies can include increased parking costs and transit cost reduction through subsidized or reduced fares. In a report prepared for the Federal Highway Administration, *Employer-Based Travel Demand Management Programs—Guidance Manual,* a good overview of TDM strategies and a procedure for evaluating the employer-based strategies are presented.[4] The discussion of TDM analysis contained in this report uses that manual as a source and only a brief summary of the analysis procedures is presented here. The user is referred to that publication from the FHWA for a more detailed description of the analysis procedures.

[4]Comsis Corporation, *Employer-Based Travel Demand Management Programs—Guidance Manual,* Prepared for US DOT, ETA, and FHA, Washington, D.C. (June 1993).

The term TDM encompasses both alternative modes to driving alone and the techniques, or strategies, that encourage use of these modes. TDM modal alternatives include

- Carpools and vanpools,
- Public and private transit (including buspools and shuttles), and
- Bicycling, walking, and other nonmotorized travel.

Alternative work hours are also a TDM strategy, such as programs that are designed to reduce the number of trips made during the peak periods, either by reducing the number of days the commuters need to travel to the worksite or by shifting commuting travel to non-peak period times of the day. Examples include

- Compressed work weeks—working 40 hours in less than 5 days,
- Flexible work schedules—shifting start and stop times to less-congested times of day, and
- Telecommuting—working 1 or more days at home or at a satellite work center closer to the home.

Employer-based TDM programs often are the most effective in reducing peak-period trips. TDM strategies can be chosen to meet a relatively narrow set of worksite, operational, and commuters' demographic and travel characteristics. There are many reasons for implementing an employer-based TDM program, with the most likely being one of the following:

- Response to a trip-reduction regulation,
- Solution to a transportation-related problem at the work site,
- Expansion of employee (or tenant) benefits package, and
- Reduction in company expenses.

Employer-Based Travel Demand Management Programs—Guidance Manual presents a manual procedure for developing and evaluating a TDM program for a specific employer site. The basic procedure requires the following steps:

Step 1: Define Site's Employment Type.

The first step is to classify the site as either office or non-office. Office sites are substantially professional/white collar jobs, with work schedules that fall within the daily peak travel periods. Non-office sites include those that are substantially blue collar or crafts/nonprofessional employment, with work schedules that may or may not fall within traditional peak periods.

Step 2: Define Site's Baseline Traffic Conditions (Starting Average Vehicle Occupancy or Average Vehicle Ridership, AVR).

The AVR for a site is computed using a worksheet. The data are collected from observed count data and through employee surveys. The number of employees arriving by each mode is converted to total vehicle trips to the site and can be compared with observed traffic counts.

Step 3:Define Site's Modal "Bias."

A basic input to the procedure is the determination of whether the site is "transit favorable, rideshare favorable, or mode neutral." A worksheet is provided to make this determination. If the number of arrivals made by transit is more than 50 percent of all other modes, then the site is considered to be transit favorable. If the rideshare number of arrivals is greater than 50 percent of all other modes, then the site is rideshare favorable. If neither of these conditions is true, then the site is considered to be mode neutral. This mode bias is used as input to the estimation of the percent vehicle-trip reduction.

Step 4: Calculate Peak Vehicle Trips (Optional).

In some situations, the trip reduction may be required or desired for a specific peak hour or peak period. A worksheet is provided for computing peak-period trips from total person trips traveling to site.

Step 5: Set TDM Goal.

The TDM goal is used to identify the appropriate type and intensity of the TDM program. The goal is typically expressed as a percent reduction in vehicle-trips. The procedure contained in this manual uses this measure for the evaluation and development of TDM programs and strategies.

Step 6: Develop TDM Program Options.

In this step, the process of identifying TDM program packages that will meet the goal is begun. More than one package of strategies will allow the achievement of the trip reduction goal. A worksheet is provided that is used to evaluate modal shift strategies, alternative work arrangements, and time-shift actions. Tables are provided that are used to look up the percent vehicle-trip reduction based on employer type, starting AVR, mode bias, and levels of transit, carpool, and vanpool support.

Step 7: Estimate Trip Reduction Impacts.

A worksheet is provided that allows for the comparison and summation of several trial TDM strategies that can be combined into the TDM program.

The final TDM program will be a result of the trial testing of multiple TDM strategies and the final packaging of multiple actions. The report contains all of the necessary worksheets, trip reduction factors, and an example application.

This example is applicable only to a single site. Often it is necessary to make a similar assessment for an entire area. *Implementing Effective Travel Demand Management Measures: Inventory of Measures and Synthesis of Experience,* which was published by the FTA, discusses techniques that may be applied to an area rather than a site.

CASE STUDY

Because transit use in the Asheville region is so small, representing less than 1 percent of the average daily person trips made in the region, we have chosen not to use a mode-choice model in this case study.

If we had wished to do so, however, we would need to build a transit network and transit travel time matrices (skim tables) and apply one of the mode-choice models described in this chapter.

CHAPTER 7

AUTOMOBILE-OCCUPANCY CHARACTERISTICS

INTRODUCTION

As the mode-split process outlines, the most commonly used modeling approach employed by urban transportation planners generates total person trips and then distributes and splits these trips into auto and transit modes. Auto-occupancy factors are then applied to the auto person-trip dataset to produce a vehicle-trip table for use in the traffic-assignment process. The importance of auto occupancy in this process becomes apparent when it is considered that a slight error in the auto-occupancy rates (e.g., 1.36 versus 1.50, or about 10 percent) translates into a difference of more than 10,000 vehicles per day on a high-volume facility carrying 150,000 person trips.

Contrary to the assumption made in *NCHRP Report 187,* the overall trend in vehicle-occupancy rates has been a decline during the last few decades. Factors that may have contributed to this decline include the increase in auto ownership and the decrease in household size. Since 1960, the number of households has increased by 73 percent while the number of persons per household has declined 21 percent. The percent of households with no vehicles available has dropped 46 percent in the same period.[1]

Decreases in the number of persons per household mean that there are fewer persons in each household that could be traveling together for any home-based trip purpose. As the number of employed persons per household has risen, people are chaining trips to accomplish different purposes on their way to and from work, such as trips to schools or day care centers, which makes it more difficult for carpools to form for work-related travel.

In the last decade, the increase in drive-alone trips to work exceeded the number of new workers.[2] Persons who travel in carpools, especially carpools involving members from different households, constitute a very small portion of all travelers. Only 13 percent of persons traveling to work will share a ride on any day, and only 7.5 percent of all vehicles transporting people to work will be a carpool or a vanpool.[3] In addition, over the last decade the shift has been to ever-smaller carpools—four- and five-person carpools declined by more than 50 percent, and two-person carpools now account for 85 percent of all carpools.[4]

Factors that may influence auto occupancy are: (1) the journeys that are made for different purposes at different times of day, (2) conditions that exist where the trip begins and ends, and (3) characteristics of the travelers and the households in which they live. These elements describe the same kinds of characteristics represented by the typical mode-choice model.

Available data from various urban areas were analyzed to develop some insight into the variation of auto occupancy with these factors, especially travel for different purposes throughout the day. Tables for estimating auto occupancy by urbanized area population, trip purpose, and time of day have been provided to assist in responding to auto-occupancy questions.

Analysis of local or work-site-based TDM efforts can often provide better information on vehicle occupancies than are presented in the tables, which are based on national data. TDM includes a variety of techniques to cope with escalating traffic. Metropolitan areas of all sizes are looking to a mix of transportation modes and are initiating programs such as ridesharing, developer requirements, and the exclusive use or preferential treatment of transportation facilities to serve high-occupancy vehicles. Work-site-based strategies include carpool matching, subsidized transit passes, free and priority parking for carpools, and flex-time. Programs like these are meant to reduce vehicle trips, either regionwide or to a specific site, to provide additional capacity, conserve energy, and improve air quality. In many areas, vehicle occupancies should be viewed as a policy input to the planning process rather than as an output. The section, Usefulness of Regionally Developed Models, discusses how TDM or other local data can be used to augment the tables and produce better estimates of auto occupancy.

BASIS FOR DEVELOPMENT

Investigation indicates that, although many reports have been written to describe the results of counts or surveys of

[1] *Journey-to-Work Trends in the United States and its Major Metropolitan Areas, 1960–1990,* for US DOT, FHWA, and Office of Highway Administration (1994) p.2-2.

[2] Alan Pisarski, *New Perspectives in Commuting* for US DOT, FHWA, and Office of Highway Management (1992) p.5.

[3] *Journey-to-Work Trends,* page 2-6, 5-16, 5-17.

[4] Alan Pisarski, *Travel Behavior Issues in the 90s,* US DOT and Federal Highway Administration for Office of Highway Information and Management (1992).

vehicle occupancy, relatively little attention has been given to the development of procedures to determine auto occupancy. It appears to be common practice to develop auto-occupancy factors by trip purpose from base year data and to use this one set of factors for all subsequent planning efforts.

The major data sources used in the development of the auto-occupancy rates presented here were

- The *Nationwide Personal Transportation Study* (NPTS, 1990),
- *Travel Behavior Issues in the 90s* (Alan Pisarski, US DOT, and Federal Highway Administration for Office of Highway Information and Management),
- *Vehicle Occupancy Determinants* (Barton-Aschman Associates, Inc., Arizona Department of Transportation, US DOT, and FHWA, Report Number FHWA-AZ89-252, August 1989), and
- Various urban transportation study reports.

FEATURES AND LIMITATIONS

The modeler needs to evaluate the output of the mode-choice model. Some mode-choice models produce trip tables that are given in person trips while others produce vehicle trips. If vehicle trips were produced, then the auto-occupancy calculation has already been made and does not need to be repeated here. The information in this chapter is useful, however, as a test of the reasonableness of the auto occupancies generated by the mode-choice model.

In an effort to develop auto-occupancy estimates for use in urbanized areas of varying population size, investigation was undertaken to determine what factors influenced auto-occupancy rates and what differences are observed in various urban areas, and by trip purpose, time of day, trip length, and household income.

The data presented here reflect average auto-occupancy rates as of approximately 1990 (transportation studies conducted after 1985 and the NPTS conducted in 1990).

VARIATION IN AUTO OCCUPANCY BY URBANIZED AREA POPULATION AND BY TRIP PURPOSE

Trip purpose is the most significant factor influencing auto occupancy, where other factors such as household income and trip distance are less important determinants of vehicle occupancy.[5] Going shopping or to different forms of entertainment are the most likely trip purposes to represent higher vehicle occupancies. While persons may travel together in carpools to get to work in order to save money or because they have no other form of transportation available, people will usually travel together for other trip purposes because they want to be together during travel and when they get to a common destination.

Table 37 presents average auto-occupancy values by urban area size and trip purpose for 1990. These values reflect *average daily* auto-occupancy rates. Compared with the *NCHRP Report 187* rates, the 1990 rates are significantly lower for all purposes except home-based other and non-home-based. This reflects the rise in auto ownership and drive-alone trips, as well as the increase in suburb-to-suburb travel discussed earlier.

VARIATION IN AUTO OCCUPANCY BY TIME OF DAY

As percentage of trips by purpose shifts throughout the day, vehicle-occupancy rates also vary by time of day. A larger portion of trips during the AM peak are home-based work trips, which exhibit the lowest occupancy rates; therefore, average vehicle occupancy for peak periods is often lower than for non-peak periods. As noted above, shopping and social trips generally exhibit higher vehicle occupancies; these purposes account for a greater portion of all trips made during off-peak periods.

In addition to the overall occupancy varying throughout the day, the auto occupancy for individual trip purposes also varies by time of day. Table 38 presents adjustment factors for time-of-day variation in the average auto occupancy by trip purpose. Because of data limitations, this table was created without regard to urban size and thus should be used for all urban sizes.

VARIATION IN AUTO OCCUPANCY BY INCOME LEVEL

In addition to the variables discussed thus far, auto occupancy is known to be a function of the income level of the trip-maker and of parking cost at the destination of a trip; that is, the auto occupancy of low-income trip-makers is higher than for similar trips by high-income trip-makers, and the auto occupancy for trips to high-parking-cost areas is higher than for comparable trips to low-parking-cost areas.

This basic relationship between auto occupancy and the economics of travel is extremely important but is often neglected in the planning process. In particular, the use of average auto-occupancy rates by trip purpose will tend to overestimate vehicular trips to areas of high parking cost and underestimate vehicular trips to areas where parking costs are either low or nonexistent.

As part of this user's guide, generalized relationships between auto occupancy and income level are provided to assist the user in assessing the effects of such variables. These rates are presented in Table 39. This table should be used for all urban sizes. More variation is indicated by demographics and income than by city size characteristics. The data did not

[5] Alan Pisarski, *New Perspectives in Commuting* for US DOT, FHWA, and Office of Highway Management, p.8 (1992).

TABLE 37 Average daily auto-occupancy rates by urbanized area population and purpose

Urban Area Size	HBW	HBShop	HBSoc	HBOther	NHB	All
	Trip Purpose					
Updated Parameters						
50,000 to 199,999	1.11	1.44	1.66	1.67	1.66	1.49
200,000 to 499,999	1.12	1.48	1.72	1.65	1.68	1.51
500,000 to 999,999	1.13	1.45	1.66	1.65	1.66	1.48
1,000,000+	1.11	1.48	1.69	1.66	1.64	1.49

Source: NPTS, 1990

Urbanized Area Population	HBW	HBShop	HBSoc	HBOther	HBNW	NHB	All
	Trip Purpose						
Parameters From NCHRP 187							
50,000 to 100,000	1.38	1.57	2.31	1.52	1.82	1.43	1.50
100,000 to 250,000	1.37	1.57	2.31	1.52	1.81	1.43	1.50
250,000 to 750,000	1.35	1.57	2.30	1.52	1.77	1.43	1.50
750,000 to 2,000,000	1.33	1.58	2.29	1.51	1.74	1.43	1.51

TABLE 38 Auto-occupancy rate adjustment factors by time of day

	HBW	HBShop	HBSoc	HBO	NHB
12:00 Midnight to 5:00 a.m.	—	—	—	—	—
5:00 a.m. to 6:00 a.m.	0.08	-0.30	-0.63	0.09	-0.24
6:00 a.m. to 7:00 a.m.	0.03	-0.23	-0.29	0.11	-0.13
7:00 a.m. to 8:00 a.m.	0.06	0.11	-0.03	0.27	0.19
8:00 a.m. to 9:00 a.m.	0.03	-0.17	-0.03	0.21	-0.02
9:00 a.m. to 10:00 a.m.	-0.07	-0.08	-0.09	-0.30	-0.24
10:00 a.m. to 11:00 a.m.	-0.04	-0.15	-0.01	-0.09	-0.06
11:00 a.m. to 12:00 Noon	-0.11	-0.01	-0.14	-0.15	-0.07
12:00 p.m. to 1:00 p.m.	-0.07	0.00	-0.11	-0.16	-0.12
1:00 p.m. to 2:00 p.m.	0.04	-0.03	0.13	-0.10	-0.18
2:00 p.m. to 3:00 p.m.	0.09	-0.10	0.00	0.22	0.03
3:00 p.m. to 4:00 p.m.	0.07	-0.06	0.09	0.22	0.06
4:00 p.m. to 5:00 p.m.	0.02	0.01	0.07	0.06	-0.05
5:00 p.m. to 6:00 p.m.	-0.04	0.09	0.05	-0.05	-0.08
6:00 p.m. to 7:00 p.m.	-0.01	0.22	0.03	0.14	0.37
7:00 p.m. to 8:00 p.m.	-0.01	0.34	0.28	0.06	0.41
8:00 p.m. to 9:00 p.m.	0.07	0.25	0.02	0.17	0.31
9:00 p.m. to 10:00 p.m.	-0.07	0.19	0.18	-0.20	0.17
10:00 p.m. to 11:00 p.m.	-0.10	-0.03	-0.01	-0.16	0.01
11:00 p.m. to 12:00 Midnight	-0.03	0.02	-0.20	-0.22	0.08

Source: NPTS, 1990.

TABLE 39 Auto-occupancy rates by income category and purpose for urban areas

Income	Trip Purpose HBW	HBShop	HBSoc	HBO	NHB
Low	1.19	1.49	1.77	1.66	1.69
Medium	1.12	1.47	1.67	1.65	1.57
High	1.11	1.43	1.56	1.58	1.50
All	1.12	1.44	1.63	1.62	1.56

Source: NPTS, 1990.

allow a direct categorization of parking costs; it is assumed for this table that these costs are related to trip type.

VARIATION IN AUTO OCCUPANCY BY FACILITY TYPE

Thus far, it has been shown that auto-occupancy rates vary by trip purpose and by time of day. Auto occupancy is also a function of trip length in time or distance, and the length of the trip often influences the type of roadway used for travel.

As home-based work trips are generally the longest distance trips made by a household, they represent a higher portion of all trips made on freeways in a planning region, especially during the peak commute hours. Other types of travel, such as parents driving their children to school or social-recreational trips, which exhibit higher occupancy rates, are more likely to be made on arterials and to be of shorter trip length.

The result of these differences in auto occupancy by trip purpose and length is that the highest vehicle occupancies on weekdays occur on lower-volume roadways, and during off-peak hours, especially on arterials in suburban areas in the evening. The lowest vehicle occupancies occur on higher-volume roadways (particularly freeways in core and urban areas) during the AM peak when work trips predominate. Vehicles traveling on freeways have lower occupancy than those on arterials and collectors because of the different types of trips these separate roadways serve. Table 40 presents auto-occupancy rates by facility type and area type for periods during a 12-hour day.

TABLE 40 Auto occupancy by roadway type and area type

Area and Roadway Type	A.M. Peak	Midday	Noon	P.M. Peak	Evening	All Day
All Facilities in the Region	1.226	1.335	1.361	1:385	1.504	1.337
All Freeways in the Region	1.204	1.308	1.332	1.297	1.396	1.291
All Arterials in the Region	1.233	1.343	1.369	1.408	1.533	1.350
All Facilities in the Core	1.191	1.289	1.331	1.293	1.403	1.282
Freeways in the Core	1.185	1.270	1.292	1.278	1.370	1.262
Arterials in the Core	1.194	1.297	1.347	1.299	1.417	1.291
All Facilities in Urban	1.195	1.315	1.324	1.361	1.494	1.312
Freeways in Urban	1.165	1.284	1.316	1.292	1.389	1.270
Arterials in Urban	1.204	1.324	1.327	1.380	1.523	1.324
All Facilities in Suburban	1.293	1.395	1.430	1.483	1.590	1.410
Freeways in Suburban	1.304	1.408	1.421	1.334	1.446	1.375
Arterials in Suburban	1.291	1.393	1.432	1.508	1.615	1.416

A.M. Peak	6:00 a.m. to 9:00 a.m.
Midday	9:00 a.m. to 12:00 p.m. and 2:00 p.m. to 4:00 p.m.
Noon	12:00 p.m.to 2:00 p.m.
P.M. Peak	4:00 p.m. to 6:00 p.m.
Evening	6:00 p.m. to 7:00 p.m.

Source: Limited urban transportation studies.

DATA REQUIREMENTS AND EXAMPLE PROBLEMS

The goal of this chapter is to provide simplified procedures to assist the user in developing answers related to auto occupancy in relatively rapid order. In the development of auto-occupancy parameters, considerable care was taken to minimize necessary data acquisition for application and yet produce reasonable estimates.

Following are several example problems designed to illustrate how the procedures developed can be employed to provided reasonable estimates of auto occupancy given limited information with which to work.

Problem 1: What are reasonable values for all-purpose trip auto occupancy and HBW-trip auto occupancy in an urbanized area of 275,000 population?

Solution 1: Table 37 indicates that for an urbanized area of 200,000 to 499,999 population, the auto-occupancy rates for total trips and HBW trips in 1990 were 1.51 and 1.12 persons per vehicle, respectively.

Problem 2: A new shopping center is under construction in an urbanized area of 225,000 population. It is estimated that the center will generate 10,000 auto person-trips per day, and that 18 percent of such trips will occur during the period 8:00 PM to 9:00 PM. How many vehicle trips can be anticipated during this peak hour?

Solution 2: Table 37 indicates that the average auto occupancy for the purpose of HBO shopping in an urbanized area of 225,000 population is about 1.48. Given that most trips during this hour will be shopping trips, it is reasonable to use this occupancy for all trips if more detailed information on trip purpose is not available. Table 38 indicates that an adjustment factor of 0.25 should be used during the period 8:00 PM to 9:00 PM. The number of vehicle trips to be anticipated is, therefore, 1,040; that is,

$$\frac{10{,}000\ \mathit{Person\ Trips} \times 0.18}{1.48 + 0.25} = 1{,}040$$

USEFULNESS OF REGIONALLY DEVELOPED MODELS

The application of the auto-occupancy estimating procedures developed through these example problems attempts to demonstrate how the user can quickly calculate reasonable values for auto occupancy under varying conditions, knowing little more than the population of the study area. It should be noted, however, that many problems facing urban planners are complex and require more sophisticated estimating procedures than those outlined here. One example would be the impact of an exclusive carpool and bus lane on air quality—a problem that requires an estimate of the shift of persons from the automobile to public transit, and from low- to high-occupancy vehicles in a corridor as a result of a change in travel time. In cases such as this, the usefulness of regionally calibrated policy-sensitive models cannot be overstated.

In addition, regionally developed information can play an important role in the refinement of the average nationwide information presented here. For example, a simple table of auto-occupancy rates by trip purpose reflecting conditions specific to the user's study area could be used in place of the rates presented in Table 37 as a more accurate starting point in the estimation process. Other local information (if available), such as auto occupancy by time of day, by land-use category, and the like could also be used to refine the tables. In summary, if similar information is available for the user's study area from the local regional planning organization, it should be used. Lacking such information, however, the procedures documented here can be applied to develop, quickly and economically, reasonable answers to a diverse set of questions relative to auto occupancy.

CASE STUDY

The estimation of vehicle trips for the purposes of the Asheville, North Carolina, case study is based on the auto-occupancy factors found in Table 37. The average values by trip purpose for urban areas with under 200,000 population were applied to convert the 520,921 total person trips into 350,077 vehicle trips, as shown in the following equations:

$$\mathit{HBW\ Vehicle\ Trips} = 124{,}875\ \mathit{HBW\ Person\ Trips} \div 1.11 = 112{,}500\ \mathit{HBW\ Vehicle\ Trips}$$

$$\mathit{HBO\ Vehicle\ Trips} = 278{,}393\ \mathit{HBO\ Person\ Trips} \div 1.67 = 166{,}702\ \mathit{HBO\ Vehicle\ Trips}$$

$$\mathit{NHB\ Vehicle\ Trips} = 117{,}652\ \mathit{NHB\ Person\ Trips} \div 1.66 = 70{,}875\ \mathit{NHB\ Vehicle\ Trips}$$

CHAPTER 8

TIME-OF-DAY CHARACTERISTICS

INTRODUCTION

Through the mode-choice step in the travel forecasting process, the forecasting procedures usually consider total travel over the full 24-hour day. For many applications, travel must be estimated for specific periods or hours of the day. These applications may include the analysis of highway facilities, transit services, and emissions. Peak-period speeds and volumes are critical for assessing the level of service provided by the transportation system, the competitiveness of transit with autos on the highway network, and the size of the transit fleet.

Analyses of special times are generally required to judge transportation system requirements. During limited periods during the day—the peak time period—the transportation system is loaded, and sometimes overloaded, with travelers. For general highway traffic, the critical peak hour most often occurs during the afternoon when people are returning from work, going shopping, completing recreational trips, and being picked up at school. However, critical traffic movements may occur at other times, particularly during the morning commute hours.

In 1990, for the first time, the census provided start-time information for work trips. In aggregate, these data show that there is no such thing anymore as a peak hour. The most heavily loaded hour in trip starts is from 7:00 AM to 8:00 AM, and this hour accounts for only 32 percent of commuting trip start times.

Geographic location can add another dimension to the time-of-day stratification to account for unique peaking characteristics of individual corridors or subareas. This is particularly applicable where a subarea contains a major generator such as a hospital or university that has significantly different peaking times than conventional commuter trips.

A final issue with regard to peaking occurs after the assignment and aggregation of link volumes by period. Several issues with regard to capacity and facility design require peak-hour estimates of volumes on highways, transit lines, transit stations, and park-and-ride lots. Mode-specific factors capture more fully the unique peaking characteristics of each mode. For example, carpools on HOV facilities tend to have peaks that are sharper than general highway traffic.

Transit use is highly oriented to the AM and PM peak periods with lesser amounts of travel at other times. The differences between auto and transit use are most visible during the evening hours when many trips are made for social and shopping purposes. Compared with auto trips, few evening trips are made via transit. Also, the peak hour for transit travel usually occurs during the AM peak period—caused by a concentration of work trips—whereas the peak hour for auto-related trips usually occurs during the PM peak period.

The AM peak is most critical for air quality analysis, as morning emissions of volatile organic compounds (VOCs) and nitrous oxides (NO_x) have a longer time to react to light than do pollutants emitted in the PM peak. As a result, ozone concentrations typically peak during the late morning or early afternoon hours. Afternoon winds also tend to disperse pollutants more than in the early morning.

On the other hand, the PM peak is critical for system analysis because areawide traffic volumes and congestion are typically higher during the afternoon peak. Ultimately, the choice of which peak period to model must take into account such considerations as the availability of count data, previous modeling efforts, local conditions, and the application for which the model is intended.[1]

Time-of-day factors are applied to the mode-specific trip tables produced by the mode-choice models. The most straightforward applications stratify the factors only by trip purpose; however, time-of-day factors can be stratified by both trip purpose and mode if mode-specific surveys and counts have been obtained. Otherwise, it is assumed that the same mix of purposes is uniform across modes.

The purpose of this chapter is to provide tables to allow determination of hourly travel from estimates of total daily travel. Material is provided in this chapter for both automobile travel and transit travel. The data are also extremely useful in converting daily work trips from census information to peak-hour all-purpose trips. The techniques used for vehicle travel are different from those used for transit time-of-day analysis; therefore, a separate section is provided for each.

[1]Greig Harvey and Elizabeth Deakin, *A Manual of Transportation Air Quality Modeling for Metropolitan Planning Organizations*, National Association of Regional Councils (1992).

BASIS FOR DEVELOPMENT

Time-of-day analyses are used for several types of studies, and, since the introduction of Transportation System Management (TSM) requirements, are becoming a more critical part of the overall transportation planning process. Examples of time-sensitive studies are as follows:

1. Traffic impact studies are analyses to determine the impact a specific residential, commercial, or other type of development has on the area transportation network.
2. Trip accumulation studies are usually done to determine the peak accumulation of vehicles for parking studies, taking into account the mix of trip purposes involved.
3. Highway v/c studies are evaluations using peak factors (essentially the type of information provided later in this chapter) to determine peak-loading conditions in vehicles per hour (VPH) for highway traffic assignment and determination of capacity requirements.
4. TSM studies specifically address transportation solutions for the critical peak period, generally in the form of traffic engineering or operations improvements.
5. TDM has found a significant place in transportation planning in the past decade. As roadway capacities have filled, ways to fit more travelers in the same road space have become an alternative to widening or building new roadways. TDM strategies are used not only to lessen the number of vehicles on the network during the peak time periods, but also to shift some trips to non-peak time periods.

This shifting can seriously affect the time-of-day trip characteristics of a region. Adjustments in the trip table must be made to compensate for TDM efforts, either in place or planned, that affect the time when trips are made.

The procedures presented here are based on observed vehicle-miles of travel (VMT). VMT is the product determined when a given trip is multiplied by its trip length (distance). As such, it is truly a measure of travel and not a measure of the distribution of trips during a 24-hour period. The trip-length distribution may vary by trip purpose over a 24-hour period. However, within the context of acceptable transportation planning procedures, such as trip-distribution modeling, the VMT distribution can be used to approximate the distribution of trips by purpose.

VEHICLE TRAVEL

Time-of-day analysis is usually undertaken at one of two points: (1) just after application of the auto-occupancy procedures to isolate a time period for further analysis or (2) after assignment of 24-hour travel in preparation for capacity analysis. The general organization of the charts provided in this chapter is by the four urbanized area population groups. Each set of charts (by urbanized area population) is further stratified to present data to

- Analyze auto driver travel by trip purpose,
- Analyze total vehicle travel,
- Determine total vehicle travel, by time period or in aggregate, from internal auto driver trips,
- Determine trip volume by route type, subregion, and orientation to study area core, and
- Determine directional split of travel by route type, subregion, and orientation to the study area core.

The tables were developed using the NPTS with confirmation from analysis of travel data of home interview data sets from around the country.

DIURNAL DISTRIBUTION

The use of diurnal factors in time-of-day analysis allows peak-hour assignments that are representative of the peak-hour direction of trips and the percent by hour. These factors are used to produce peak-hour directional volumes.

Twenty-four-hour production/attraction trip tables are converted to time-of-day-specific, origin/destination trip tables by applying time-of-day and directional split factors. The creation of time-of-day origin/destination trip tables from 24-hour origin/destination trip tables is somewhat easier as the tables need to be factored only by time-of-day factors, not by time-of-day and directional split factors.

Use of Time-of-Day Tables

This section presents tables of travel by time of day and by purpose for the different population groups. An example is presented of factoring a daily vehicle trip table by purpose to an AM peak-hour trip table.

There are two basic approaches to developing estimates of directional peak-hour vehicle volume: (1) post-processing of daily highway assignments using link-based peak-hour and directional percentages and (2) preassignment factoring of daily trip tables by purpose, using factors for AM peak, PM peak, and off-peak periods.

The first approach historically has been used in conjunction with the assignment of a daily vehicle-trip table. The peak percentages for a link may be based on 24-hour machine counts of traffic, but most commonly the assigned ADT is multiplied by a single factor ranging between 8 and 12 percent of daily traffic to achieve an estimate of total bi-directional peak-hour travel. A directional split (e.g., 60/40) based on observations of traffic conditions is then applied. This procedure yields a rough approximation of peak traffic that may be appropriate for smaller urban areas where the duration and intensity of congestion is limited.

The preassignment approach uses time-of-day factors to create the AM peak, PM peak, and off-peak trip tables by purpose that are then used in the assignment of vehicle trips to the network. An example of this method is included at the end of this section. Using this reassignment factoring process, average daily traffic assignments can be produced by summing the results of the AM peak, PM peak, and off-peak assignments. Table 41 presents the percent of vehicle trips by hour by trip purpose for different urban population groups. Table 42 shows the diurnal distribution of trips by time and purpose. The data

TABLE 41 Percent of vehicle trips by hour by trip purpose

Hour Beginning	Urban Size = 50,000 to 199,999			
	HBW	HBO	NHB	All Purposes
Midnight	0.33	0.40	0.49	0.41
1:00 a.m.	0.07	0.17	0.12	0.12
2:00 a.m.	0.50	0.23	0.27	0.33
3:00 a.m.	0.61	0.07	0.12	0.27
4:00 a.m.	1.00	0.08	0.00	0.36
5:00 a.m.	2.79	0.18	0.06	1.01
6:00 a.m.	8.34	1.10	0.46	3.30
7:00 a.m.	13.57	5.53	2.07	7.06
8:00 a.m.	7.84	5.64	2.27	5.25
9:00 a.m.	3.36	4.27	3.76	3.80
10:00 a.m.	2.79	5.86	5.40	4.68
11:00 a.m.	2.65	6.44	7.22	5.44
Noon	3.72	6.40	11.26	7.13
1:00 p.m.	3.26	6.34	8.77	6.12
2:00 p.m.	4.12	7.70	8.31	6.71
3:00 p.m.	8.30	8.06	9.74	8.70
4:00 p.m.	10.31	7.25	9.28	8.95
5:00 p.m.	10.66	7.32	8.56	8.85
6:00 p.m.	5.01	7.44	7.19	6.55
7:00 p.m.	2.79	6.71	5.52	5.01
8:00 p.m.	1.72	5.24	3.46	3.47
9:00 p.m.	2.29	3.95	3.06	3.10
10:00 p.m.	2.26	2.25	1.55	2.02
11:00 p.m.	1.69	1.37	1.06	1.37

Source: 1990 NPTS.

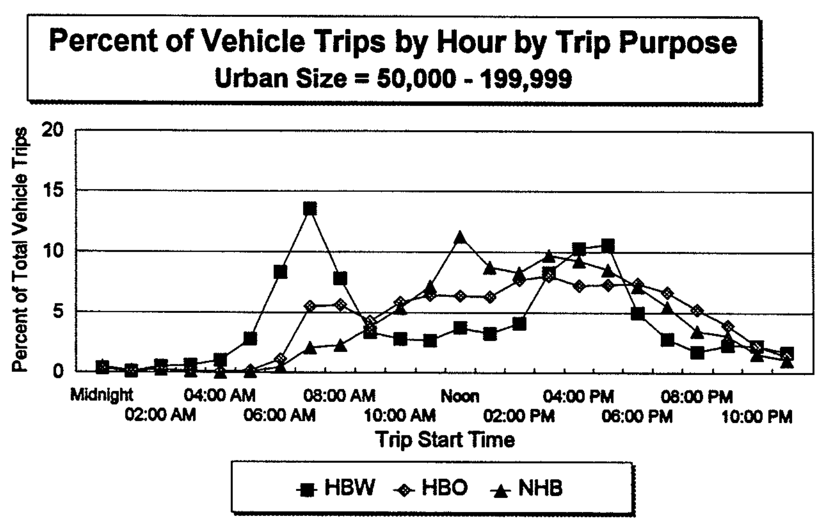
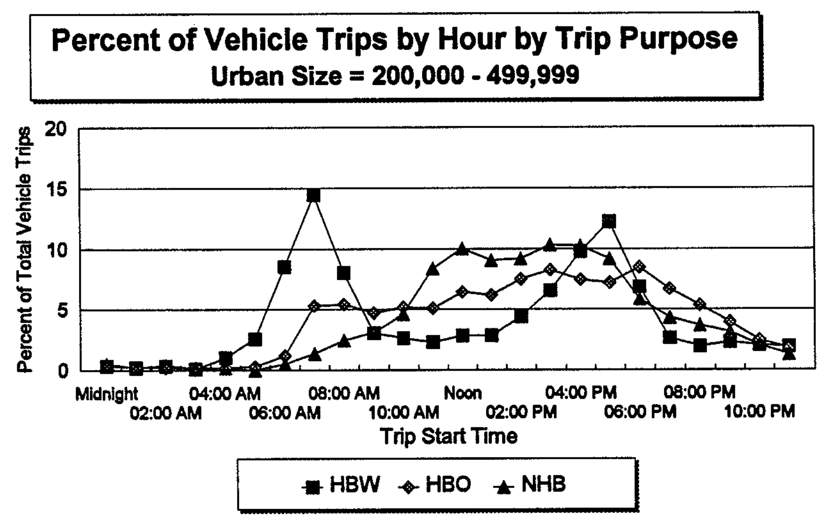


TABLE 41 *(Continued)*

Hour Beginning	HBW	HBO	NHB	All Purposes
	Urban Size = 200,000 to 499,999			
Midnight	0.35	0.29	0.48	0.37
1:00 a.m.	0.22	0.26	0.16	0.21
2:00 a.m.	0.35	0.15	0.38	0.29
3:00 a.m.	0.06	0.22	0.10	0.13
4:00 a.m.	1.03	0.17	0.16	0.45
5:00 a.m.	2.57	0.29	0.00	0.95
6:00 a.m.	8.58	1.20	0.48	3.42
7:00 a.m.	14.46	5.28	1.33	7.02
8:00 a.m.	8.06	5.43	2.45	5.31
9:00 a.m.	3.03	4.72	3.08	3.61
10:00 a.m.	2.63	5.15	4.62	4.13
11:00 a.m.	2.29	5.09	8.39	5.26
Noon	2.86	6.43	10.04	6.44
1:00 p.m.	2.86	6.19	9.08	6.04
2:00 p.m.	4.40	7.50	9.20	7.03
3:00 p.m.	6.58	8.25	10.36	8.40
4:00 p.m.	9.78	7.45	10.25	9.16
5:00 p.m.	12.24	7.23	9.20	9.56
6:00 p.m.	6.86	8.47	5.84	7.06
7:00 p.m.	2.63	6.72	4.31	4.55
8:00 p.m.	1.94	5.36	3.67	3.66
9:00 p.m.	2.29	3.96	3.14	3.13
10:00 p.m.	2.05	2.47	2.02	2.18
11:00 p.m.	1.89	1.76	1.28	1.64

Source: 1990 NPTS.



are presented separately for the three trip purposes—HBW, HBO, NHB, and for all purposes combined.

Table 42 breaks down the frequency distribution of start time and trip purpose into a diurnal format. From this table, either peak hour, peak period, or, for air quality modeling, 8-hour period can be determined.

Transit Hourly Distributions

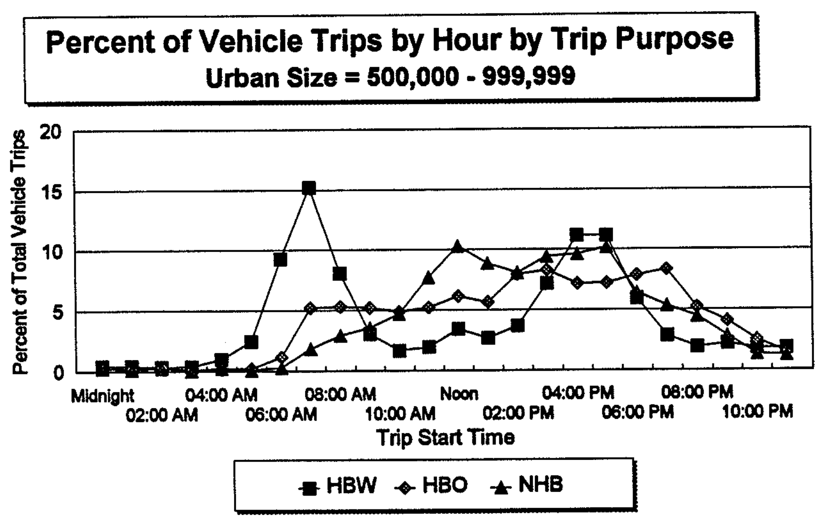
Most analyses of time-of-day distribution of transit volumes center about a peak period or specific segments of the peak period. It is the peak-period volume that dictates the required size of the transit fleet; therefore, the following approach for transit time-of-day analysis has been taken.

Table 43 gives factors for deriving ridership estimates for any of the following time periods if patronage for any one of the time periods is known: (1) total transit patronage expected to occur on an average weekday; (2) peak-period trips where the peak period is the sum of transit patronage expected for the 2 morning peak hours and the 2 evening peak hours; (3) the peak hour of transit patronage for the day, usually occurring between 8:00 AM and 9:00 AM; and

TABLE 41 *(Continued)*

Hour Beginning	Urban Size = 500,000 to 999,999 HBW	HBO	NHB	All Purposes
Midnight	0.43	0.24	0.25	0.31
1:00 a.m.	0.43	0.27	0.12	0.27
2:00 a.m.	0.34	0.33	0.23	0.30
3:00 a.m.	0.37	0.12	0.03	0.17
4:00 a.m.	0.98	0.15	0.25	0.46
5:00 a.m.	2.46	0.22	0.08	0.92
6:00 a.m.	9.31	1.14	0.29	3.58
7:00 a.m.	15.21	5.22	1.83	7.42
8:00 a.m.	8.07	5.28	2.92	5.42
9:00 a.m.	3.04	5.21	3.55	3.93
10:00 a.m.	1.64	4.89	4.69	3.74
11:00 a.m.	1.95	5.19	7.71	4.95
Noon	3.44	6.16	10.32	6.64
1:00 p.m.	2.67	5.63	8.88	5.73
2:00 p.m.	3.70	7.93	8.06	6.56
3:00 p.m.	7.16	8.25	9.43	8.28
4:00 p.m.	11.14	7.15	9.63	9.31
5:00 p.m.	11.17	7.21	10.17	9.52
6:00 p.m.	5.93	7.83	6.39	6.72
7:00 p.m.	2.83	8.30	5.36	5.50
8:00 p.m.	1.92	5.21	4.44	3.86
9:00 p.m.	2.20	4.08	2.83	3.04
10:00 p.m.	1.80	2.50	1.32	1.87
11:00 p.m.	1.80	1.49	1.21	1.50

Source: 1990 NPTS.



(4) peak-hour direction where transit patronage is estimated in the direction of peak flow during the peak hour.

The user should keep in mind that the factors are to be applied to all-purpose transit trips and not to trips by purpose.

Trip Matrix Conversion Factors

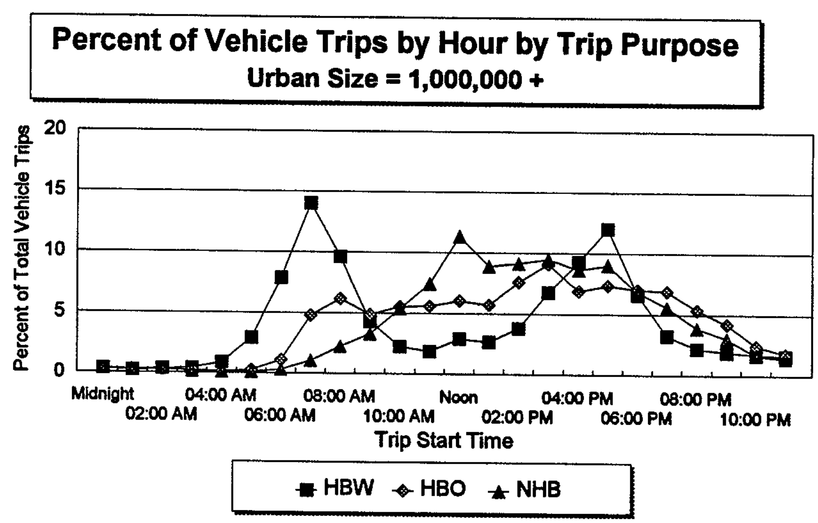
It is conceivable the user may be required to perform an analysis within a period of time so brief that a full analysis of all trip purposes (HBW, HBO, NHB) is not practical. For example, the user may wish to know the consequences of total trip movement within a major travel corridor and only have time to generate a trip matrix describing the HBW trip purpose. For this reason, Tables 44 and 45 have been provided to permit a quick application of generalized factors by urban area population to the work trips to produce total daily trips or total trips for a designated time period.

The tables cross-relate total travel and HBW travel by the time periods most used for travel and air quality analysis. The

TABLE 41 *(Continued)*

Hour Beginning	Urban Size = 1,000,000+ HBW	HBO	NHB	All Purposes
Midnight	0.35	0.32	0.34	0.34
1:00 a.m.	0.21	0.19	0.25	0.22
2:00 a.m.	0.36	0.26	0.32	0.31
3:00 a.m.	0.37	0.19	0.12	0.23
4:00 a.m.	0.88	0.06	0.06	0.33
5:00 a.m.	2.94	0.24	0.07	1.08
6:00 a.m.	7.90	1.08	0.31	3.10
7:00 a.m.	14.06	4.79	1.05	6.63
8:00 a.m.	9.63	6.18	2.25	6.02
9:00 a.m.	4.30	4.88	3.32	4.17
10:00 a.m.	2.26	5.55	5.39	4.40
11:00 a.m.	1.86	5.61	7.47	4.98
Noon	2.92	6.06	11.37	6.78
1:00 p.m.	2.68	5.72	8.92	5.77
2:00 p.m.	3.80	7.63	9.15	6.86
3:00 p.m.	6.78	9.10	9.51	8.46
4:00 p.m.	9.31	6.90	8.64	8.28
5:00 p.m.	12.04	7.37	9.01	9.47
6:00 p.m.	6.61	7.04	6.82	6.82
7:00 p.m.	3.26	6.92	5.61	5.26
8:00 p.m.	2.20	5.38	3.89	3.82
9:00 p.m.	1.91	4.25	3.04	3.07
10:00 p.m.	1.75	2.48	1.67	1.97
11:00 p.m.	1.61	1.79	1.42	1.61

Source: 1990 NPTS.



analyst should be aware of the definition of each time period and of inherent subtleties contained in the tables. The definitions of the time periods contained in Tables 44 and 45 are as follows:

- Total Travel—the sum of travel for all purposes (i.e., HBW, HBO, and NHB) occurring during the 24-hour analysis day,
- Total Work Travel—the total travel for the HBW purpose estimated to occur during the 24-hour analysis day, and
- 8-Hour Peak Period—the 8-hour period during the analysis day during which the greatest percentage of the total daily trips occur.

As the user becomes familiar with the conversion tables, it will be discovered that the conversion factors are useful from the standpoint of gaining a perspective about the distribution of travel as well as helpful for detailed analysis purposes.

Table 42 Diurnal distribution by purpose and direction

Start Time	Home-Based Work From Home	Home-Based Work To Home	Home-Based Other From Home	Home-Based Other To Home	Non-Home Based	Total
Midnight	0.000	0.004	0.000	0.002	0.003	0.003
1:00 a.m.	0.000	0.002	0.000	0.001	0.002	0.002
2:00 a.m.	0.000	0.003	0.000	0.002	0.002	0.003
3:00 a.m.	0.002	0.002	0.000	0.001	0.001	0.002
4:00 a.m.	0.009	0.001	0.001	0.000	0.001	0.003
5:00 a.m.	0.032	0.001	0.002	0.000	0.001	0.008
6:00 a.m.	0.093	0.002	0.010	0.001	0.004	0.026
7:00 a.m.	0.136	0.006	0.050	0.004	0.015	0.062
8:00 a.m.	0.076	0.004	0.048	0.008	0.026	0.054
9:00 a.m.	0.030	0.003	0.038	0.011	0.035	0.043
10:00 a.m.	0.014	0.004	0.039	0.017	0.053	0.047
11:00 a.m.	0.010	0.006	0.029	0.024	0.078	0.052
Noon	0.011	0.013	0.029	0.032	0.110	0.066
1:00 p.m.	0.011	0.011	0.029	0.027	0.087	0.057
2:00 p.m.	0.014	0.021	0.026	0.045	0.087	0.069
3:00 p.m.	0.012	0.062	0.028	0.060	0.100	0.089
4:00 p.m.	0.011	0.092	0.029	0.040	0.093	0.082
5:00 p.m.	0.009	0.114	0.035	0.039	0.091	0.088
6:00 p.m.	0.008	0.057	0.042	0.032	0.065	0.071
7:00 p.m.	0.006	0.026	0.036	0.033	0.053	0.058
8:00 p.m.	0.004	0.017	0.016	0.036	0.037	0.043
9:00 p.m.	0.003	0.018	0.009	0.031	0.029	0.034
10:00 p.m.	0.005	0.015	0.004	0.018	0.015	0.021
11:00 p.m.	0.003	0.015	0.002	0.013	0.012	0.015
Total	0.500	0.500	0.500	0.500	1.000	1.000

Source: NPTS, 1990.

CREATION OF AN ORIGIN-DESTINATION TRIP TABLE

Before a traffic assignment can be performed, the trip tables must represent actual trips between TAZs (though assignment of trips in a production-attraction format can be useful in identifying atypical directionalities). Productions indicate the location of the home end of the trip and attractions indicate the work, school, or shop end of the trip, but the trip movements in a production-attraction trip table are not in the correct direction. For this example, it is assumed that this is a daily trip table. The procedure for obtaining the origin-destination trip table is to add one-half of the table to one-half of the transposed trip table. The equation for HBW trips is

TABLE 43 Conversion factors for critical periods of transit patronage

	Annual Average Weekday Volumes	Combined Peak Period (4-Hour) Volumes	Peak-Hour Volumes	Peak-Hour Peak-Direction
Annual Average Weekday Volumes	—	0.41	0.14	0.12
Combined Peak-Period (4-Hour) Volumes	2.40	—	0.33	0.28
Peak-Hour Volumes	7.37	3.07	—	0.88
Peak-Hour Peak-Direction	8.35	3.47	1.13	—

TABLE 44 Conversion factors for critical periods of internal person travel

	Total Daily Travel	Daily Work Travel	Total A.M. Peak Hour	Total P.M. Peak Hour	Combined Peak Period (8-Hour)
Urbanized Area Population 50,000 to 199,000					
Total Daily Travel	—	0.24	0.08	0.09	0.57
Daily Work Travel	4.08	—	0.33	0.37	2.35
Total A.M. Peak Hour	12.53	3.07	—	1.14	7.20
Total P.M. Peak Hour	11.03	2.70	0.88	—	6.34
Combined Peak Period (8-Hour)	1.74	0.43	0.14	0.16	—
Urbanized Area Population 200,000 to 499,999					
Total Daily Travel	—	0.26	0.08	0.10	0.58
Daily Work Travel	3.84	—	0.31	0.37	2.23
Total A.M. Peak Hour	12.49	3.25	—	1.20	7.23
Total P.M. Peak Hour	10.43	2.71	0.84	—	6.04
Combined Peak Period (8-Hour)	1.73	0.45	0.14	0.17	—
Urbanized Area Population 500,000 to 999,999					
Total Daily Travel	—	0.27	0.09	0.09	0.57
Daily Work Travel	3.65	—	0.31	0.33	2.07
Total A.M. Peak Hour	11.62	3.19	—	1.06	6.60
Total P.M. Peak Hour	10.94	3.00	0.94	—	6.21
Combined Peak Period (8-Hour)	1.76	0.48	0.15	0.16	—
Urbanized Area Population 1,000,000+					
Total Daily Travel	—	0.28	0.08	0.09	0.56
Daily Work Travel	3.60	—	0.27	0.34	2.02
Total A.M. Peak Hour	13.18	3.66	—	1.23	7.38
Total P.M. Peak Hour	10.73	2.98	0.81	—	6.01
Combined Peak Period (8-Hour)	1.79	0.50	0.14	0.17	—

TABLE 45 Conversion factors for critical periods of internal auto driver travel

	Total Daily Travel	Daily Work Travel	Total A.M. Peak Hour	Total P.M. Peak Hour	Combined Peak Period (8-Hour)
Urbanized Area Population 50,000 to 199,000					
Total Daily Travel	—	0.32	0.08	0.08	0.57
Daily Work Travel	3.12	—	0.23	0.26	1.78
Total A.M. Peak Hour	13.32	4.27	—	1.10	7.61
Total P.M. Peak Hour	12.10	3.88	0.91	—	6.91
Combined Peak Period (8-Hour)	1.75	0.56	0.13	0.14	—
Urbanized Area Population 200,000 to 499,999					
Total Daily Travel	—	0.33	0.08	0.10	0.57
Daily Work Travel	3.05	—	0.25	0.31	1.75
Total A.M. Peak Hour	12.28	4.03	—	1.23	7.04
Total P.M. Peak Hour	9.94	3.26	0.81	—	5.70
Combined Peak Period (8-Hour)	1.74	0.57	0.14	0.18	—
Urbanized Area Population 500,000 to 999,999					
Total Daily Travel	—	0.35	0.08	0.10	0.55
Daily Work Travel	2.85	—	0.23	0.27	1.58
Total A.M. Peak Hour	12.35	4.33	—	1.18	6.85
Total P.M. Peak Hour	10.44	3.66	0.85	—	5.79
Combined Peak Period (8-Hour)	1.80	0.63	0.15	0.17	—
Urbanized Area Population 1,000,000+					
Total Daily Travel	—	0.34	0.07	0.10	0.55
Daily Work Travel	2.90	—	0.21	0.28	1.60
Total A.M. Peak Hour	13.82	4.77	—	1.33	7.64
Total P.M. Peak Hour	10.38	3.58	0.75	—	5.73
Combined Peak Period (8-Hour)	1.81	0.62	0.13	0.17	—

$$HBW_{od} = 0.5 \times HBW_{pa} + 0.5 \times HBW'_{pa} \quad (8\text{-}1)$$

where

HBW_{od} = HBW trip table in origin-destination format,
HBW_{pa} = HBW trip table in production-attraction format, and
HBW'_{pa} = transposed HBW trip table, production-attraction format.

Table 46 shows the production-attraction trip table before application of the equation.

Table 47 is the resulting origin-destination trip table.

TABLE 46 Example production-attraction table

Production Zone	Attraction Zone 1	2	3	Total
1	50	30	20	100
2	100	70	30	200
3	250	200	50	500
Total	400	300	100	800

TABLE 47 Example origin-destination table

Origin Zone	Destination Zone 1	2	3	Total
1	50	65	135	250
2	65	70	115	250
3	135	115	50	300
Total	250	250	300	800

This example is for the conversion of a 24-hour trip table. To prepare the trip table for a time of day (peak hour or peak period), assignment factors presented previously can be applied using the same basic equation as shown above. The major difference is the different factors used for the production-to-attraction direction versus the attraction-to-production direction (the transpose of the trip table).

The conversion equation needs to be applied only to the HBW and HBO trip tables. The NHB production-attraction trip table is by definition the same as the origin-destination table and therefore the daily table does not have to be converted to origin-destination format. However, if a peak-period NHB is to be produced, then the time-of-day factors must be applied.

The diurnal factors in Table 42 can be applied to convert the trip tables by purpose in production-attraction format to an origin-destination trip table for a selected time period. Note that the non-home-based trip table is already in origin-destination format as the trips have no home end.

The AM peak-hour trip table from 7:00 AM to 8:00 AM can be created as follows:

$$\begin{aligned} AMPK(O\text{-}D)_{ij} &= HBW\text{-}FAC\ (From\ Home) \times HBW\text{-}TRP_{ij} \\ &+ HBW\text{-}FAC\ (To\ Home) \times HBW\text{-}TRP_{ji} \\ &+ HBO\text{-}FAC\ (From\ Home) \times HBO\text{-}TRP_{ij} \\ &+ HBO\text{-}FAC\ (To\ Home) \times HBO\text{-}TRP_{ji} \\ &+ NHB\text{-}FAC \times NHB\text{-}TRP_{ij} \end{aligned}$$

where

$AMPK\ (O\text{-}D)_{ij}$ = AM peak-hour trips from origin i to destination j,

$HBW\text{-}FAC$ = time-of-day/direction split factor for the selected time period in the direction from home to work,

$HBW\text{-}TRP_{ij}$ = home-based work trips in production-attraction format from production i to attraction j, and

$HBW\text{-}TRP_{ji}$ = Transpose matrix of $HBW\text{-}TRP_{ij}$.

If the daily HBW trip table looks like the following:

	$j = 1$	$j = 2$	$j = 3$	Total
$i = 1$	10	40	20	70
$i = 2$	15	25	35	75
$i = 3$	30	50	5	85
Total	55	115	60	230

and the daily HBO trip table looks like the following:

	$j = 1$	$j = 2$	$j = 3$	Total
$i = 1$	80	70	50	200
$i = 2$	75	85	55	215
$i = 3$	60	45	35	140
Total	215	200	140	555

and the daily NHB trip table looks like the following:

	j = 1	j = 2	j = 3	Total
i = 1	20	10	35	65
i = 2	15	25	45	85
i = 3	5	30	15	50
Total	40	65	95	200

then the O-D trip table is created as follows:

AMPK (O-D) =

	j=1	j=2	j=3
i=1	(0.136 × 10 + 0.006 × 10) + (0.050 × 80 + 0.004 × 80) + (0.015 × 20)	(0.136 × 40 + 0.006 × 15) + (0.050 × 70 + 0.004 × 75) + (0.015 × 10)	(0.136 × 20 + 0.006 × 30) + (0.050 × 50 + 0.004 × 60) + (0.015 × 35)
i=2	(0.136 × 15 + 0.006 × 40) + (0.050 × 75 + 0.004 × 70) + (0.015 × 15)	(0.136 × 25 + 0.006 × 25) + (0.050 × 85 + 0.004 × 85) + (0.015 × 25)	(0.136 × 35 + 0.006 × 50) + (0.050 × 55 + 0.004 × 45) + (0.015 × 45)
i=3	(0.136 × 30 + 0.006 × 20) + (0.050 × 60 + 0.004 × 50) + (0.015 × 5)	(0.136 × 50 + 0.006 × 35) + (0.050 × 45 + 0.004 × 55) + (0.015 × 30)	(0.136 × 5 + 0.006 × 5) + (0.050 × 35 + 0.004 × 35) + (0.015 × 15)

	$j = 1$	$j = 2$	$j = 3$	Total
$i = 1$	6.04	9.48	6.165	21.69
$i = 2$	6.535	8.515	8.665	23.72
$i = 3$	7.475	9.93	2.825	20.23
Total	20.05	27.93	17.66	65.64

With an origin-destination table, vehicle trips made during the AM peak hour can be assigned to the highway network.

The table shown above lists fractional trips for all of the interchanges. Although fractional trips do not exist in reality, many of the procedures used in the travel model process produce noninteger values. Rounding of the trips tables before assignment could result in a loss of accuracy. A better approach is to carry the fractional trips through assignment, but round the assigned volumes on individual links.

CASE STUDY

The vehicle trip tables built in Chapter 7 were still in production-attraction (P-A) format. Therefore, the trip interchanges did not reflect the true direction of the trips from one zone to another. Before the desired O-D matrix was for the whole day, the split from home to activity was assumed to equal out over an entire day for HBW and HBO trips. The conversion from production-attraction format to origin-destination format used the following equation:

$$\textit{Daily Vehicle Trips (O-D)} = 0.5 \times HBW_{PA} + 0.5 \times HBW_{AP} + 0.5 \times HBO_{PA} + 0.5 \times HBO_{AP} + NHB + \textit{Through Trips}$$

where HBW_{AP} is the transpose of HBW_{PA}. The non-home-based and through trips are not factored because they are already balanced in origin-destination format.

The time-of-day characteristics presented in this chapter provide the ability to factor a daily trip table to create peak-period and off-peak period trip tables. Assigning traffic by time-of-day considers the relative levels of congestion and the alternate optimal travel paths between zone pairs that vary by time period. By adding traffic volumes from each of the time periods together, an estimate of the daily volume on a link is produced.

The results of trip distribution for Asheville have indicated that the difference between free-flow and congested conditions is minimal. As a result, assigning the trips by time period would not necessarily produce a better assignment. For the purposes of this case study, the daily trip table was converted to a peak-hour trip table by factoring the entire trip table by a 10 percent factor. The trip table assigned to the network was calculated by applying the 10 percent factor to all trips such that

$$\textit{Hourly Vehicle Trips}\ (O\text{-}D) = 0.10 \times \textit{Daily Vehicle Trips}\ (O\text{-}D)$$

CHAPTER 9

TRAFFIC ASSIGNMENT PROCEDURES

INTRODUCTION

Assignment is the fourth and last major step of the traditional four-step process. This includes both highway and transit assignment of vehicle and person trips, respectively. The assignment of trips to the network is the final output of the modeling process and becomes the basis for validating the model set's ability to replicate observed travel in the base year as well as to evaluate transportation improvements in future years. Depending on the level of analysis being done, the assignment can be to a regional highway and transit system for systemwide planning or to a detailed network for a subarea or corridor study.

The level of precision of the assignment procedure is a function of the detail of the coding on the networks and the size of the associated zone system. Traditionally, highway and transit assignment procedures were used primarily for systems analysis of large-scale transportation improvements. In recent years, the necessity for peak-hour or peak-period forecasts of vehicle demand on the highway system has required refinement of the traffic assignment procedures and parameters. Associated with the better assignment algorithms and parameters, the level of detail in the highway network increased dramatically (both in the amount of highway system actually coded into the network and more specific definition of link attributes such as link capacity and intersection delay).

Historically, only lane capacities by facility type were coded on the network and a single volume-delay function, the Bureau of Public Roads (BPR) curve, was used to estimate link travel times resulting from the assigned volumes. This chapter will present recommended modifications to the coefficients for the basic structure of the BPR curve that are consistent with the 1985 *Highway Capacity Manual*. As with other techniques in this report, it is assumed that the modeler will use one of the popular travel-demand forecasting software packages that can implement highway assignment from a coded network. Also consistent with the needs of small- to medium-sized urban areas, the focus will be on the highway assignment procedures. Most of the available software packages have transit assignment procedures. However, the transit procedures are not usually capacity constrained, and therefore the key to transit assignment is the assignment of transit trips to the proper path and modes of access.

In addition to the more detailed coding of the link and zone system, standard procedures have come to include assignment by time of day. The outmoded procedure for obtaining a 24-hour assignment was either to factor the daily trip table by 10 percent to obtain a peak-hour trip table or to multiply the hourly capacity by 10 to get daily capacities. These were then used as input to the capacity-constrained assignment algorithm. For example, the UTPS software package included a parameter called "CONFAC" that was defined as the percentage of the daily trip table that represented peak hour. This factoring procedure was used to produce a 24-hour capacity-constrained assignment. In fact, there is no such thing as daily capacity, but this was a close approximation of daily assignments that reflected congestion on the highway networks. The more current and accepted procedure for obtaining daily highway volumes is to sum the results of three separate assignments: AM peak period, PM peak period, and off-peak.

The capacity-constrained assignment procedures were all designed to produce assigned traffic that approximated the equilibrium of congested travel paths in the network. This was done through some combination of incremental and iterative assignment of the vehicle trip tables to the network. Now most of the available software packages include the equilibrium assignment algorithm in which iterations of assignments are made until the available travel paths all have the same travel times. The state of equilibrium is now computed mathematically rather than being treated as a goal by simple capacity constraint. The same volume-delay function can be used in equilibrium assignment as was used in the previous capacity-constraint procedures. Equilibrium assignment is the recommended procedure to be used in highway assignment.

The input for highway and transit assignments include the coded networks and the trip tables produced by the mode-choice model. If the mode-choice model produces person trips instead of vehicle trips, auto occupancy rates can be used to convert the person trips to vehicle trips (Chapter 7). Time-of-day factors can be used to convert the daily trip tables to peak period, peak direction (Chapter 8).

This chapter contains the following sections:

- Parameters for traffic assignment models,
- A post-assignment traffic-smoothing technique, and
- A corridor traffic diversion/traffic shift technique.

The last two techniques are extracted directly from *NCHRP Report 187* and can be applied using any of the available spreadsheet programs. The smoothing technique is a post-assignment procedure that can be used to obtain more precise link-specific volumes from a regional travel-demand forecast. The corridor traffic diversion technique can be used to evaluate quickly, on a sketch level, the impact of major capacity changes to a facility within a defined corridor on both the facility itself and on competing roadways within the corridor.

BASIS FOR DEVELOPMENT

The source for the parameters for the volume-delay relationships used in the traffic assignment algorithms is Alan Horowitz's report for the FHWA, *Delay-Volume Relations for Travel Forecasting,* based on the 1985 *Highway Capacity Manual.*[1] The parameters were derived using the basic BPR formulation of volume-delay. The parameters were fit to the speed/volume relationships contained in the Highway Capacity Software, Version 1.5, which closely approximate those in the HCM. The coefficient, α, of the BPR function was determined by forcing the curve to fit the speed/volume data at zero volumes (free-flow speed) and at capacity (level of service [LOS] E). The second coefficient, β, was found by nonlinear regression.

The traffic-smoothing and corridor traffic diversion/traffic shift techniques are the same as contained in the original *NCHRP Report 187.* Both of these techniques continue to be useful post-assignment analysis and sketch-planning tools. No changes to either technique were required.

TRAFFIC ASSIGNMENT MODEL PARAMETERS

The traffic assignment process is driven by the relationship of assigned volume and the resulting delay caused by congestion. As traffic volumes increase, travel speeds decrease because of increased congestion. The following BPR formulation has been used to estimate link travel times as a function of the volume-to-capacity ratio

$$T_c = T_f \times \left(1 + \alpha \times \left[\frac{v}{c}\right]^{\beta}\right) \qquad (9\text{-}1)$$

where

T_c = congested link travel time,
T_f = link free-flow travel time,
v = assigned link traffic volume (vehicles),
c = link capacity, and
α,β = volume/delay coefficients.

[1]Alan J. Horowitz, *Delay-Volume Relations for Travel Forecasting,* based on the 1985 *Highway Capacity Manual,* prepared for the Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. (1991).

The basic BPR formula used the values of 0.15 and 4.0 for α and β, respectively. This formula continues to be used in many urban areas. In Horowitz's work for the FHWA, coefficients were calibrated for the BPR formulation that better replicated delay as computed using the 1985 *Highway Capacity Manual* procedures. In that work the BPR coefficients presented in Table 48 were developed.

These functions are depicted in Figure 21. The speeds shown in the above table are design speeds of the facility, not the free-flow speeds. Capacities used in the *v/c* ratio are ultimate capacity, not a design capacity as used in the standard BPR curve. The curves based on the HCM exhibit a speed of about 35 mph at a *v/c* ratio of 1.0. This is consistent with standard capacity rules that the denser traffic flows occur at this speed. The ultimate capacity used for these curves was 1,800 vehicles per hour, per lane for a 1-mile section. This value is the ultimate capacity for typical prevailing conditions, not those under ideal conditions, which would have a capacity of 2,000 vehicles per hour, per lane.

For each curve the BPR standard curve with coefficients of $\alpha = 0.15$ and $\beta = 4.0$ is plotted to illustrate the change that the HCM curves represent. The BPR curve has a much higher speed at a *v/c* equal to 1.0 than do the HCM curves. It can also be observed that the multi-lane curves have a steeper decline with the $v/c < 1.0$ than do the freeway sections for the same design speed. Another characteristic of both the BPR and HCM curves is that they extend beyond the point where the *v/c* ratio is equal to 1.0, or where the flow has reached capacity. In capacity analysis, this portion of the curve is considered to be unstable and curves in the 1985 *Highway Capacity Manual* end at this point. For travel-demand modeling, however, the curve must extend beyond 1.0 to account for the theoretical assignment of the traffic.

Application of Volume-Delay Curves in Highway Assignment

The many highway assignment software packages all vary in how the volume-delay function is determined. Many simply default to the standard BPR formulation and require special input to vary the curve. They may or may not allow for multiple curves to be used for different facility types. Some require the curves to be input as data points in the form of a look-up table. The user will have to refer to the appropriate documentation of how many curves can be used in the software and how these are input.

Three possible levels of volume-delay formulations could be applied to highway assignment algorithms. These are

- A single formula used for all facility types,
- Multiple formulas that vary by facility type, and
- Multiple formulas that vary by facility type combined with estimation of delay at controlled intersections.

The first level is the most typical and the second is becoming more common. The third level is based on the recognition

TABLE 48 BPR coefficients

Coefficient	Freeways			Multi-lane		
	70 mph	60 mph	50 mph	70 mph	60 mph	50 mph
α	0.88	0.83	0.56	1.00	0.83	0.71
β	9.8	5.5	3.6	5.4	2.7	2.1

that the major source of delay on urban streets is at the controlled intersection. This control includes both traffic signals and stop signs.

The volume-delay relationship for interrupted flow (interrupted by a traffic control device) comprises

- The delay on the link using the above formulas, and
- The delay at the intersection caused by the probability of being stopped and the time stopped at the control device.

The 1985 *Highway Capacity Manual* includes procedures for estimating delay for each approach to the intersection. As with the uninterrupted highways described earlier, the delay function is well behaved up to a v/c ratio of 1.0, and then it becomes unstable. In Horowitz's report, coefficients were developed for the BPR formulation that fit a curve to the delay at a signalized intersection. Inputs to the model (for each intersection) are the cycle length, green time, saturation flow rates, and arrival type. Arrival type is a general categorization of the quality of progression on the approach and includes dense platoons arriving at the beginning or middle of the red/green phase, and totally random arrivals. For most assignments of long-range future trip tables, standard green times can be developed as a function of the facility types of the intersecting links. A uniform cycle length of 90 could be used, and it could be assumed that the arrival type is random. Even under these average circumstances, if the network is composed of freeways, expressways, major and minor arterials, and collectors (five facility types), there would have to be 25 different volume-delay functions for each combination of intersecting links. Only a few of the currently available travel-demand software packages can process this many different functions.

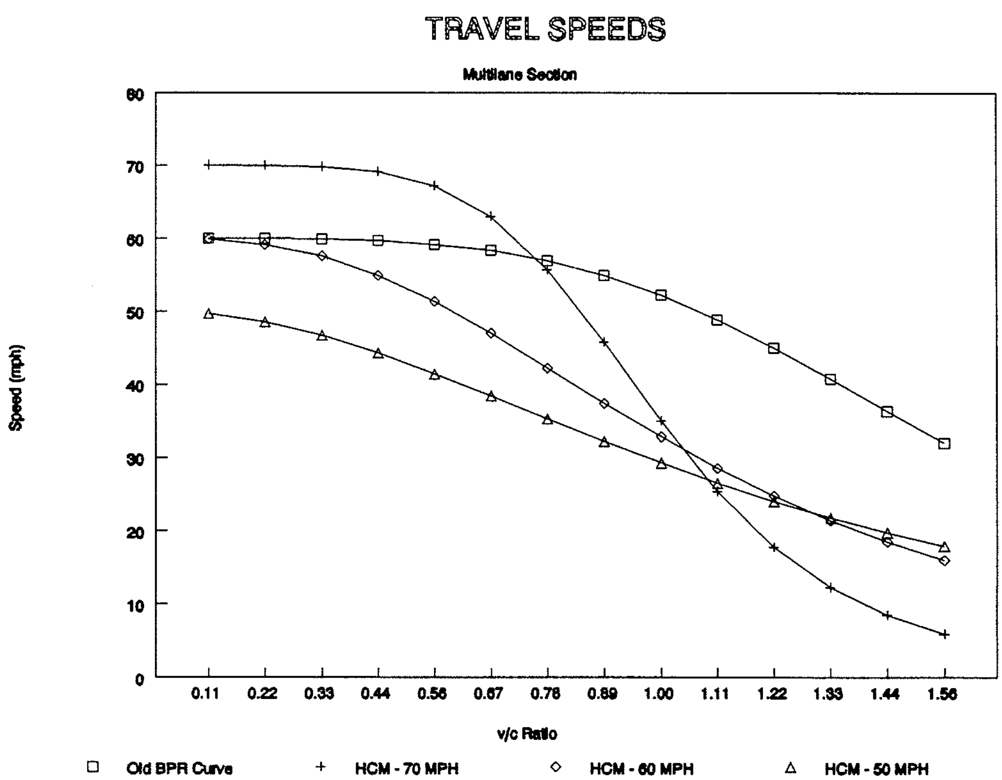


Figure 21. Multi-lane volume delay.

Recognizing the complexity of incorporating intersection delay into the volume-delay function, it is recommended that this level of detail be considered only if the local urban area has both the software and the experience to implement this function in the travel-demand software. Software packages that incorporate intersection delay into the assignment algorithm contain specific applications of those procedures that should be followed rather than nationally developed default functions. Inclusion of intersection delay in the assignment models is emerging as the most significant improvement in the algorithm.

A small urban area that is using the default parameters discussed and wishes only to use a single volume-delay function, should use the following coefficients:

$\alpha = 0.84$

$\beta = 5.5$

An urban area that wishes to use a unique function for each facility type can use a combination of the coefficients for freeways and multi-lane highways. Judgments will have to be made relating major/minor arterials and collectors to the multi-lane highway coefficients. The design speed can be used as a surrogate for facility type. Most freeways or interstate highways are constructed for a 70-mph design speed, and that should be the value used for freeways unless a freeway is older and was built to lower design standards. Many urban major arterials are multi-lane, and one of the multi-lane sets of coefficients can be chosen. The selection of the volume-delay functions is not absolute, and the final set of functions chosen will be those that best produce highway assignments that reflect observed traffic volumes. For example, if the major arterial system has consistently high volumes, then the next lower set of coefficients may be used. This will "slow" down the congested speeds and shift traffic to other facility types.

Node Characteristics

Some modeling software accommodates the input of node characteristics. Specifically, the type of intersection control device and cycle characteristics may be input.

Validation of Highway Assignment and Network

Although this manual is not intended as a how-to report for calibrating and validating the highway networks and the associated assignment, some basic steps in the process are helpful in applying the volume-delay functions. The validation of the highway assignment is the final validation of the complete travel-demand model set. The check of assigned volumes with observed traffic counts is done at the following levels:

- Screenlines (checks trip distribution as well as assignment),
- Cordon lines (CBD, for example, checks both trip generation and trip distribution),
- Cutlines for major corridors (checks assignment functions and link attributes),
- Link-specific volumes, and
- Regional statistics (such as root mean square of error [RMS] that produces statistics on assigned versus observed traffic by facility type and volume groups).

Once the cordon lines and screenlines are validated and the trip distribution model is judged to be producing acceptable results, the assignment volume-delay functions can be modified systematically to produce the desired assignments. It has been the practice in some urban areas to adjust individual link attributes to get an assignment that matches the link counts. In many cases these adjustments have produced unrealistic values of link speeds and capacities (free-flow speeds of 5 mph, for example) that worked only to get the desired assignment results. The adjustment of link attributes should be limited to minor systematic adjustments to speeds and capacities for groups of links that have the same facility and area type.

DISTRIBUTION OF ASSIGNED VOLUMES AMONG AVAILABLE FACILITIES

In any assignment of travel to a highway network, whether by manual methods or through the use of a computerized technique, the link-assigned volumes may require some redistribution between available facilities to more closely reflect actual operating conditions. Historically, transportation planning procedures have used screenlines and auxiliary cutlines to validate and analyze assignment results, and the redistribution technique described follows the same approach.

The technique described to reallocate travel among competing facilities after traffic assignment is based on screenline theory and was developed by R. H. Pratt Associates.[2] This technique requires analysis of multiple overlapping cutlines of major screenlines within an analysis area. It may appear to the user that the procedure is difficult and time-consuming, but it will be found that an analysis area containing 10 vertical and 10 horizontal major screenlines can be processed and summarized in 2 person-days. The analysis for most areas will not be as extensive.

The underlying assumption of the redistribution procedure is that forecast-year volumes on parallel facilities should tend to be distributed proportionally to the volumes as observed on the facilities in the base year. Further stated, if no capacity changes (e.g., widenings and new facilities)

[2]R.H. Pratt Assoc. *A Method for Distributing Traffic Volumes Among Competing Facilities,* Kensington, Maryland (1976).

occur between the year observations are made and the forecast year, the forecast-year volumes on the links intercepted by the screenline are inclined to be proportional to the base-year system. All capacity changes to the forecast year system are interpreted as new facilities, including widening to existing facilities.

Figure 22 shows the beginning point for applying the volume-redistribution technique. It is assumed the user will employ these techniques after the appropriate vehicle trips have been assigned to the highway network via the all-or-nothing assignment procedure. The major screenlines to be used in balancing the trips between competing and available facilities are shown, along with the facilities under study. The following points should be kept under consideration while constructing the analysis lines. Screenlines need be defined only across facilities within the *directional* analysis area. That is, if only north/south highways are under investigation, only screenlines A-A, B-B, C-C, and D-D would be required. Major screenlines should be constructed midway between major intersections or every 2 miles, whichever is less. Except in special cases, screenlines should cut a minimum of three facilities.

The manner in which each screenline is subdivided into cutlines is as follows. Starting at one end of the screenline, the first cutline should normally extend across at least three facilities (Figure 23). The second cutline should do the same, and overlap the first cutline such that the overlap extends across approximately half of each individual cutline. Preferably, more than one facility should be intercepted within the overlap. The third cutline should be similarly laid out and should start where the first cutline terminates. Additional cutlines as needed should be similarly established. Unless irregularities in the street system dictate otherwise, the cutlines in parallel screenlines should be opposite each other so as to intercept the same sets of highway facilities.

As an example, Figure 23 shows the subdivision of Screenline A-A into three overlapping cutlines (i.e., p-p, q-q, and r-r) to be used in the redistribution of forecast-year assignment volumes. Screenline A-A will be analyzed using the hypothetical traffic data given in Table 49. Note that the forecast-year assignment volumes are supposed to have been obtained from all-or-nothing assignment procedures. Note also that link 50-51 is a proposed facility for the forecast year and is expected to add capacity across screenline A-A.

The work sheet used for redistribution of assigned volumes is given in Table 40. Link description, plus traffic data for columns a, c, and e are filled in Table 40 using the data given in Table 49. Such information is recorded for each of the three cutlines of Screenline A-A shown on Figure 23. The cutlines are processed one at a time and the total

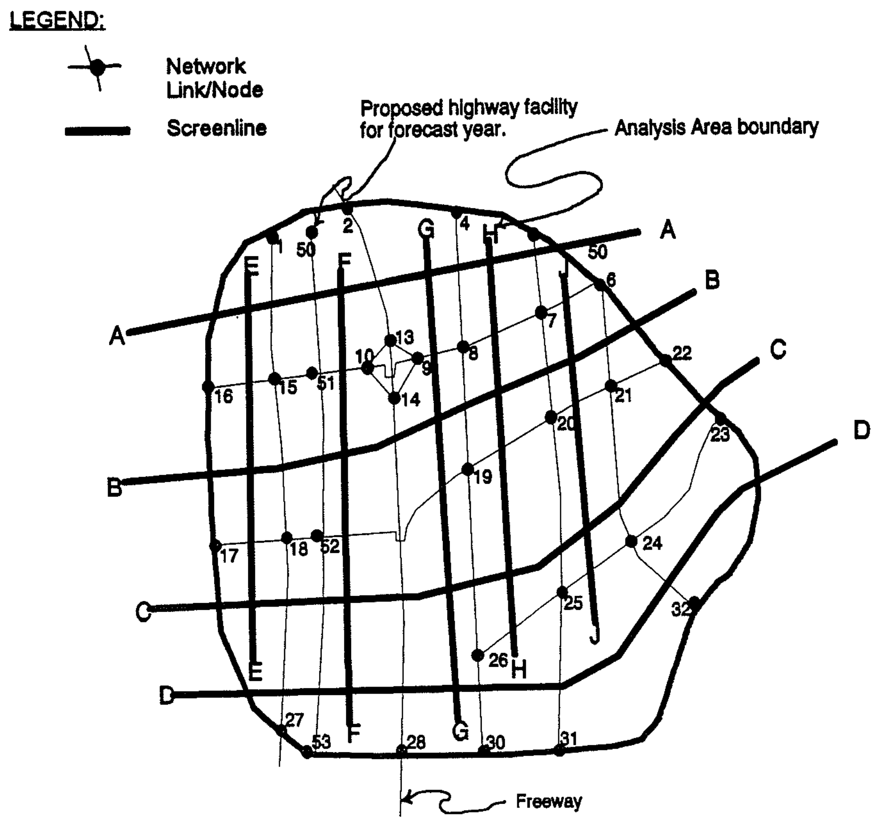


Figure 22. Definition of major screenlines.

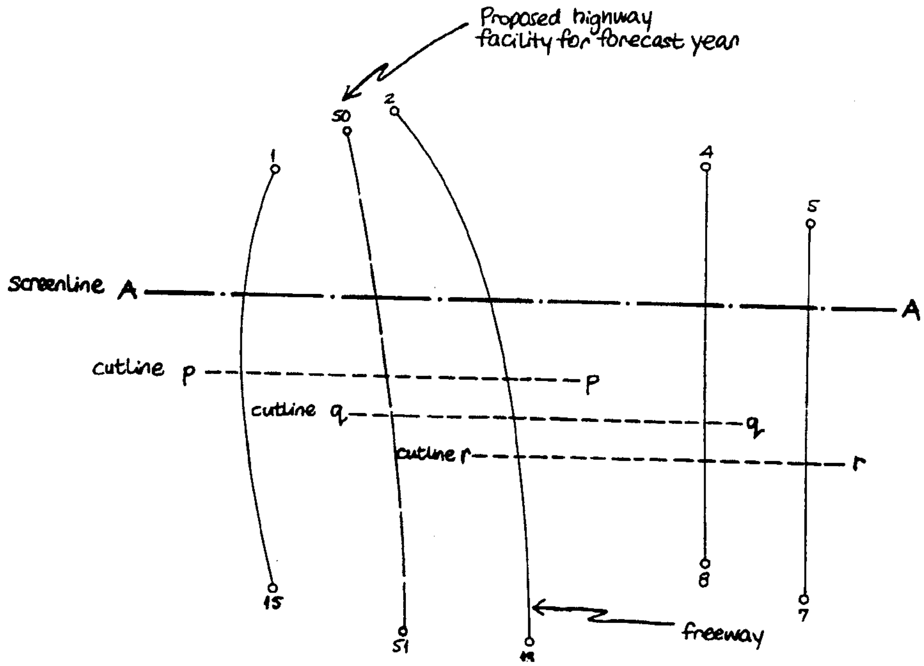


Figure 23. Cutlines of screenline A-A for redistribution analysis.

assignment-adjustment volumes (column h, Table 40) are input, when appropriate, into column e of the subsequent cutline analysis. The order in which the cutlines are processed is arbitrary, but such computations should proceed in an orderly fashion from one end of the screenline to the other (e.g., from left to right).

The calculations necessary for completing Table 50 are as follows:

1. Sum the base-year volumes; that is, traffic counts (column a), and determine the percent volume contribution (column b) for each link of cutline p-p. Note that because link 50-51 is a new facility, base-year traffic counts do not exist and therefore columns a and b are left blank.
2. Because link 50-51 contributes additional capacity in the forecast year, columns c and d are filled in a manner similar to Step 1.
3. Column e is now completed using the forecast-year assignment volumes in Table 49 (from the all-or-nothing assignment).
4. As a capacity change is expected to occur across cutline p-p, column f is completed for link 50-51. Thus, the capacity-assignment adjustment for link 50-51 is 23.1% × 12,200 = 2,818 (i.e., this volume of traffic can be expected for the new facility). The remaining

TABLE 49 Traffic data for highway links crossing screenline A-A

Link Descriptor				
A Node	B Node	Base Year Traffic Count	Capacity	Forecast Year Assignment Volume
1	15	1,850	2,200	—
50	51	—	3,000	4,000
2	13	5,000	7,800	8,200
4	8	2,500	2,750	2,500
5	7	2,650	3,500	4,800
Total		12,000	19,250	19,500

TABLE 50 Worksheet for balancing forecast-year assignment volumes

	Link Descriptor		(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
Cutline #	A Node	B Node	Base Year Volume	Percent Base Year Volume on Cutline	Capacity	% of Total Capacity on Cutline	Forecast Year Assignment Volume	Capacity Assignment Adjustment	Volume Assignment Adjustment (g)=(b)×(Σ(e)-Σ(e))	Total Assignment Adjustment (h)=(f)+(g)
p-p	1	15	1,850	27.0	2,200	16.9	0	—	2,533	2,533 [2]
	50	51	—	—	3,000	23.1	4,000	2,818	—	2,818
	2	13	5,000	73.0	7,800	60.0	8,200	—	6,849	6,849
Σ			6,850	100.0	13,000	100.0	12,200 -	2,818 =	9,382	12,200
q-q	50	51	—	—	3,000	22.1	2,818	2,689	—	2,689 [2]
	2	13	5,000	66.7	7,800	57.6	6,849	—	6,322	6,322
	4	8	2,500	33.3	2,750	20.3	2,500	—	3,156	3,156
Σ			7,500	100.0	13,550	100.0	12,167 -	2,689 =	9,478	12,167
r-r	2	13	5,000	49.3	no new facilities proposed across this cutline; thus calculations not necessary for these columns		6,322	see note in columns (c) and (d)	7,039	7,039 [2]
	4	8	2,500	24.6			3,156		3,512	3,512 [2]
	5	7	2,650	26.1			4,800		3,727	3,727 [2]
Σ			10,150	100.0			14,278		14,278	14,278

[1] All traffic data are two-directional and measured in vehicles per hour.
[2] Final, balanced volumes as a result of traffic redistribution.

forecast-year assignment volume in column f (i.e., 12,200 − 2,818 = 9,382) is distributed to the other links of cutline p-p.

5. Hence the *volume-assignment adjustments* (column g) for links 1-15 and 2-13 can be computed in the proportion given in column b. Hence, for the former link, this adjustment is 27.0% × 9,382 = 2,533 (i.e., this volume of traffic can be expected for link 1-15).
6. Finally, the *total-assignment adjustment* for each link crossing cutline p-p is computed by adding the volumes in columns f and g. Note that the totals for columns e and h are the same for cutline p-p; only the traffic within the cutline has been redistributed among the three links.

The six steps are repeated for cutlines q-q and r-r. For q-q, the volumes for links 50-51 and 2-13 in column e are the assignment adjustments from column h of the previous calculations for cutline p-p. A similar transformation is made for r-r (the volumes for links 2-13 and 4-8 in column e are adjustments from column h for cutline q-q). For r-r, however, no new facilities cross the cutline. Therefore, the computations in columns c, d, and f are not necessary. The adjustments in column g are now derived by proportioning the sum of traffic in column e using the percentages in column b. Thus, for link 4-8, the proportioned traffic equals 24.6% × 14,278 = 3,512. The asterisks in column h of Table 50 indicate the final balanced volumes resulting from the redistribution technique. To refine these volumes, Screenline A-A could be reprocessed through the six steps outlined previously. This second iteration might result in a small gain in accuracy of the balanced volumes; iterations beyond the second one are not recommended. Figure 24 shows the capacity, the base-year volumes, the forecast-year assignment volumes, and the balanced volumes for links crossing Screenline A-A. The user can observe the effect of the redistribution of volumes among the facilities.

The user is cautioned that this technique *does not* keep track of turning movement volumes and does, in fact, negate the turning movement volumes from the all-or-nothing assignment procedure. Reestablishing a table of turning movements is possible, but the redistribution procedure requires many iterations to reach convergence and is not practical as a manual tool. If the user is interested in analyzing turning movements, the trips from the original assignment application should be used.

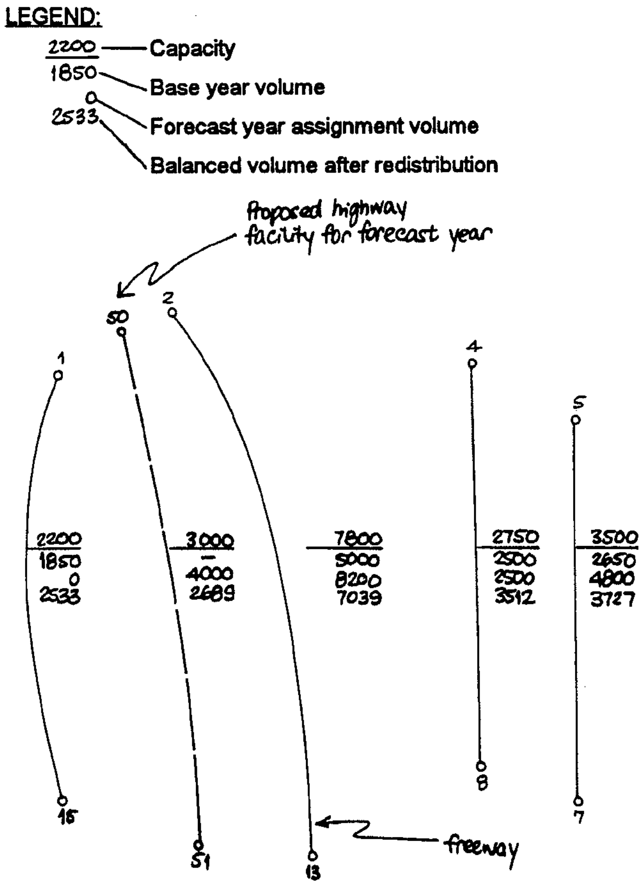


Figure 24. Comparison of capacity and base year, forecast year, and balanced volumes.

TRAFFIC SHIFT METHODOLOGY FOR CORRIDORS

For corridor analysis, often a sketch-planning technique is desirable to evaluate the effects of an improvement in one of the facilities in the corridor. Such a process, if it is to be applied quickly, should not consider origin-destination movements but rather a general shift of traffic between facilities. Such a process has been suggested by the multi-route probabilistic process developed by Dial.[3] The required equations for the usual two competing-route problem areas are

$$V_{mtr} = \frac{1}{1+e^{\theta}(t_m - t_i)} \times (V_T) \qquad (9\text{-}2)$$

$$V_i = \frac{e^{\theta}(t_m - t_i)}{1+e^{\theta}(t_m - t_i)} \times (V_T) \qquad (9\text{-}3)$$

$$\theta = \frac{\ln \frac{V_i}{V_{mtr}}}{t_m - t_i} \qquad (9\text{-}4)$$

[3]Dial, R.B. *A Probabilistic Multipath Traffic Assignment Model which Obviates Enumeration,* prepared for the US DOT, Washington, DC (1970).

where

V_{mtr} = volume on minimum time route,
θ = diversion parameter,
t_m = time on alternate route [Note: $(t_m - t_i)$ is always negative],
V_T = total volume on two facilities ($V_T = V_{mtr} + V_i$), and
V_i = volume on alternate route.

The process assumes that current traffic volumes and operating characteristics for a base condition are known. These data may be obtained from traffic volume counts and speed/delay travel-time studies or from the results of the planning process. To describe application of the process, the following simplified example is offered. The example of two competing facilities is shown at the top of Figure 25.

To calculate the diversion parameter (based on existing conditions and volumes), the function given in Equation 9-4 would be used as follows:

$$\theta = \frac{\ln \frac{1{,}240}{7{,}500}}{7.1 - 12.0} = \frac{-1.8}{-4.9} = 0.367$$

This parameter describes the diversion of traffic between the two routes being considered. Assume an improvement is to be made in route A by adding another lane in each direction. A speed of 50 mph for the improved facility is estimated based on a capacity calculation using the original volume of 7,500 vehicles. The *v/c* ratio would be developed from

$$\frac{7{,}500\ vph}{5\ lanes \times 2{,}000\ vph\ capacity} = 0.75$$

The travel time for the 5-mile route A section would then be calculated as:

$$\frac{5\ mi}{50\ mi/hr} \times \frac{60\ min}{hr} = 6.0\ min$$

Based on this improvement, a new estimate of the average volumes can be calculated using Equations 9-2 and 9-3 as follows:

$$V_{mtr} = \frac{1}{1 + e^{0.367(6.0-12.0)}} \times (7{,}500 + 1{,}240) = 7{,}869\ vph$$

$$V_i = \frac{e^{0.367(6.0-12.0)}}{1 + e^{0.367(6.0-12.0)}} \times (8{,}740) = 871\ vph$$

The *v/c* ratio for route A would now be [7,869 ÷ (5 × 2,000)], or 0.79, resulting in a speed of about 48 mph as calculated from capacity curves. Route B would carry about 871 vehicles per hour. Another iteration of the process could be carried out to try to effect a closer relationship between volume and speed, but for sketch-planning purposes and

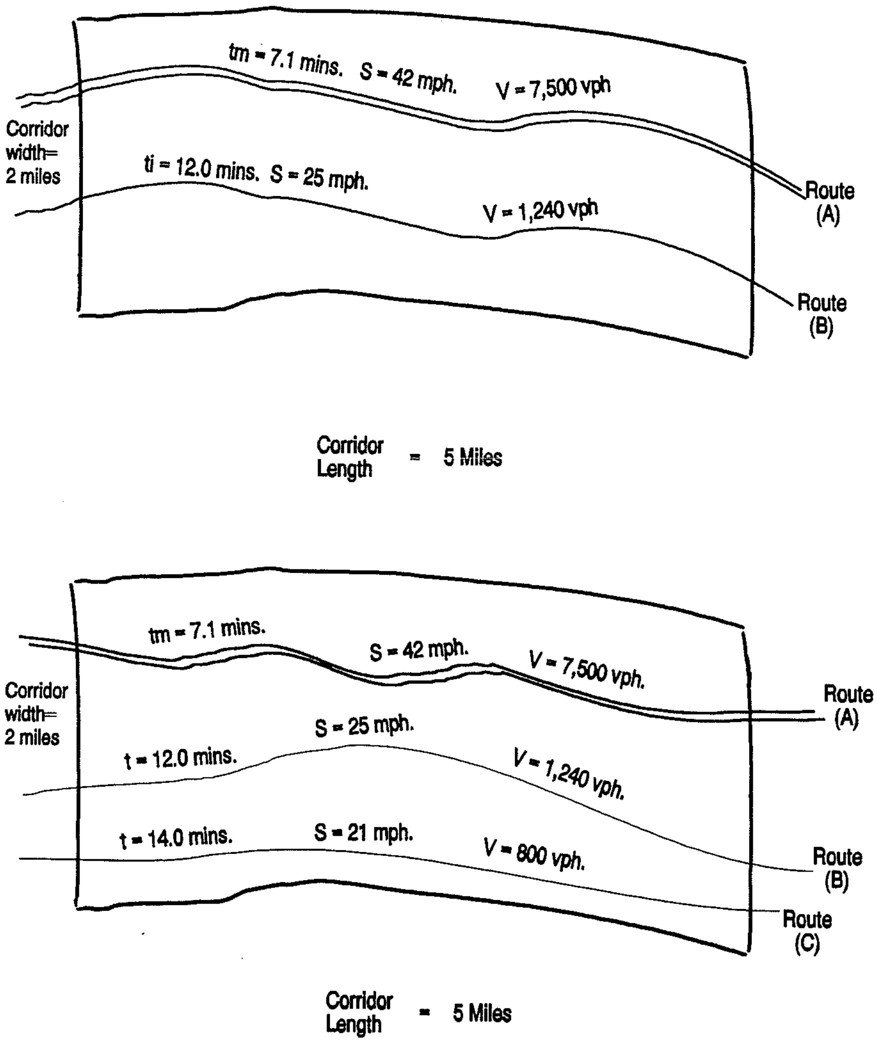


Figure 25. Example corridors for traffic shift analyses.

because of the inaccuracies of volume/capacity/speed relationships, especially for arterials, it is not expected to improve the results. Only if a large imbalance exists in resulting volumes and speeds should additional iterations be tried (i.e., greater than 5 mph difference between input and calculated speeds).

To demonstrate how the foregoing process handles variations in operating conditions, Table 51 is provided for the example case described previously.

Where three competing facilities exist in a corridor, the process must be applied twice, with the calculation of two θ values. Assume routes A, B, and C as shown in the lower half of Figure 25. As shown previously, the θ for route pair A and B would be calculated as shown previously and equals 0.367. Using Equation 9-4, the θ value for route pair B and C would be calculated as follows:

$$\theta = \frac{\ln \dfrac{800}{1{,}240}}{12 - 14} = \frac{-0.438}{-2.0} = 0.219$$

To calculate the effects of the improvement in route A to 50 mph, the volume on routes A and B would be calculated at 7,869 and 871, respectively, as shown previously. To calculate the effect relative to routes B and C, the following computations would be made:

$$V_{mtr} = \frac{1}{1 + e^{0.219(12-14)}} \times (871 + 800) = 1{,}016\ vph$$

$$V_i = \frac{e^{0.219(12-14)}}{1 + e^{0.219(12-14)}} \times (1{,}671) = 655\ vph$$

These calculations may be iterated a few times to bring the results to a more stable condition. For example, now considering the volumes of 7,869, 1,016, and 655, a new calculation between routes A and B would result in volumes of 8,000 and 885 for A and B, respectively. The three-route case for a corridor is unusual; generally, only two competing routes will be handled.

Capacity analysis should be considered as part of this traffic-shift analysis. After the process is applied, volume/

TABLE 51 Variations in traffic volumes with changes in speed

Base Conditions:	Five-Mile Section % Route A Volume 86% Route A Speed = 42 mph; Route B Speed = 25 mph Calculated θ= 0.367		
Speed		Difference in Travel Time = Route B-Route A	% Volume on Route B
Route A	Route B		
30	25	-2.0	67
35	25	-3.4	78
40	25	-4.5	84
45	25	-5.3	87
50	25	-6.0	90
55	25	-6.5	83
30	35	+1.4	37
35	35	0.0	50
40	35	-1.1	60
45	35	-1.9	67
50	35	-2.6	72
55	35	-3.1	76
30	45	+3.3	23
35	45	+1.9	33
40	45	+0.8	43
45	45	0.0	50
50	45	-0.7	56
55	45	-1.2	61

capacity/speed calculations should be performed to determine if the resulting speed is in balance with the speed used in the preceding described process. If not, the new speed should be used to redo the calculations.

Usually, a number of sections will exist along each facility in a corridor in which volumes and speeds may vary. The approximate speeds and section distances should be used to calculate section times and added to obtain the total time through the corridor. An average volume should be used based on the calculation

$$Average\ Volume = \frac{\Sigma\ (Volume\ in\ Section \times Section\ Length)}{\Sigma\ Section\ Lengths}$$

Traffic shifts also can be determined graphically by using a simple set of curves as shown on Figure 26. To use the graph, the user has to know at least two variables:

1. If the diversion parameter, θ, for routes within a corridor is to be determined, then the user must input the percent volume on the minimum time route; that is, V_{mtr}, and the travel time difference, Δt, between the faster and slower routes; that is, $t_m - t_i$.
2. If the percent volume on any route is to be determined, then the user must input the diversion parameter θ and the travel time difference Δt. Note that in all cases, the following relationships hold:

$$\%\ V_{mtr} + V_i = 100\% \quad and$$
$$\Delta t = t_m - t_i < 0\ (always\ negative)$$

Usually, the diversion parameter is first determined for a corridor, given travel volumes and travel times on the two routes. Then to study the effects of a travel time change on any one route, θ is held constant and the new volumes are determined.

To illustrate the use of the graph shown in Figure 26, consider the example illustrated in the upper portion of Figure 25. In the condition shown, the user knows the following variables:

$$V_{mtr} = \frac{V_{mtr}}{V_{mtr} + V_i} \times 100$$
$$= \frac{7{,}500}{7{,}500 + 1{,}240} \times 100 = 85.8\%$$

therefore

$$\%\ V_i = 100 - 85.8 = 14.2\%$$
$$\Delta t = t_m - t_i = 7.1 - 12 = -4.9 \text{ min}$$

By entering the curves in Figure 26 at V_{mtr} = 86 percent and Δt = −4.9 min, θ is interpolated at 0.37, which checks with that calculated mathematically in the example described earlier.

Now suppose, as before, route A is improved so that the travel time on this route is reduced to 6 min from the original 7.1 min. Thus,

$$\Delta t = 6 - 12 = -6 \text{ min}$$

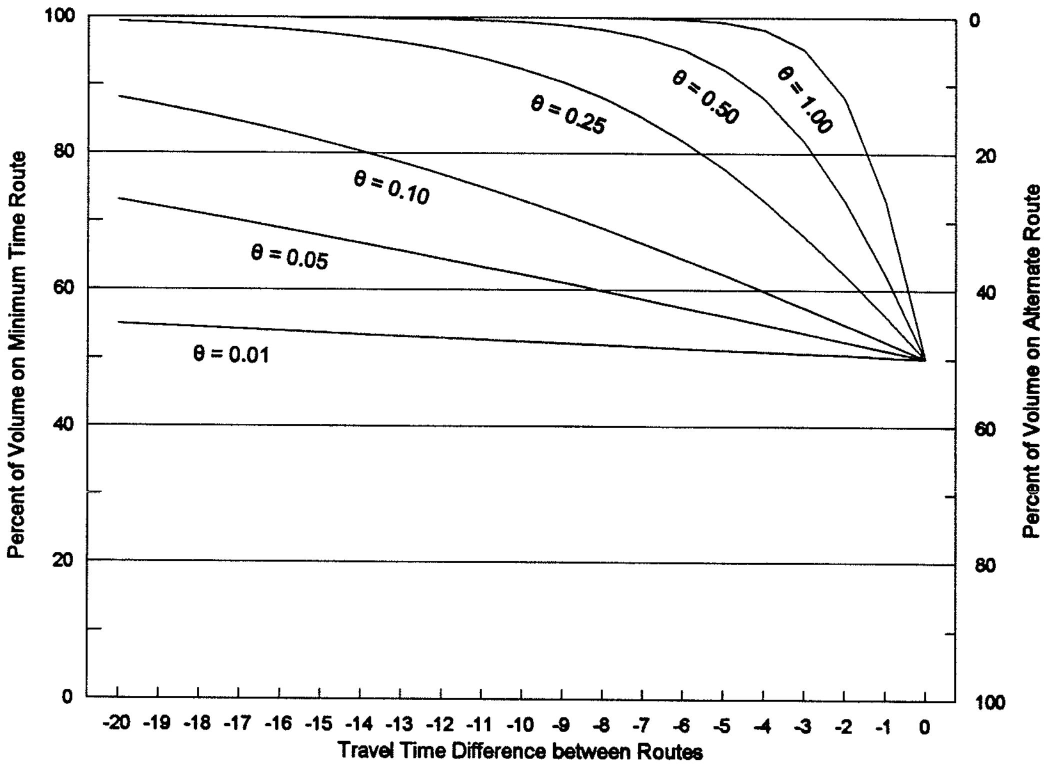


Figure 26. Graph for determining traffic shifts between facilities in a corridor.

Entering the graph in Figure 26 at $\Delta t = -6$ min and $\theta = 0.37$, the corresponding $\%V_{mtr}$ is read off at 90 percent and $\%V_i$ at 10 percent. Because the total volume entering the corridor is known to be 8,740 vph, then

$$V_{mtr} = \frac{90}{100} \times 8{,}740 = 7{,}866\ vph$$

$$V_i = \frac{10}{100} \times 8{,}740 = 874\ vph$$

These results check with the values of V_{mtr} and V_i obtained in the previous example.

Thus, the traffic diversion method is accurate enough for sketch-planning and quite simple to use, and it is recommended if time is not available to complete modeled alternatives analysis.

CASE STUDY

Delay on the roads caused by congestion is calculated using the Bureau of Public Roads curve shown in this chapter. Coefficients for the formula were obtained from Table 48. Freeway links used values of 0.83 for α and 5.5 for β that correspond to a design speed of 60 miles per hour. Arterial links used values of 0.71 for α and 2.1 for β that correspond to a design speed of 50 miles per hour on multi-lane roads. Congested travel time is calculated using the following formulas:

$$\textit{Freeway Travel Time} = \left(\left(\frac{length}{speed}\right) \times 60\right) \times \left(1 + 0.83 \times \left(\frac{volume}{capacity} \times lanes\right)^{5.5}\right)$$

$$\textit{Arterial Travel Time} = \left(\left(\frac{length}{speed}\right) \times 60\right) \times \left(1 + 0.71 \times \left(\frac{volume}{capacity} \times lanes\right)^{2.1}\right)$$

The equilibrium traffic assignment produced traffic volumes for each link in the network. Volumes were factored by a value of 10 to reflect total daily conditions. Traffic volumes have been summarized at a number of screenlines. A comparison of the estimated and observed daily traffic volumes provides an indication of the accuracy of the travel models. A summary of estimated and observed volumes can be found in Chapter 12.

CHAPTER 10
CAPACITY ANALYSIS

INTRODUCTION

This chapter addresses capacity analysis as used in the planning of transportation facilities. Capacity analysis is used at two stages in the planning process:

- As input to the link attributes required in the network-based travel-demand models and
- As a post-modeling analysis tool to evaluate the ability of the transportation system to serve the future traffic demand adequately or to determine how much additional demand the existing transportation system can accommodate before improvements are necessary.

As noted in Chapter 2, link capacity is usually input as the number of vehicles per hour (vph) per lane or as directional capacity per hour, depending on the requirements of the travel demand software. The preferred method for deriving link capacity is to use the procedures contained in the 1994 *Highway Capacity Manual* (HCM) and compute capacities specific to the physical limitations of each link. However, this is often not feasible, and the alternative method is to use link capacities that reflect average conditions for various link types. Tables 52 through 59 provide initial link capacities that can be used in the building of the highway network. These capacities are based on the ultimate, or LOS E, capacity.

The post-modeling analysis is typically done for both roadway segments and critical intersections within the urban area. The link-based or roadway-segment analysis is accomplished by comparing the assigned volume with the link's capacity. This is done by computing the link volume/capacity ratio (v/c) and posting the result on network plots.

The intersection analysis is based on the use of one of the two procedures outlined in the 1994 *Highway Capacity Manual*.

The more rigorous of the two procedures is the operations or design analysis of signalized intersections. This analysis requires detailed information about the geometrics of the intersection, the proposed signal plan, the volumes for each turning movement, the mix of vehicles in the traffic flow, and the arrival type of the traffic flow. This level of detail is not available for long-range transportation planning and, more important, is not appropriate for use in such planning. It is useful, however, to apply a generalized procedure for capacity analysis of intersections in the plan development process. The objective of such a procedure is to determine if an intersection would operate over, at, near, or under capacity under the future travel demand. The 1994 *Highway Capacity Manual* provides a procedure that is presented in this chapter. The user is directed to the manual for information on applying a more detailed analysis of signalized intersections.

This chapter contains two sets of capacity parameters and procedures. The first is the provision of initial values of link capacities that can be used by travel forecasting models. The second is the planning procedure for determining the capacity of a signalized intersection.

BASIS FOR DEVELOPMENT

The techniques and procedures in this chapter have been selected to address the types of problems a user of this report is likely to encounter. The initial capacities of facilities that are needed as input parameters in the building of a highway network and the procedure for capacity analysis of signalized intersections for use once the volume projections from the model are available are two such procedures.

The first part of the chapter concentrates on initial estimates of capacities for different facilities. These estimates are provided for use in the initial building of a travel forecasting model and are based on information contained in *Delay/Volume Relations for Travel Forecasting* which is based on the 1985 *Highway Capacity Manual*.[1] Estimates based on the 1994 HCM are provided in *NCHRP Report 387*, "Planning Techniques to Estimate Speeds and Service Volumes for Planning Applications."

The chapter ends by outlining procedures for signalized intersection capacity analysis based on the planning methodology in Chapter 9 of the 1994 *Highway Capacity Manual*.[2] These procedures are closely linked to the operational analysis of signalized intersections contained in the same chapter of the 1994 HCM.

The operating condition of a highway facility is generally measured using the concept of level of service. Level of service has been stratified into six classes defined as follows:

[1] Alan J. Horowitz, *Delay/Volume Relations for Travel Forecasting*, based on the 1985 *Highway Capacity Manual*, prepared for the Federal Highway Administration, U.S. Department of Transportation (1991).

[2] Transportation Research Board, *Highway Capacity Manual* Chapter 9 (Signalized Intersections) (1994).

Level of Service	Operating Conditions
A	Free flow, low volume, high operating speed, high maneuverability
B	Stable flow, moderate volume, speed somewhat restricted by traffic conditions, high maneuverability
C	Stable flow, high volume, speed and maneuverability determined by traffic conditions
D	Unstable flow, high volumes, tolerable but fluctuating operation speed and maneuverability
E	Unstable flow, high volumes approaching roadway capacity, limited speed (≈ 30 mph), intermittent vehicle queuing
F	Forced flow, volumes lower than capacity because of very low speeds, heavy queuing of vehicles, frequent stops

Historically, LOS C has been used as the goal for evaluation of the performance of the highway system. Recent limitations of financial and physical resources have pushed this goal lower, to LOS D in larger, congested urban areas. The user should be aware that many traditional travel demand models use a capacity value that is equated to a given LOS, usually C. In these cases, a *v/c* of 1.0 indicates that the link will operate at LOS C. The initial capacities provided in this chapter are for LOS E, or ultimate capacity.

There are two basic and independent indicators of level of service—the *v/c* ratio and the operating speed. Where applicable, the procedures in this chapter use only the *v/c* ratio to assess service levels. For a detailed discussion of the concepts discussed above, the user is directed to the 1994 *Highway Capacity Manual.*[3]

INITIAL SETTINGS FOR CAPACITIES FOR USE IN TRAVEL FORECASTING MODELS

Ideally, capacities should be set according to those obtained from the 1994 HCM or from the Highway Capacity Software (HCS) or similar programs. However, setting capacities separately on every link or on every intersection approach can be quite tedious, especially considering that many of the values may change during network calibration. One approach is to start with rough estimates of capacities and then refine these estimates during calibration.

Depending upon the forecasting software, the capacities can be entered in various ways. For example, Urban Transportation Planning System (UTPS) and similar packages require that capacities be computed as a function of area type, facility class, and number of lanes. A look-up table must be prepared giving the maximum lane volume as a function of area type and facility class. The software determines the capacity of the link by multiplying the looked-up maximum lane volume by the number of lanes. Other software packages allow capacities to be set for individual links, thereby providing the user with more flexibility during calibration.

The capacities provided in Tables 52 through 58 are recommended for starting values. These capacities have been determined in accordance with the guidelines provided in the 1985 *Highway Capacity Manual.* Where the capacities are given as total directional capacities, they can be divided by the number of through lanes to obtain maximum lane volumes. These values should not be varied by more than ±20 percent unless justified by abnormal deviation from ideal conditions.

Assumptions and Extensions for Initial Capacity

The initial capacities for uncontrolled road segments assume 14 percent trucks, 4 percent recreational vehicles, and 0 percent buses, as suggested for default by the 1994 HCM for two-lane roads. The forecast period is 1 hour. Otherwise, ideal conditions are assumed.

Priority of signalized intersections in Tables 55 through 57 relates to percent of available green time for the approach as follows: 33 percent = low priority; 50 percent = medium; and 67 percent = high. Turns in those tables relate to the percentage of non-through movements: 0 percent = low turns; 25 percent = high turns. Initial capacities for a medium number of turns may be interpolated from the values for low and high turns.

Consistency of priority must be maintained for all approaches at any given intersection. For example, it would be inappropriate to have more than two high-priority approaches at an intersection.

The ultimate capacity of an intersection will be greater if the intersection has exclusive right-turn lanes. Ultimate capacity for an exclusive right-turn lane can be added as follows for each through lane: 0 vph for low turns; 75 vph for medium turns; and 150 vph for high turns. Additional design

[3]Transportation Research Board, *Highway Capacity Manual, Special Report 209,* 3rd Ed. (1994).

TABLE 52 Initial capacities for multi-lane highways, each lane: ultimate capacity

			60, 70 mph	50 mph
Rural	Divided	Level Terrain	1,800	1,700
		Rolling Terrain	1,350	1,250
	Undivided	Level Terrain	1,700	1,600
		Rolling Terrain	1,250	1,200
Suburban	Divided	Level Terrain	1,600	1,500
		Rolling Terrain	1,150	1,100
	Undivided	Level Terrain	1,450	1,350
		Rolling Terrain	1,050	1,000

capacity for an exclusive right-turn lane should be provided as follows for each through lane: 0 vph for low turns; 50 for medium turns; and 100 for high turns. For example, the initial ultimate capacity for an approach with two through lanes, both exclusive left- and right-turn lanes, high priority, and high turns should be 2,300 (2,000 + [2 × 150]).

For signalized approaches with three or more lanes, it is necessary to extrapolate from the data for one and two lanes. For example, the initial ultimate capacity for a three-lane approach with high turns, medium priority, and an exclusive left-turn lane may be computed as follows:

- Two lanes, exclusive left, medium priority, high turns — 1,300
- One lane, exclusive left, medium priority, high turns — 825
- Additional capacity for each lane beyond the first — 475
- Total capacity of three-lane approach — 1,775

Two-way stops are seldom included in regionwide networks. Capacity varies greatly with the amount of conflicting traffic for signed approaches at a two-way stop. Ultimate capacity for each lane should not exceed 1,000 vph. See Chapter 10 of the 1994 HCM for more information about two-way stops.

For travel forecasting software packages that explicitly allow signs and signals in the network, consult the software reference manual. For example, QRS II requires that the capacity be set to the total saturation flow rate of the through lanes at the approach, without adjusting for signalization priority (amount of green) or amount of turning. For roadway

TABLE 53 Initial capacities for freeways, each lane: ultimate capacity

	60, 70 mph	50 mph
Level Terrain	1,800	1,700
Rolling Terrain[1]	1,350	1,250

[1] For planning purposes, grades of two percent or higher may be considered rolling. For more detailed evaluation of terrain, refer to Chapter 3 of the 1985 *Highway Capacity Manual.*

TABLE 54 Initial capacities for two-lane roads: ultimate capacity

		Level	Rolling
Peak	Little No-Passing	1,500	1,050
	Extensive No-Passing[1]	1,500	950
Off Peak	Little No-Passing	1,200	800
	Extensive No-Passing[1]	1,200	750

1 When no-passing zones exceed 50 percent of the length of roadway being evaluated, extensive no-passing may be assumed.

sections containing multiple intersections, choose the smallest capacity.

DETERMINATION OF INTERSECTION CAPACITY

Once the volume projections from a travel forecasting model are available, it is often necessary to perform capacity analysis at signalized intersections in the network to test the adequacy of these intersections and to identify improvements if necessary. The methodology outlined in this section enables the user to perform this task.

The intersection capacity analysis methodology described here is based on the new methodology for planning application contained in Chapter 9 of the 1994 *Highway Capacity Manual.* The operational analysis method provides an extremely detailed treatment of the operation of a traffic signal. The level of precision inherent in this analysis often exceeds the accuracy of available data. The requirement for a complete description of the signal timing plan is data intensive, especially when the method is being applied in transportation planning situations. The planning analysis method described in this section, on the other hand, makes use of carefully determined default values for most of the data required and is, therefore, much less data intensive. For a more detailed explanation of the procedures explained in the following sections, the user is directed to Chapter 9 of the 1994 *Highway Capacity Manual.*

Input Data Requirements

It is possible to perform an approximate capacity analysis at a traffic signal through the use of assumed values for most of the data that are required. For planning purposes, the only site-specific data required are the traffic volumes and the number of lanes on each approach, with a minimal description of the signal design and other operating parameters. Tables 59 and 60 contain recommended default values for other data items to be used in the planning analysis.

The planning analysis described here is intended for use in sizing the overall geometrics of a signalized intersection or in identifying the general capacity sufficiency of an intersection for planning purposes. This procedure is based on the sum of critical lane volumes and requires minimum input

TABLE 55 Initial capacities for single-lane, signalized intersection approaches: ultimate capacity

		Low Turns	High Turns
No Exclusive Left	Low Priority[1]	550	350
	Medium Priority[2]	825	550
	High Priority[3]	1,100	900
Exclusive Left	Low Priority[1]	550	550
	Medium Priority[2]	825	825
	High Priority[3]	1,100	1,100

TABLE 56 **Initial capacities for two-lane, signalized intersection approaches: ultimate capacity**

		Low Turns	High Turns
No Exclusive Left	Low Priority[1]	1,100	650
	Medium Priority[2]	1,650	900
	High Priority[3]	2,200	1,400
Exclusive Left	Low Priority[1]	1,100	850
	Medium Priority[2]	1,650	1,300
	High Priority[3]	2,200	2,000

information. Three worksheets are provided for this analysis; they include the basic worksheet shown on Figure 27, the lane volume worksheet shown on Figure 28, which is used to establish individual lane volumes on each approach, and the signal operations worksheet shown on Figure 29, which is used to synthesize the signal-timing plan and to determine the operational status of the intersection. The relationship between these worksheets is illustrated schematically on Figure 30. The objective of using these worksheets is to determine the critical movement *v/c* ratio, X_{cm}, which is an approximate indicator of the overall sufficiency of the intersection geometrics. Although it is not possible to assign a level of service to the intersection based on X_{cm}, it is possible to evaluate the operational status of the intersection for planning purposes. Table 61 expresses the status using descriptive terms "over," "at," "near," or "under" capacity.

WORKSHEET APPLICATIONS

The relationship between the Lane Volume Worksheet and the Signal Operations Worksheet is shown on Figure 30. Note that one Lane Volume Worksheet is required for each of the four approaches. This will determine the equivalent hourly lane volume for each approach. The hourly volumes are then combined on the Signal Operations Worksheet to determine the critical movement sum and the intersection status. Optionally, the cycle length and phase times may also be determined.

Computational Requirements

The capacity analysis design parameters must be based on the traffic volumes and lane configuration of each approach to the intersection. The steps in performing the analysis follow:

1. Determine the lane volumes for each movement. The detailed instructions for the lane volume worksheet describe this process.
2. Determine the type of left-turn protection for each direction. For planning applications, the actual left-turn protection should be used if known. A left turn is

TABLE 57 **Initial capacities for each lane beyond two, signalized intersection approaches: ultimate capacity**

		Low Turns	High Turns
No Exclusive Left	Low Priority[1]	550	300
	Medium Priority[2]	825	350
	High Priority[3]	1,100	500
Exclusive Left	Low Priority[1]	550	300
	Medium Priority[2]	825	475
	High Priority[3]	1,100	900

[1] When the green time for the cross street at a signalized intersection exceeds the green time for the approach being evaluated, then the approach being evaluated has low priority.

[2] When the green time for the approach being evaluated and the cross street at a signalized intersection are approximately equal, then the approach being evaluated has medium priority.

[3] When the green time for the approach being evaluated exceeds that of the cross street at a signalized intersection, the approach being evaluated has high priority.

TABLE 58 Initial capacities for all-way stops: ultimate capacity

	Low Conflicting Volume	High Conflicting Volume
One Lane	1,000	500
Two or More Lanes	2,000	600

considered to be protected if it is able to proceed at some point in the cycle while the oncoming through movement is stopped. If the actual left-turn protection is unknown, a simple method will be presented later for determining an appropriate choice.

3. Select the phase plan from a choice of six alternative plans that will provide the desired degree of left-turn protection and will accommodate the observed left-turn volume balance.
4. Determine the sum of the critical volumes for each phase and the intersection status (under, near, at, or over capacity).

This completes the planning analysis. If an estimate of the level of service based on stopped delay is required, two additional steps are involved. In this case, the user is directed to Chapter 9 of the 1994 *Highway Capacity Manual.*

Instructions for the Lane Volume Worksheet

The following instructions cover the step-by-step procedure for completing all of the items on the lane volume worksheet. Each step is numbered to correspond with the row on the worksheet.

1. Left-Turn Volume: The first item is the left-turn volume (in vehicles per hour) on the approach. In the case of protected-plus-permitted phasing with an exclusive left-turn lane, two vehicles per cycle should be removed from the left-turn volume to account for the effect of sneakers. If the cycle length has not been established, the maximum cycle length should be used. To prevent unreasonably short protected left-turn phase durations, this volume adjustment step should not reduce the left-turn volume to a value below four vehicles per cycle.

TABLE 59 Default values for use in planning analysis

Traffic Characteristics		
Ideal saturation flow rate	1,900 pcphgpl*	
Pedestrian crossing volume	Low	50 peds/hr
	Moderate	200 peds/hr
	High	400 peds/hr
Percent heavy vehicles	2%	
Grade	0%	
Number of buses	0	
Parking maneuvers	20/hr. where parking exists	
Arrival type	4 if coordinated	
	3 if isolated	
Peak-hour factor	0.90	
Lane use factor	See Table 60	
Facility and Traffic Signal Characteristics		
Signal type	Pre-timed	
Cycle length range	60 sec. to 120 sec.	
Lost time	3.0 sec./phase	
Yellow plus all-red	4.0 sec./phase	
Area type	Non-CBD	
Lane width	12 ft.	

* Passenger cars per hour of green time per lane.

TABLE 60 Lane use factors

Lane Group Movements	Number of Lanes in Lane Group	Percent of Traffic in Heaviest Lane	Lane Use Factor, U
Through or shared	1	100.0	1.00
	2	52.5	1.05
	3	36.7	1.10
Exclusive left turn	1	100.0	1.00
	2	51.5	1.03
Exclusive right turn	1	100.0	1.00
	2	56.5	1.13

2. Opposing Mainline Volume: Opposing mainline volume is defined as the total approach volume minus the left-turn volume from exclusive lanes or from a single lane (in vehicles per hour). The cross product ([2] × [1]) may now be computed by multiplying the opposing mainline volume by the left-turn volume. This gives a value for comparison to determine if a protected phase should be assumed.
3. Number of Exclusive Left-Turn Lanes: This would be the number of lanes exclusively designated to accommodate the left-turn volumes.
4. Left-Turn Adjustment Factor: The left-turn adjustment factor applies only to protected left turns from exclusive left-turn lanes or to left turns that are not opposed. This factor is given as 0.95 for single lanes and is further reduced to 0.92 for dual lanes. If the left-turn movement is not opposed because of a one-way street or T-intersection, pedestrian interference must be considered. The corresponding value of 0.85 for one lane and 0.75 for two lanes should be used.
5. Left-Turn Lane volume ([1]/[3] × [4]): The total left-turn volume from Step 1 should be divided by the product of the number of exclusive left-turn lanes (Step 3) and the left-turn adjustment factor (Step 4). The left-turn volume should be entered directly if there is no exclusive left-turn lane. The result is expressed in vehicles per hour per lane. Zero should always be entered if the left turns are permitted.
6. Right-Turn Volume: Right-turn volumes (in vehicles per hour) from either a shared through and right-turn lane or from an exclusive turn lane or lanes should be entered. If available, the right-turn-on-red volume should be subtracted.
7. Exclusive Lanes: This is the number of lanes assigned exclusively for right turns, if any.
8. Right-Turn Adjustment Factor: The right-turn adjustment factor is given as 0.85 for a single lane or a shared lane and reduced to 0.75 for two lanes.

9,10. Right-Turn Lane Volume ([6]/([7] × [8])): The total right-turn volume from Step 6 should be divided by the product of the number of exclusive right-turn lanes (Step 7) and the right-turn adjustment factor (Step 8). If there is no exclusive right-turn lane, a value of 1.0 should be used for Step 7. The result is entered as Step 9 if one or more exclusive right-turn lanes exist or as Step 10 if right turns must share the lane.

11. Through Volume: Total through volume for the approach excluding left and right turns should be placed in the appropriate column to correspond with the applicable treatment for left turns (permitted, protected, or not opposed).
12. Parking Adjustment Factor: The parking adjustment factor should be placed in the appropriate column, as explained in Step 11. This factor corresponds to the assumed value of 20 parking maneuvers per hour and depends on the number of through lanes available. The values are 0.800, 0.900, and 0.933 for one, two, and three lanes, respectively. If no parking exists, the factor equals 1.0.
13. Number of Through Lanes Including Shared Lanes: This step is self-explanatory. Exclusive turn lane or lanes should be excluded.

At this point it is necessary to distinguish between exclusive left-turn lanes and shared left-turn lanes. The procedure for exclusive left-turn lanes will be described first. Note that Steps 15 and 17 do not apply to exclusive left-turn lanes.

14. Total Approach Volume (([10] + [11])/[12]): The total approach volume is the total of the shared lane right-turn volumes plus the through volumes. Note that the through volumes are adjusted (increased) by the parking adjustment factor to account for the effect of parking on through volumes, for example, momentary lane blockage. Note also that left-turn volumes are excluded because they are not a part of the lane group.
15. Not applicable to exclusive left-turn lanes.
16. Left-Turn Equivalence: Left-turn equivalence, determined from Table 62, is not used in lane volume calculations when exclusive left-turn lanes exist. This step is, however, required for permitted left turns to assess the adequacy of the left-turn treatment in Step 20.

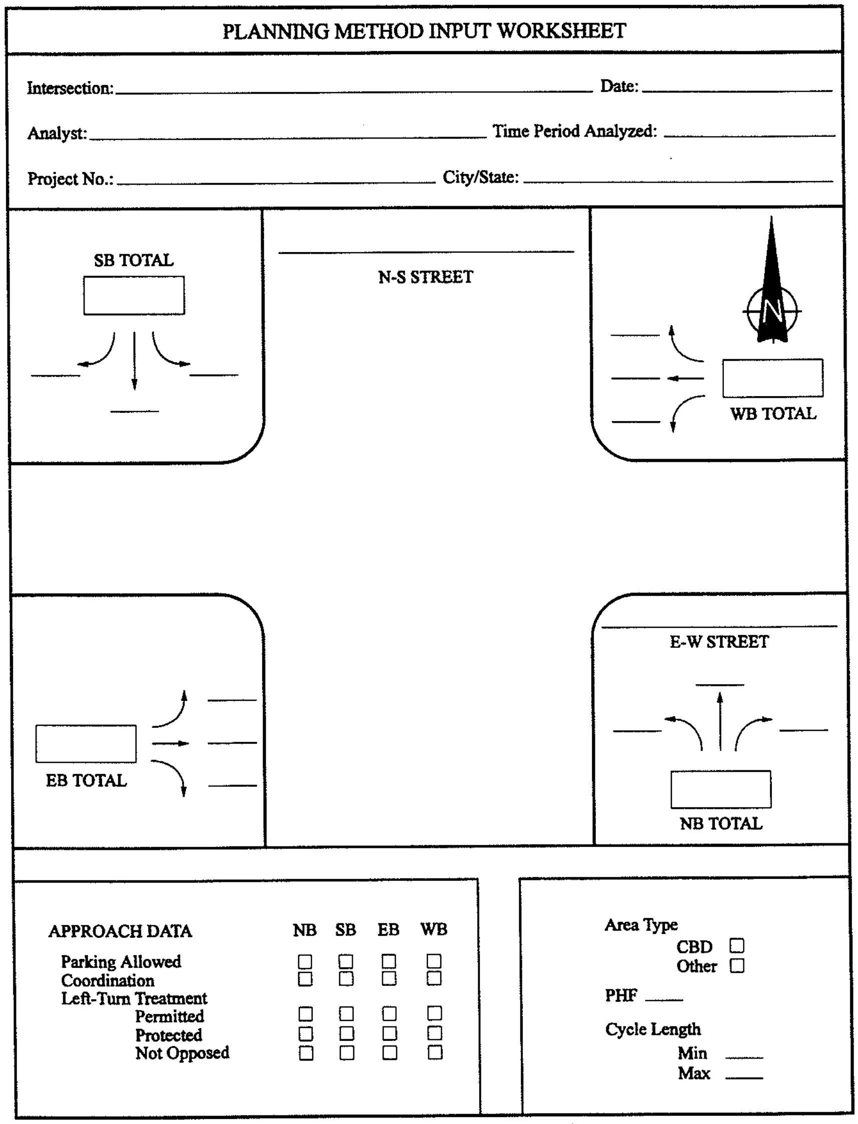


Figure 27. Planning method input worksheet.

17. Not applicable to exclusive left-turn lanes.
18. Through-Lane Volume ([14]/[13]): The total approach volume should be divided by the number of lanes to obtain volume per lane, which is the basis for computing critical lane volumes.
19. Critical Lane Volume: Step 19 is normally the same as Step 18 except when the right turn has an exclusive lane or the left turn is not opposed and either of these movements is more critical than the through movement. If both conditions apply, the critical lane volume will be Max ([5],[9],[18]). If a shared lane exists for the right turn, Step 9 should be eliminated. If the left turn is permitted or protected, Step 5 should be eliminated.

The case of shared left-turn lanes is more complicated and therefore requires a more detailed procedure. Steps 14 through 18 are used to approximate the effect that left-turning vehicles have in reducing available lanes for through volumes. Left-turning vehicles blocking the shared left-turn and through lane will prevent through vehicles from proceeding until the turning vehicles have been able to make the turn.

14. Total Approach Volume: The total approach volume is computed in nearly the same manner as in Step 14 for exclusive left-turn lanes, that is, ([10] + [11])/[12]. The difference is that the volume from Step 5 must be added to the through volume in Step 11 if the left turn is not opposed.
15. Proportion of Left Turns in Lane Group: Step 15 is self-explanatory. This data item is required for the follow-up computations.
16. Left-Turn Equivalence: Determined from Table 62, this is one of the factors needed to compute the applicable formulas from Table 63 for shared-lane permitted left turns. It is not used at all when the left turn is protected.

PLANNING METHOD LANE VOLUME WORKSHEET

Location: ________________________ Direction ________________________

Left Turn Movement		**Right Turn Movement**	Exclusive RT Lane	Shared RT Lane
1. LT volume	________	6. RT volume	________	________
2. Opposing mainline volume	________	7. RT Lanes	________	1
3. No of exclusive LT lanes	________	8. RT adjustment factor	________	________
4. LT adjustment factor	________	RT lane vol:	[9] ________	[10] ________
(See instructions)				

		Permitted	Protected	Not Opposed
Cross product: [2] * [1]	________ --->			
5. LT lane volume: [1] / ([3] * [4])		0	________	________

Through Movement	Permitted	Protected	Not Opposed
11. Through volume	________	________	________
12. Parking adjustment factor	________	________	________
13. No. of through lanes including shared lanes	________	________	________
------------ **Exclusive LT lane computations** ------------------	------------	------------	------------
14. Total approach volume: ([10] + [11]) /[12]	________	________	________
16. Left turn equivalence: (Figure 9-7)	________	XXXXXXXXX	XXXXXXXXX
18. Through lane volume: [14] / [13]	________	________	________
19. Critical lane volume: (See instructions)	________	________	________
------------ **Shared LT lane computations** ----------------------	------------	------------	------------
14. Total approach volume: (See instructions)	________	________	________
15. Proportion of left turns in the lane group	________	XXXXXXXXX	XXXXXXXXX
16. Left turn equivalence: (Figure 9-7)	________	XXXXXXXXX	XXXXXXXXX
17. Left turn adjustment factor: (Table 9-15)	________	________	1.0
18. Through lane volume: [14] / ([13] * [17])	________	________	________
19. Critical lane volume: Max([9],[18])	________	________	________

Left Turn Check (if [16] > 8)	Permitted	Protected	Not Opposed
20. Permitted left turn sneaker capacity: 7200 / C_{max}	________	XXXXXXXXX	XXXXXXXXX

Figure 28. Planning method lane volume worksheet.

PLANNING METHOD SIGNAL OPERATIONS WORKSHEET

Phase Plan Selection from Lane Volume Worksheets		**EASTBOUND**	**WESTBOUND**	**NORTHBOUND**	**SOUTHBOUND**
Critical Through-RT lane volume: [19]		____	____	____	____
LT lane volume: [5]		____	____	____	____
Left turn protection: (Perm, Prot, N/O)		____	____	____	____
Dominant left turn: (Indicate by '*')		____	____	____	____
Selection Criteria based on the specified left turn treatment:	**Plan 1:**	**Perm**	**Perm**	**Perm**	**Perm**
		Perm	**N/O**	**Perm**	**N/O**
		N/O	**Perm**	**N/O**	**Perm**
	Plan 2a:	**Perm**	**Prot**	**Perm**	**Prot**
	Plan 2b:	**Prot**	**Perm**	**Prot**	**Perm**
*** Indicates the dominant left turn for each opposing pair**	**Plan 3a:**	***Prot**	**Prot**	***Prot**	**Prot**
	Plan 3b:	**Prot**	***Prot**	**Prot**	***Prot**
	Plan 4:	**N/O**	**N/O**	**N/O**	**N/O**
Phase plan selected (1 to 4)		____		____	

Min. cycle $[C_{min}]$ ____ Max cycle $[C_{max}]$ ____ [PHF] (From Input Worksheet) ____

Phasing Plan From Table 9-16	**Note**	**Value**	**EAST-WEST Phase 1**	**EAST-WEST Phase 2**	**EAST-WEST Phase 3**	**NORTH-SOUTH Phase 1**	**NORTH-SOUTH Phase 2**	**NORTH-SOUTH Phase 3**
Movement codes			____	____	____	____	____	____
Critical Phase Volume [CV]			____	____	____	____	____	____
Critical Sum [CS]	1	____						
Lost time/phase [PL]			____	____	____	____	____	____
Lost time/cycle [TL]	2	____						
CBD adjustment [CBD]	3	____						
Critical v/c ratio $[X_{cm}]$	4	____						
Intersection status	5	____						
Optional Timing Plan Computation								
Reference Sum [RS]	6	____						
Cycle length [CYC]	7	____						
Green time	8		____	____	____	____	____	____

Notes

1. Critical sum = Sum of critical phase volumes [CV's] for all phases.
2. Lost time/cycle = Sum of all lost times/phase, [PL's].
3. CBD adjustment = .9 within CBD, 1.0 elsewhere.
4. Critical v/c ratio = CS /((1-[TL]/C_{max}) * 1900 * [CBD] * [PHF]).
5. Status: (See instructions).
6. Reference Sum = 1710 * [PHF] * [CBD].
7. Cycle length = [TL] / (1-(Min([CS],[RS]) / [RS])), Subject to $[C_{min}]$ and $[C_{max}]$.
8. Green time = ([CYC]-[TL]) * ([CV]/[CS]) + [PL].

Figure 29. Planning method signal operations worksheet.

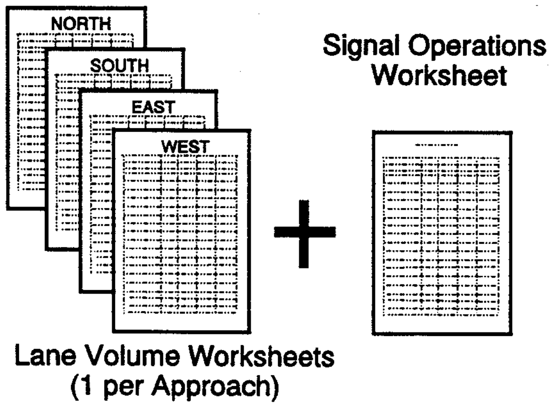


Figure 30. Planning method worksheet relationships.

17. Left-Turn Adjustment Factor for Through Traffic f_{DL}: The appropriate formula in Table 63 should be used. This is a reduction factor applied to the through volumes to account for the effect of left-turn vehicles waiting for a gap in the opposing traffic to make the turn. Note that for lanes that are not opposed, the factor must be 1.0 because these vehicles will have gaps in which to turn.
18. Through-Lane Volume: Total through volume in the approach should be divided by the number of through lanes. Note that the number of lanes is reduced by the factor obtained in Step 17 to account for the effect of the left-turning vehicles.
19. Critical Lane Volume: The critical lane volume is the maximum of either the value computed by Step 18 or the right-turn volume from an exclusive right-turn lane as computed in Step 9.
20. Left-Turn Check: If one or more left turns have been designated as permitted (i.e., no protected phase has been assigned), the need for a protected phase should be reexamined at this point. If the cross product ([2] × [1]) exceeds the adopted thresholds, a protected left-turn phase should be assigned for planning purposes unless existing traffic volumes have been used and it is known that such a phase does not exist.

    It was indicated in Table 62 (left-turn equivalence) that values above 8.0 indicate that left-turn capacity is derived substantially from sneakers. Therefore, if the left-turn equivalence [16] is greater than 8 and the left-turn volume is greater than two vehicles per cycle (i.e., [1] > 7,200/C_{max}), it is most likely that the subject left turn will not have adequate capacity without a protected phase.

TABLE 61 Intersection status criteria for signalized intersection planning analysis

Critical *v/c* Ratio X_{cm}	Relationship to Probable Capacity
$X_{cm} \le 0.85$	Under Capacity
$.85 < X_{cm} \le 0.95$	Near Capacity
$.95 < X_{cm} \le 1.00$	At Capacity
$X_{cm} > 1.00$	Over Capacity

Signal Operations Worksheet

Of the six steps involved in the planning method, only the first two are carried out by the lane volume worksheet. The last four steps are included in the signal operations worksheet, which is shown in Figure 29. To facilitate the use of the signal operations worksheet, the lane volumes are transferred from the lane volume worksheet before the computations begin. Note that the through-movement lane volume is taken as the heavier of the through or right-turning movement when an exclusive right-turn lane is present. In other words, if the volume of a right turn from an exclusive lane is heavier than that of the through movement, the right-turn lane volume will be considered as the through volume for design purposes.

1. Transcribed Data Items: The peak hour factor (PHF) was entered on the Planning Method Input Worksheet. The appropriate value is discussed in connection with the description of that worksheet. The left-turn treatment is also transcribed to the signal operations worksheet from the input worksheet. It is not necessary to specify whether the treatment includes a permitted phase for the left turn in addition to a protected phase. The synthesis of the signal timing plan does not consider protected-plus-permitted operation. That, of course, does not preclude specification of this type of operation in the analysis. At this time, only determination of reasonable values for the cycle length and phase times is of interest.
2. Phase Plan Selection: The phase plan is selected from six alternatives that cover the full range of left-turn protection requirements. A phase plan deals with only one street at a time. The complete signal sequence will involve two phase plans: one for the east-west street and one for the north-south street. The choice between phase plans is made by examining the left-turn protection for both pairs of opposing left turns. The alternatives include the following:

    - Plan 1: No left-turn protection in either direction. In this case, the phase plan includes only one phase, in which all through and left-turn movements may proceed, with the left turns yielding to the opposing through traffic.
    - Plans 2a and 2b: These two plans involve left-turn protection for only one of the two opposing left turns. Two phases will be involved in this case. In the first phase, the protected left turn will proceed with the through movement in the same direction. In the second phase, the two through movements will proceed. Plans 2a and 2b differ only in terms of which of the two opposing left turns is protected.

TABLE 62 Through-car equivalents, E_{LI}, for permitted left turns[4]

Total No. of Signal Phases	Type of Left Turn Lane	No. of Opposing Lanes	Opposing Flow, V_o						
			0	200	400	600	800	1000	≥1200
2	Shared	1	1.05	2.0	3.3	6.5	16.0*	16.0*	16.0*
		2	1.05	1.9	2.6	3.6	6.0	16.0*	16.0*
		≥3	1.05	1.8	2.5	3.4	4.5	6.0	16.0*
	Exclusive	1	1.05	1.7	2.6	4.7	10.4*	10.4*	10.4*
		2	1.05	1.6	2.2	2.9	4.1	6.2	10.4*
		≥3	1.05	1.6	2.1	2.8	3.6	4.8	10.4*
More than 2	Shared	1	1.05	2.2	4.5	11.0*	11.0*	11.0*	11.0*
		2	1.05	2.0	3.1	4.7	11.0*	11.0*	11.0*
		≥3	1.05	2.0	2.9	4.2	6.0	11.0*	11.0*
	Exclusive	1	1.05	1.8	3.3	8.2*	8.2*	8.2*	8.2*
		2	1.05	1.7	2.4	3.6	5.9	8.2*	8.2*
		≥3	1.05	1.7	2.4	3.3	4.6	6.8	8.2*

* Generally indicates turning capacity only available at end of phase—"sneakers" only.

4 MESSER, C. J., and FAMBRO, D. B., "Critical Lane Analysis for Intersection Design." *Transportation Research Record 644*, Transportation Research Board, Washington, D.C. (1977).

- Plans 3a and 3b: Both opposing left turns are protected here. In the first phase, the two opposing left turns will proceed. In the second, the dominant left turn will continue with the through movement in the same direction. In the third, the two through movements will proceed. Plans 3a and 3b differ only in terms of the dominant left turn that governs the display in the second phase.
- Plan 4: This is generally known as "split-phase" operation. Two phases are involved, with the through and left-turn movements from one of the two opposing directions proceeding on each phase. This has the effect of full directional separation between the two approaches. From a capacity analysis point of view, it is equivalent to two one-way streets that meet at a common point.

The selection criteria are presented in a table on the signal operations worksheet. Note that the selection is made on the basis of the user-specified left-turn protection and the dominant left-turn movement identified from the lane volume worksheet.

3. Critical Phase Volume, CV: When the phase plan has been selected, the movement codes, critical phase volumes (CVs), and lost time per phase may be entered on the worksheet. The appropriate choice for critical lane volumes is given in the phase plan summary shown in Table 64 along with a code that identifies the movements allowed to proceed on each phase. The movement codes are defined in a note to Table 64. For example, "NST" indicates that the northbound and southbound through movements have the right-of-way on the specified phase. The corresponding code for the two opposing left turns moving concurrently is "NSL." If the northbound through and left turns are moving together, the code is "NTL." Table 64 also indicates the lost time to be assigned to each phase.

   Thus, the movement codes and CVs must be determined for each phase from Table 64 and entered on the signal operations worksheet. When all phases have been completed, the critical sum (CS) of the CVs must be entered on the next line.
4. Lost Time Determination: For planning purposes, it is assumed that there is a lost time value of 3 sec per phase in which any movement is both started and stopped. For one- and two-phase plans, there is a lost time associated with each phase. For three-phase plans (Plans 3a and 3b), the second phase requires no lost time because

TABLE 63 Shared-lane left-turn adjustment computations for planning-level analysis

PERMITTED LEFT TURN
Lane groups with two or more lanes:
$[17] = \{[13] - 1 + e^{(-[13]*[1]*[16]/600)}\}/[13]$
Subject to a minimum value that applies at very low left-turning volumes when some cycles will have no left-turn arrivals:
$[17] = \{[13] - 1 + e^{(-[1]*C_{max}/3600)}\}/[13]$
Lane groups with only one lane for all movements:
$[17] = e^{-(0.02*([16]+10*[15])*[1]*C_{max}/3600)}$
PROTECTED-PLUS-PERMITTED LEFT TURN (ONE DIRECTION ONLY)
If [2] < 1220
$[17] = 1/\{1 + [(235 + 0.435*[2])*[15]]/(1400 - [2])\}$
If [2] ≥ 1220
$[17] = 1/(1 + 4.525*[15])$

none of the movements are both started and stopped. Thus, as a simple rule, phase Plan I involves 3 sec of lost time per cycle, and all other plans require 6 sec.

When the lost times have been determined for each phase, the total lost time per cycle (TL) may be computed and entered on the worksheet.

5. Critical v/c Ratio, X_{cm}: The planning-level critical v/c ratio, X_{cm}, is the ratio of the critical sum, CS, to the sum of the critical lane volumes that could be accommodated at the maximum cycle length, computed as

$$(1 - TL/C_{max}) \times 1{,}900 \times CBD \times PHF$$

The intersection status is determined directly from X_{cm} using the threshold values given in Table 61.

6. Timing Plan Development: The development of a timing plan is optional. For many planning applications, a knowledge of the intersection status is sufficient. The timing plan is required only if the planning analysis is to be extended to estimate the level of service.

The cycle length may be determined from the following formula:

$$C = \frac{TL}{1 - [\mathrm{Min}(CS, RS) / RS]} \qquad (10\text{-}1)$$

where RS is the reference sum of phase volumes representing the theoretical maximum value that the intersection could accommodate at an infinite cycle length.

The recommended value for the reference sum is (1,710 × PHF). This value should be reduced by 10 percent in CBD locations. The value of 1,710 is 90 percent of the ideal saturation flow rate of 1,900 pcphgpl. It will attempt to produce a 90 percent v/c ratio for all critical movements. The cycle length determined from this equation should be checked against reasonable minimum and maximum values. The determination of appropriate values is discussed in connection with the Planning Method Input Worksheet.

The lost time per cycle must be subtracted from the total cycle time to determine the effective green time per cycle, which must then be apportioned among all the phases. This is based on the proportion of the critical phase volume sum for each phase determined in a previous step. The phase time should be entered on the worksheet.

As a final step, the lost time must be added to the effective green time for each phase to determine the total phase time per cycle. The phase times for all of the phases should be equal to the cycle length and should be entered on the last line of the worksheet.

TABLE 64 Phase plan summary for planning analysis

			EAST-WEST		NORTH-SOUTH	
PHASE PLAN	PHASE NO.	LOST TIME	MOVEMENT CODE	CRITICAL SUM	MOVEMENT CODE	CRITICAL SUM
1	1	3	EWT	Max(ET,EL,WT,WL)	NST	Max(NT,NL,ST,SL)
2a	1	3	WTL	WL	STL	SL
	2	3	EWT	Max(WT-WL, ET)	NST	Max(ST-SL, NT)
2b	1	3	ETL	EL	NTL	NL
	2	3	EWT	Max(ET-EL, WT)	NST	Max(NT-NL, ST)
3a	1	3	EWL	WL	NSL	SL
	2	0	ETL	EL-WL	NTL	NL-SL
	3	3	EWT	Max(WT,ET-(EL-WL))	NST	Max(ST,NT-(NL-SL))
3b	1	3	EWL	EL	NSL	NL
	2	0	WTL	WL-EL	STL	SL-NL
	3	3	EWT	Max(ET,WT-(WL-EL))	NST	Max(NT,ST-(SL-NL))
4	1	3	ETL	Max(ET,EL)	NTL	Max(NT,NL)
	2	3	WTL	Max(WT,WL)	STL	Max(ST,SL)

NOTE: EWT = eastbound and westbound through; ETL = eastbound through and left; WTL = westbound through and left; NST = northbound and southbound through; STL = southbound through and left; NTL = northbound through and left; ET = eastbound through; EL = eastbound left; WT = westbound through; WL = westbound left; NT = northbound through; NL = northbound left; ST = southbound through; SL = southbound left.

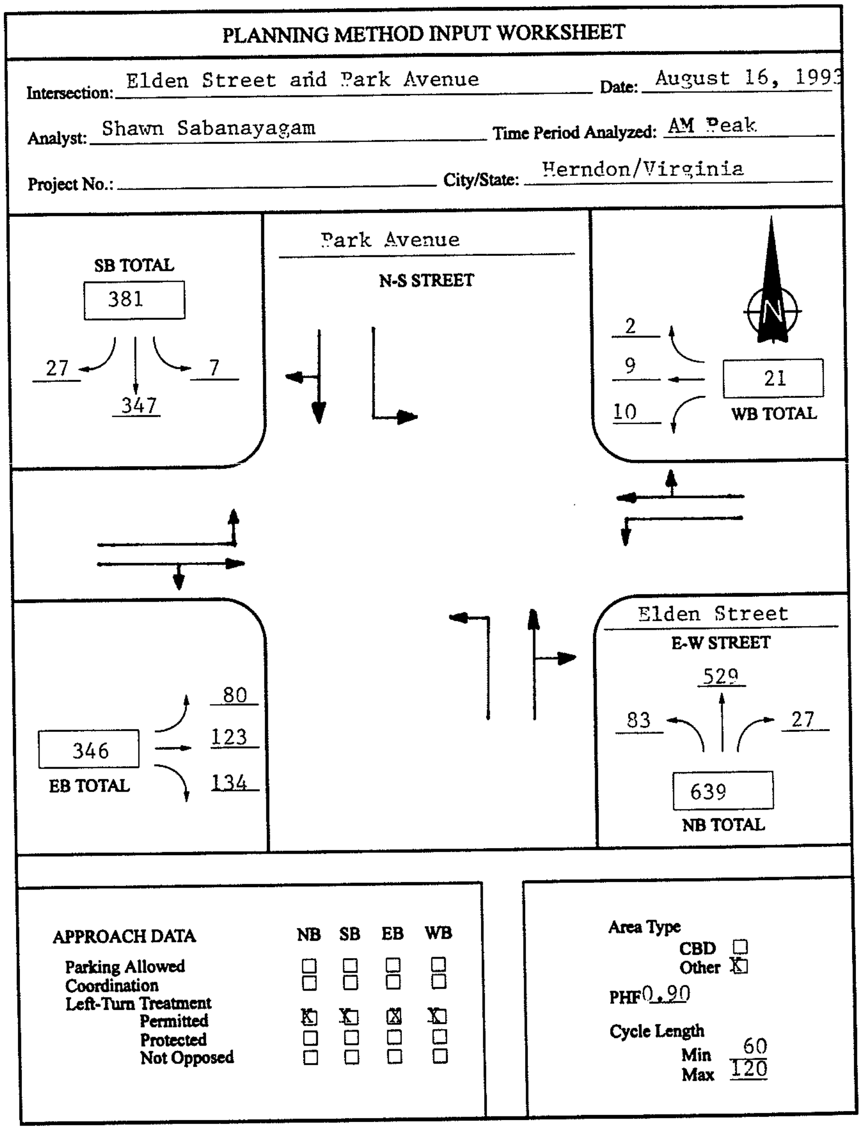


Figure 31. Planning method input worksheet—illustrated example.

LIMITATIONS OF THE PLANNING METHOD

The planning analysis technique described in this chapter offers a method for synthesizing a reasonable and effective signal-timing plan based on the traffic volumes and lane utilization at an intersection. Using the worksheets included here, it is possible to determine the approximate status of the operation of a signalized intersection with respect to its capacity.

It is also possible to take the analysis considerably further and obtain the level of service on each approach by the operational analysis method. Software has already been developed that will implement the worksheets and invoke the operational analysis method. This introduces a very powerful capability. However, the numerical precision of the results may greatly exceed the accuracy of the original data. In particular, great caution should be employed when using traffic volume projections to some point in the future. Unless there is strong confidence in the validity of the traffic data, this method should not be taken beyond the worksheet stage.

Illustrated Example

The following pages illustrate an example using the methodology for capacity analysis of signalized intersections described in this chapter. The volumes shown on Figure 31 are existing volumes. Typically, the volumes used are future-year projections from a travel forecasting model, though existing volumes may be used. The purpose of the analysis is to determine whether this intersection is operating below, near, at, or over capacity in the year for which volumes are available.

Figures 32 through 36 present an illustrated example of the planning application methodology for capacity analysis of signalized intersections.

PLANNING METHOD LANE VOLUME WORKSHEET

Location: Elden Street and Park Ave. Direction Eastbound

Left Turn Movement		**Right Turn Movement**	**Exclusive RT Lane**	**Shared RT Lane**
1. LT volume	80	6. RT volume	–	134
2. Opposing mainline volume	9	7. RT Lanes	–	1
3. No of exclusive LT lanes	1	8. RT adjustment factor	–	0.85
4. LT adjustment factor (See instructions)	N A (permitted)	RT lane vol:	[9] –	[10] 158

		Permitted	**Protected**	**Not Opposed**
Cross product: [2] * [1]	720 --->			
5. LT lane volume: [1] / ([3] * [4])		0	–	–

Through Movement	**Permitted**	**Protected**	**Not Opposed**
11. Through volume	123	–	–
12. Parking adjustment factor	1.0	–	–
13. No. of through lanes including shared lanes	1	–	–
Exclusive LT lane computations			
14. Total approach volume: ([10] + [11]) /[12]	281	–	–
16. Left turn equivalence: (Figure 9-7)	1.1	XXXXXXXXX	XXXXXXXXX
18. Through lane volume: [14] / [13]	281	–	–
19. Critical lane volume: (See instructions)	281	–	–
Shared LT lane computations			
14. Total approach volume: (See instructions)	–	–	–
15. Proportion of left turns in the lane group	–	XXXXXXXXX	XXXXXXXXX
16. Left turn equivalence: (Figure 9-7)	–	XXXXXXXXX	XXXXXXXXX
17. Left turn adjustment factor: (Table 9-15)	–	–	1.0
18. Through lane volume: [14] / ([13] * [17])	–	–	–
19. Critical lane volume: Max([9],[18])	–	–	–

Left Turn Check (if [16] > 8)

20. Permitted left turn sneaker capacity: 7200 / C_{max}	–	XXXXXXXXX	XXXXXXXXX

Figure 32. Planning method lane volume worksheet—illustrated example: eastbound.

PLANNING METHOD LANE VOLUME WORKSHEET

Location: Elden Street and Park Ave. Direction Westbound

Left Turn Movement		**Right Turn Movement**	**Exclusive RT Lane**	**Shared RT Lane**
1. LT volume	10	6. RT volume	-	2
2. Opposing mainline volume	123	7. RT Lanes	-	1
3. No of exclusive LT lanes	1	8. RT adjustment factor	-	0.85
4. LT adjustment factor (See instructions)	N A(permitted)	RT lane vol:	[9] -	[10] 2

	Permitted	**Protected**	**Not Opposed**
Cross product: [2] * [1] 1,230 --->			
5. LT lane volume: [1] / ([3] * [4])	0	-	-
Through Movement			
11. Through volume	9	-	-
12. Parking adjustment factor	1.0	-	-
13. No. of through lanes including shared lanes	1	-	-
------------ **Exclusive LT lane computations** ------------			
14. Total approach volume: ([10] + [11]) /[12]	11	-	-
16. Left turn equivalence: (Figure 9-7)	2.0	XXXXXXXXX	XXXXXXXXX
18. Through lane volume: [14] / [13]	11	-	-
19. Critical lane volume: (See instructions)	11	-	-
------------ **Shared LT lane computations** ------------			
14. Total approach volume: (See instructions)	-	-	-
15. Proportion of left turns in the lane group	-	XXXXXXXXX	XXXXXXXXX
16. Left turn equivalence: (Figure 9-7)	-	XXXXXXXXX	XXXXXXXXX
17. Left turn adjustment factor: (Table 9-15)	-	-	1.0
18. Through lane volume: [14] / ([13] * [17])	-	-	-
19. Critical lane volume: Max([9],[18])	-	-	-
Left Turn Check (if [16] > 8)			
20. Permitted left turn sneaker capacity: 7200 / C_{max}	-	XXXXXXXXX	XXXXXXXXX

Figure 33. Planning method lane volume worksheet—illustrated example: westbound.

PLANNING METHOD LANE VOLUME WORKSHEET

Location: Elden Street and Park Ave. Direction Northbound

Left Turn Movement		Right Turn Movement	Exclusive RT Lane	Shared RT Lane
1. LT volume	83	6. RT volume	-	27
2. Opposing mainline volume	374	7. RT Lanes	-	1
3. No of exclusive LT lanes	1	8. RT adjustment factor	-	0.85
4. LT adjustment factor (See instructions)	N A(permitted)	RT lane vol:	[9] -	[10] 32

Cross product: [2] * [1] 31,042 --->

	Permitted	Protected	Not Opposed
5. LT lane volume: [1] / ([3] * [4])	0	-	-
Through Movement			
11. Through volume	529	-	-
12. Parking adjustment factor	1.0	-	-
13. No. of through lanes including shared lanes	1	-	-
------------ **Exclusive LT lane computations** ------------			
14. Total approach volume: ([10] + [11]) /[12]	561	-	-
16. Left turn equivalence: (Figure 9-7)	2.5	XXXXXXXXX	XXXXXXXXX
18. Through lane volume: [14] / [13]	561	-	-
19. Critical lane volume: (See instructions)	561	-	-
------------ **Shared LT lane computations** ------------			
14. Total approach volume: (See instructions)	-	-	-
15. Proportion of left turns in the lane group	-	XXXXXXXXX	XXXXXXXXX
16. Left turn equivalence: (Figure 9-7)	-	XXXXXXXXX	XXXXXXXXX
17. Left turn adjustment factor: (Table 9-15)	-	-	1.0
18. Through lane volume: [14] / ([13] * [17])	-	-	-
19. Critical lane volume: Max([9],[18])	-	-	-

Left Turn Check (if [16] > 8)

20. Permitted left turn sneaker capacity: 7200 / C_{max}	-	XXXXXXXXX	XXXXXXXXX

Figure 34. Planning method lane volume worksheet—illustrated example: northbound.

PLANNING METHOD LANE VOLUME WORKSHEET

Location: Elden Street and Park Ave   Direction: Southbound

Left Turn Movement		Right Turn Movement	Exclusive RT Lane	Shared RT Lane
1. LT volume	7	6. RT volume	–	27
2. Opposing mainline volume	556	7. RT Lanes	–	1
3. No of exclusive LT lanes	1	8. RT adjustment factor	–	0.85
4. LT adjustment factor (See instructions)	N A(permitted)	RT lane vol:	[9] –	[10] 32

Cross product: [2] * [1] 3,982 --->

	Permitted	Protected	Not Opposed
5. LT lane volume: [1] / ([3] * [4])	0	–	–
Through Movement			
11. Through volume	347	–	–
12. Parking adjustment factor	1.0	–	–
13. No. of through lanes including shared lanes	1	–	–
Exclusive LT lane computations			
14. Total approach volume: ([10] + [11]) /[12]	379	–	–
16. Left turn equivalence: (Figure 9-7)	4.2	XXXXXXXXX	XXXXXXXXX
18. Through lane volume: [14] / [13]	379	–	–
19. Critical lane volume: (See instructions)	379	–	–
Shared LT lane computations			
14. Total approach volume: (See instructions)	–	–	–
15. Proportion of left turns in the lane group	–	XXXXXXXXX	XXXXXXXXX
16. Left turn equivalence: (Figure 9-7)	–	XXXXXXXXX	XXXXXXXXX
17. Left turn adjustment factor: (Table 9-15)	–	–	1.0
18. Through lane volume: [14] / ([13] * [17])	–	–	–
19. Critical lane volume: Max([9],[18])	–	–	–

Left Turn Check (if [16] > 8)

20. Permitted left turn sneaker capacity: 7200 / C_{max}	–	XXXXXXXXX	XXXXXXXXX

Figure 35. Planning method lane volume worksheet—illustrated example: southbound.

PLANNING METHOD SIGNAL OPERATIONS WORKSHEET

Phase Plan Selection from Lane Volume Worksheets

	EASTBOUND	WESTBOUND	NORTHBOUND	SOUTHBOUND
Critical Through-RT lane volume: [19]	281	11	561	379
LT lane volume: [5]	0	0	0	0
Left turn protection: (Perm, Prot, N/O)	perm	perm	perm	perm
Dominant left turn: (Indicate by '*')	*	–	*	–

Selection Criteria based on the specified left turn treatment:		EASTBOUND	WESTBOUND	NORTHBOUND	SOUTHBOUND
	Plan 1:	Perm	Perm	Perm	Perm
		Perm	N/O	Perm	N/O
		N/O	Perm	N/O	Perm
	Plan 2a:	Perm	Prot	Perm	Prot
	Plan 2b:	Prot	Perm	Prot	Perm
* Indicates the dominant left turn for each opposing pair	Plan 3a:	*Prot	Prot	*Prot	Prot
	Plan 3b:	Prot	*Prot	Prot	*Prot
	Plan 4:	N/O	N/O	N/O	N/O

Phase plan selected (1 to 4)   East-West: 1   North-South: 1

Min. cycle $[C_{min}]$ 60   Max cycle $[C_{max}]$ 120   [PHF] (From Input Worksheet) 0.90

Phasing Plan From Table 9-16

	Note	Value	EAST-WEST Phase 1	EAST-WEST Phase 2	EAST-WEST Phase 3	NORTH-SOUTH Phase 1	NORTH-SOUTH Phase 2	NORTH-SOUTH Phase 3
Movement codes			EWT			NST		
Critical Phase Volume [CV]			281			561		
Critical Sum [CS]	1	842						
Lost time/phase [PL]			3			3		
Lost time/cycle [TL]	2	6						
CBD adjustment [CBD]	3	1.0						
Critical v/c ratio $[X_{cm}]$	4	.052						
Intersection status	5	under capacity						
Optional Timing Plan Computation								
Reference Sum [RS]	6							
Cycle length [CYC]	7							
Green time	8							

Notes

1. Critical sum = Sum of critical phase volumes [CV's] for all phases.
2. Lost time/cycle = Sum of all lost times/phase, [PL's].
3. CBD adjustment = .9 within CBD, 1.0 elsewhere.
4. Critical v/c ratio = CS /((1-[TL]/C_{max}) * 1900 * [CBD] * [PHF]).
5. Status: (See instructions).
6. Reference Sum = 1710 * [PHF] * [CBD].
7. Cycle length = [TL] / (1-(Min([CS],[RS]) / [RS])), Subject to $[C_{min}]$ and $[C_{max}]$.
8. Green time = ([CYC]-[TL]) * ([CV]/[CS]) + [PL].

Figure 36. Planning method signal operations worksheet—illustrated example.

CHAPTER 11

DEVELOPMENT DENSITY/HIGHWAY SPACING RELATIONSHIPS

INTRODUCTION

The trend toward lower population densities in and around major metropolitan areas has been underway for decades and apparently is continuing. The 1990 census disclosed that almost 60 percent of the population of all metropolitan areas lived outside the central city. A large percentage of people seem to prefer low-density living. In addition, employment opportunities have followed the increase in households in suburban areas. This has resulted in a growing tendency for people to both live *and* work in relatively low-density suburban areas. The 1990 census reports that nearly 60 percent of the work trips made by people who live in the suburbs are to the suburbs.

This basic change in the structure of urban areas has been accompanied by increased demands for travel by automobile. Almost three-quarters of work travel is made by people driving alone in metropolitan areas, and the trends (despite improvements to transit systems) indicate that auto travel will continue to increase in suburban areas. Almost all travel for purposes other than work in suburban areas is made by automobile. In turn, people are becoming increasingly dependent on the automobile. A major difficulty is that the auto, especially under low-density conditions that force lengthy travel, generates the need for substantial investments in the highway system.

New or widened freeways and arterials will be required in growing suburban areas if the level of transportation service is to remain at acceptable levels. Transportation facilities, however, are not now and never have been ends in themselves. It is becoming obvious to decision makers that it will no longer be possible to provide an unlimited supply of new transportation facilities to meet these travel demands, and that other alternatives must be pursued. Such alternatives can include mixed public transportation systems, including taxi, dial-a-ride, or some other form of flexible-route systems interfacing with line-haul transit modes. Other alternatives include ride-sharing modes such as van pooling. These systems are being planned and made operational in many urban areas and show promise in reducing the need for new and improved highway systems. Another method of reducing travel demands is to locate new development in a manner to more fully use available capacity or to place development where capacity can be provided, rather than permitting such development to overload existing facilities.

The purpose of this chapter is to present a methodology designed to relate suburban development to estimates of highway levels of service so that the planner and policy maker can rapidly assess the highway transportation needs of land-use growth and change. The method developed in *NCHRP Report 187* is restated. This method interrelates land development and its subsequent transportation demands with highway system supply and the level of highway transportation service to be provided.

The following sections describe the methodology and provide examples to illustrate the various steps involved. An example application is presented at the end of the chapter to enable the user to execute and become acquainted with the entire methodology. This example provides the specifics of computation, definitions of analysis areas, and the like.

BASIS FOR DEVELOPMENT

The methodology described here is designed to provide a simple, straightforward means of computing the need for improved highways based on increasing land-use activities in suburban areas.

NCHRP Report 187 listed several criteria considered desirable in developing such a method, as well as simplifying assumptions that must be made. The criteria and assumptions are as follows:

1. Desirable criteria:
   a. An absolute minimum amount of information would be required.
   b. The terms and concepts would be understandable to citizens and politicians, as well as planners.
   c. The method could be applied quickly and easily so that many alternatives could be evaluated.
   d. No computer would be required.
2. Simplifying assumptions:
   a. The levels of transportation service being examined would not so radically depart from today's service levels that travel demand would be altered significantly.
   b. The pricing of transportation service would not so radically depart from today's costs that travel demands would be altered significantly.

DATA REQUIRED FOR APPLICATION

The basic data required consist of two parts: (1) land-use activity data and (2) data about the highway transportation system. If a major investment in transit is to be considered, some information is needed about that system as well.

The land-use activity data needed are used as the means to generate the amount of highway travel by analysis areas (districts). Some experimentation may be required to determine the size and number of analysis areas to be used. The developers of the Community Aggregate Planning Model (CAPM) recommend that the size of the basic analysis units range in area from 8 to 30 square miles.

Land use activity data required include as a minimum

- Number of households and
- Number of jobs (at-place employment).

As an option, slightly better (more accurate) results may be obtained if the household information is subdivided further into

- Number of apartment units,
- Number of townhouse units, and
- Number of single-family units.

Also, the employment information may be divided into

- Office employment,
- Manufacturing employment,
- Retail employment, and
- Other employment.

The existing highway transportation system data needed include the number of miles of highway by type by analysis area. Types of highways include

- Two-lane arterials and major collectors,
- Four-lane arterials,
- Six-lane arterials, and
- Freeways.

The method does not deal explicitly with non-line-haul transit improvements such as jitneys or dial-a-ride systems. Existing levels of conventional bus service resulting in typical levels of suburban transit use are assumed by the method used. Corrections may be made, if desired, to account for variations from the typical "mode split" percentage assumed. Corrections for auto-occupancy levels above or below those assumed may also be made, if desired.

FEATURES AND LIMITATIONS

The development density/highway spacing methodology is designed to produce the number of lane-miles of arterial highways required in an analysis area given a level of land-use activity, a freeway system, and a desired level of arterial traffic service for that analysis area.

An estimate of the number of miles of freeway to be provided is made outside the procedure, but the method does indicate where such additional facilities would be desirable to improve the level of transportation service provided.

Limitations of the Methodology and Substitutability of Local Data

The development density/highway spacing method described is quite similar to the Community Aggregate Planning Model (CAPM).[1] (CAPM is a computer-based model, not a manual procedure, that is used to generate regional system-sensitive travel demand, distribute the demand to the freeway and arterial system in each community, and compute a full range of useful evaluation measures.) The density/spacing methodology does not, however (as CAPM does), output economic, social, and environmental measures, being limited in scope to the land use/highway spacing area. But because the methodology does contain performance measures (the amount of VMT on freeways, and the arterial level of service distribution), it is possible to produce travel speed measures on an areawide basis if the user so desires.

For such a case, it may be useful to express level of service as a speed, as well as a percentage of VMT, over a specified level of service. Figure 37 expresses the relationship between these variables. The curve was constructed for arterial routes by assuming the level-of-service speeds given in Table 65 and weighting those speeds by the amount of travel at different levels of service. The daily curve reflects an assumption of no congestion in the off-peak period.

Estimates of the average speed of travel, along with VMT, can be used in conjunction with emission rates by speed of travel to provide first-cut estimates of changes in air quality. Speed of travel may also be used in estimating changes in operating, accident, and travel-time costs in an area. This information can be used in evaluating the cost-effectiveness of alternative program proposals. Because most social, economic, and environmental measures require vehicle-miles of travel and speed as inputs to subsequent calculations of accessibility, mobility, value of travel time, and air quality computations, it would be possible to add such output capabilities to the density/spacing methodology.

As volumes increase on a facility (the new volumes being output from a traffic assignment), speed declines, and operating, accident, and time costs (i.e., user costs) increase. At some point, a new or widened facility, HOV, or greater transit investment is warranted because the costs of improving the system are exceeded by the costs in allowing congestion to continue.

[1]H. Schleirer, S.L. Zimmerman, and D.S. Gendell, "CAPM—The Community Aggregate Planning Model," *Transportation Research Record 582*, pp 14–27 (1976).

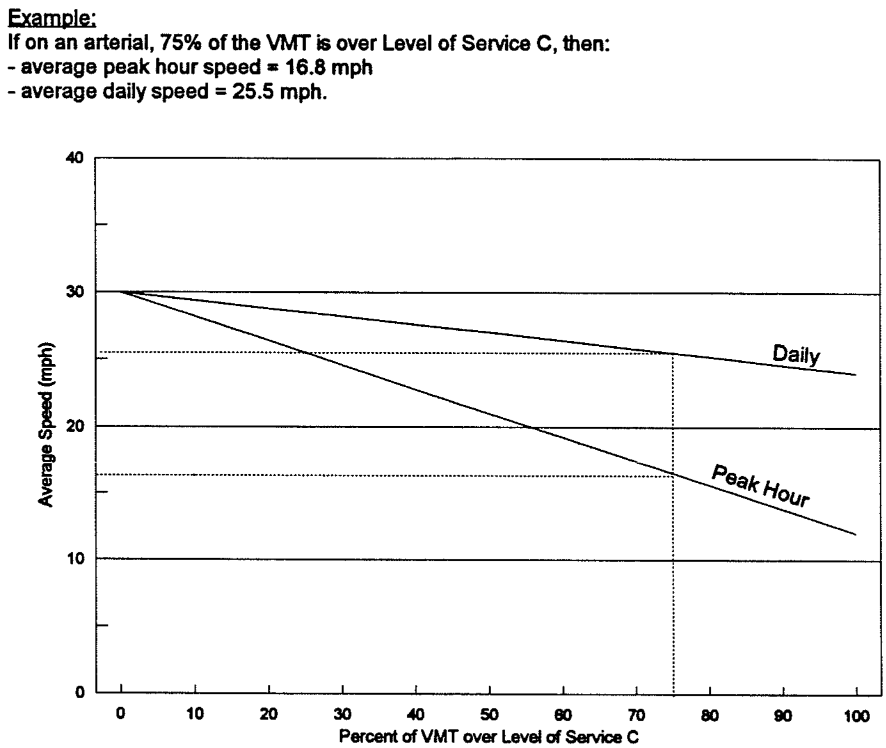


Figure 37. Arterial level of service speeds by analysis area.

Other limitations revolve about the assumptions made and the use of average trip rates and trip lengths. These can be overridden, however, and locally supplied data substituted. There probably is no adequate substitute for a complete set of traffic counts in this regard. Many problems of limitations in accuracy owing to generalization can be overcome based on traffic counts and with the use of common sense.

APPLYING THE DEVELOPMENT DENSITY/HIGHWAY SPACING METHODOLOGY

At least three distinct, potential applications of the density/spacing method exist. The method is an attempt to fill a critical void in transportation planning—that is, the rapid

TABLE 65 Arterial level of service volumes

Approximate Peak-Hour Operating Speed (mph)	Traffic Volumes All Lanes: Two-Lane		Four-Lane		Six-Lane		Level of Service
	Peak Hour[a]	Daily[b]	Peak Hour[a]	Daily[b]	Peak Hour[a]	Daily[b]	
35	<250	<4,150	<800	<8,330	<1,300	21,500	A
30	250	4,150	800	8,300	1,300	21,500	B
25	375	6,250	1,200	10,000	1,950	32,500	C
20	450	7,500	1,440	14,000	2,340	39,000	D
15	500	8,333	1,600	26,600	2,600	43,300	E
10	>500	>8,333	>1,600	>26,600	>2,600	>43,300	F

a. one way
b. two-way (peak hour factor (K) = 0.10 and directional factor (D) = 0.60)

estimation of the effects of alternative land-use and transportation plans on the level of transportation service.

The first application would be

Given existing land development and existing transportation facilities, what level of service is being provided by the transportation system?

The density/spacing method would indicate the following key items:

- Percentage of vehicle-miles of travel accommodated on freeways and arterials,
- Average volume per lane on the freeway system, and
- Percentage of arterial vehicle-miles of travel over level of service C.

A second application would be

Given a future land use plan, what increases in transportation facilities are required in order to maintain an existing (or desired) level of transportation service?

The density/spacing method would indicate the following key items:

- Computation of vehicle-miles of travel on freeways and arterials, given a fixed or revised freeway system;
- Number of equivalent lane-miles of arterials that need to be added, either by widening existing routes or by adding new construction, to achieve an existing (or desired) level of service; and
- Construction of enlarged or new freeways or improved transit service to reduce the need for arterial improvements.

A third possible application would be

Given an existing or future transportation plan, what amount of land development can be added without allowing the level of traffic service to deteriorate below a specified level?

This third application is best accommodated through a trial-and-error process, successively increasing (or reducing) the amount of land development by analysis area until the level-of-service limitation is reached. Because the technique can be applied rapidly, many iterations can be made in a reasonable time. The effect of freeways and additional transit service can also be taken into account.

Steps in Application

Applying the density/spacing method requires undertaking the following steps for each analysis area in the study area of interest.

Step 1: Computation of Vehicle Trip Ends

Vehicle trip generation rates are based on those given in Chapter 3, Trip Generation. Two methods (I and II) can be used, one assuming that only the number of households and the number of at-place jobs are known by analysis area, and the other assuming further breakdowns into type of dwelling unit and kinds of employment as outlined in the preceding section, Data Required for Application. Note that because trips have both an origin and destination trip end, and because the procedure involves calculation of trip-end generation for both residential and nonresidential activities, the sum derived for trips to and from all trip generators will be twice the area total number of one-way trips. Accordingly, the number of trip ends estimated must be cut in half for use in computing vehicle-miles of travel.

Method I uses just total households and total employment for each analysis area. Rates for this method are derived from data given in Table 3, Chapter 3. For example, a trip rate per household of 4.8 one-way vehicle trips daily (9.55 ÷ 2) would be used for single-family dwellings, 2.9 for medium-density dwellings, and 3.2 for apartments. Based on the approximate proportion of areawide single-, medium- and high-density dwelling units expected, a single overall rate per dwelling unit can be computed and used.

Method I uses (for nonresidential activities) an average trip rate per employee derived from a weighted average of rates for individual employment categories. For example, if the proportion of total jobs in a study area were 21.5 percent for office employment, 18.5 percent for retail, 10.0 percent for manufacturing, 23.0 percent for military, and 27.0 percent for other, and the trip rates were, respectively, 1.75, 10, 1.5, 1.25, and 5 one-way vehicle trips daily, the weighted average daily vehicle trip rate per job would be 4.0. This average trip rate is applied to all analysis areas.

Method II uses these rates directly by type of residential unit for each analysis area rather than develops the single overall rate previously described. In this case, a breakdown by type of unit is needed for each analysis area.

For nonresidential activities, trip-generation rates can be expressed as functions of at-place employment, floor space, or acres as given in the ITE *Trip Generation* manual. Again, vehicle trips per day are used, but reduced by half to reflect the one-way nature of travel. The best measure, if available, is employment, as this can be summed to a control total for the area as a check.

Method II applies individual rates to each land-use or employment category for each analysis area, thereby requiring more detailed input information than Method I.

Step 2: Computation of Transit Use and Auto-Occupancy Adjustment

In some urban areas, particularly larger ones, transit improvements may be planned which could have significant impacts on future vehicle-miles of travel within the area. Figure 38 shows the effect of changes in the percentage use of transit on the percentage of auto driver trips (of total person trips), and hence on VMT. For example, if an analysis area had a percentage transit use of 6 percent, and this could be increased to 15 percent, the percentage of auto-driver trips would drop (given an auto-occupancy rate of 1.33) from 70 to 64 percent. This represents a change of 8.6 percent, assuming that total travel would remain constant. Where changes in the relative use of transit are contemplated, this curve can estimate the effect on auto use and VMT. In addition to this curve, local relationships can be used (or derived) to estimate changes in transit use.

Changes in auto occupancy also affect vehicular travel and VMT. Figure 39 shows the percentage change in auto-driver trips as vehicle occupancy increases. Again, reductions in vehicular miles of travel can be computed for various increases in auto occupancy using a method similar to that illustrated for transit increases. This is particularly applicable where

Example:
Given an auto occupancy rate of 1.33 persons/auto, then
- @ 6% transit use, auto driver trips = 71%
- @ 15% transit use, auto driver trips = 64%
- therefore, the percent change = (64 - 71) / 71 x 100 = 9.6% reduction in auto driver trips.

If the auto occupancy rate were to concurrently increase from 1.33 to 1.50 persons/auto, then:
- @ 6% transit use and 1.33 persons/auto, auto driver trips = 71%
- @ 15% transit use and 1.50 persons/auto, auto driver trips = 57%
- therefore, the percent change = (57 - 71) / 71 x 100 = 19.8% reduction in auto driver trips.

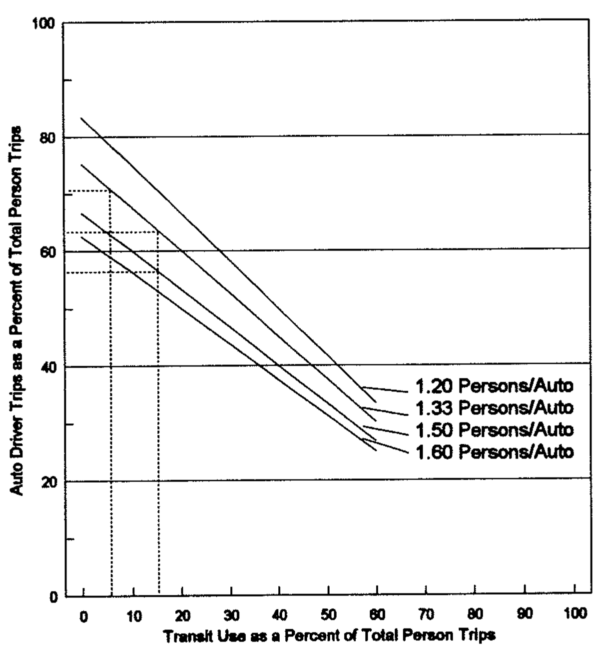


Figure 38. Effect of change in transit use on auto driver trips.

Example:
- @ 1.4 auto occupancy, auto driver trips = 71%
- @ 1.5 auto occupancy, auto driver trips = 67%
- therefore, the percent change = (67 - 71) / 71 x 100 = 6.7% reduction in auto driver trips.

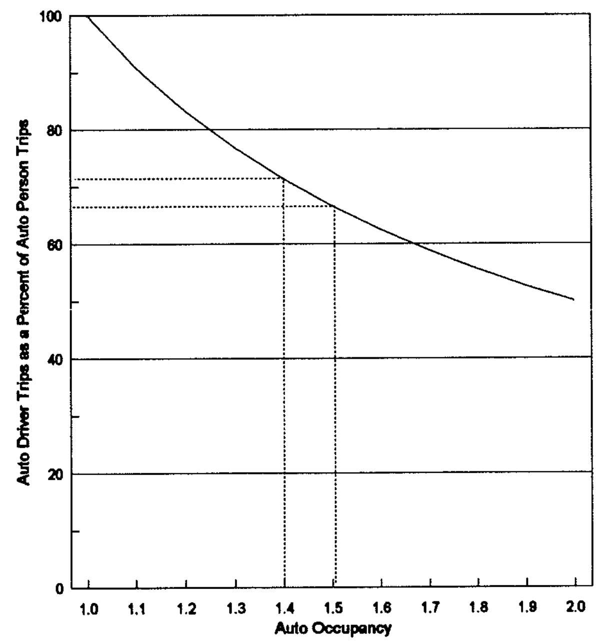


Figure 39. Effect of change in auto occupancy on auto driver trips.

vigorous carpooling and vanpooling programs are planned. Local area experience can be used as required. Present daily car occupancies range from about 1.1 for HBW trips to 1.7 for home-based social and recreation trips.

Adjustments for transit use and auto occupancy are optional, but the use of high-occupancy vehicles can affect freeway and arterial highway requirements and should be considered, if warranted.

Step 3: Computation of Vehicle-Miles of Travel

The third step is to compute vehicle-miles of travel for each analysis area by multiplying the results of Step 1 (i.e., vehicle-trip ends) by the areawide, average over-the-road vehicular trip length. The average work-trip distance can be obtained from the census sample data for individual MSAs. Alternatively, the airline trip distance can be estimated from Figure 40. The data points shown were collected in the 1960s and the average trip lengths adjusted upward to account for increased speeds and lower densities of development in urbanized areas since these data were obtained. For future years, an estimate of such corrections to be applied can be obtained from Figure 41 for home-based work trips.

To illustrate the use of Figure 41, suppose that the average network speed change is +10 percent over the base-year

Example:

For a city of 3,000,000 population, the average vehicle trip distance is approximately 4.8 airline miles.

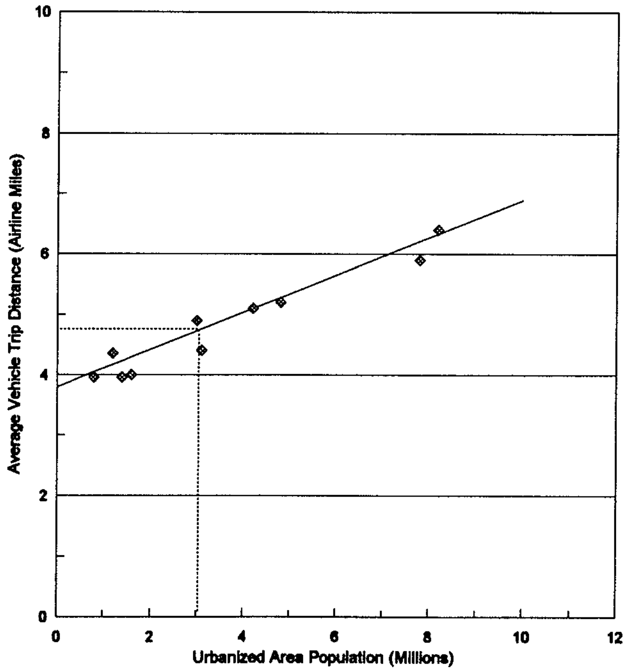


Figure 40. Average vehicle trip distance (airline) vs. urbanized area population

Example:

Assuming that the average network speed change is +10 percent for a region. (Revised/Base Speed = 1.10.)

Then, the average auto HBW trip distance change is given by (Revised/ Base Distance) = 1.15. That is, the change in average trip distance is +15 percent.

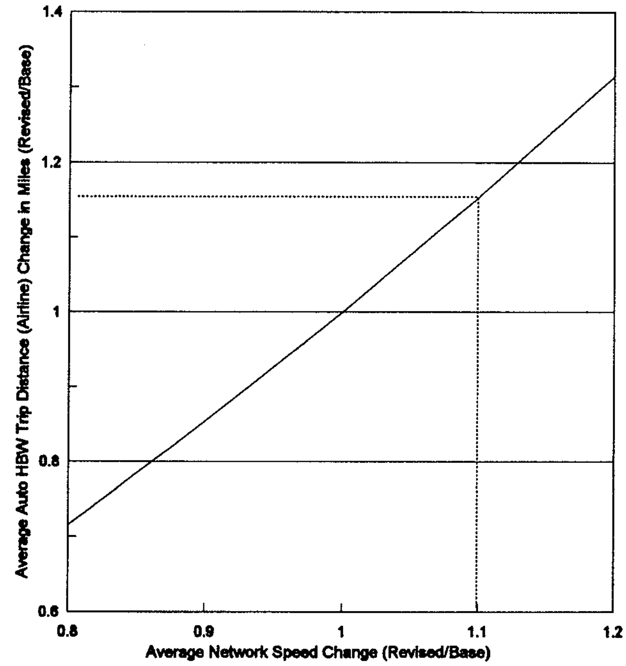


Figure 41. Adjustment to average auto home-based work trip distance (airline) for average network speed change.

conditions, that is, $S_2/S_1 = 1.10$. Entering Figure 41, the average auto HBW trip distance (airline) change would be given by $L_2/L_1 = 1.15$, that is, a change in trip distance of +15 percent.

If the average trip distance for a study area is known, it should be used. If the average HBO trip distance is estimated using Figure 42 (which relates the length of HBW and HBO trips), then by weighting the trip lengths by the amount of HBW and HBO travel, one can obtain an estimate of total trip length. For example, in Washington, D.C., the average HBW airline trip length is then 8.0 mi. Table 9 (Chapter 3) indicates that about 21 percent of all trips are for work purposes. Therefore, the daily weighted average is $[(8.0 \times 0.21) + (4.0 \times 0.79)]$, or 4.84 airline miles. Note that Figure 40 shows that the result for a city of just over 3 million population is approximately 4.8 airline miles, thus confirming the aforementioned results.

As these figures represent airline distance travel, they need to be expanded to over-the-road trip distances by multiplying by a circuity factor. This factor can range from 1.2 to 1.4 (or even higher) depending on the configuration of the highway network in the urbanized area. The presence of rivers or topographic barriers cause higher values. Thus, having obtained the areawide average over-the-road trip distance, this figure is then multiplied by the results of Step 1 (i.e., vehicle-trip ends) to compute vehicle-miles of travel by analysis area.

Step 3A: Computation of external vehicle-miles of travel adjustment. In addition to the vehicle-miles of travel generated by the residential and nonresidential activities within each analysis area, an adjustment has to be made for traffic generated *beyond* the boundaries of the study area. This adjustment, however, need only be applied to those analysis areas located on the periphery of the study area; here, the "external" traffic contributes significantly to the VMT calculated from Step 2. This correction was deemed necessary through empirical testing of the density/spacing methodology.

This external traffic is obtained from counts located at the circumference (cordon) of the analysis area in question. Note that the count must first be adjusted to account for the double-counting of through trips. Should any of the count stations be located at a freeway, such counts must be excluded altogether from the adjustment process. This is based also on empirical evidence gathered through testing of the density/spacing method.

Because some of the external trips at non-freeway cordon locations are already reflected at one end in the peripheral analysis areas, they should be reduced by half. The result is

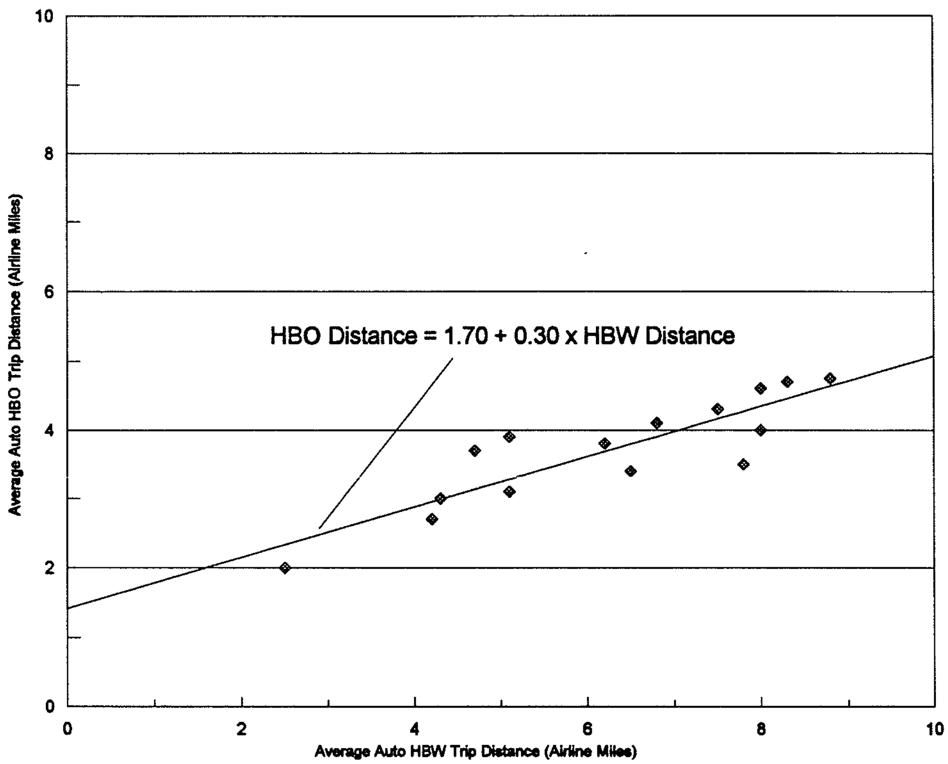


Figure 42. Relationship between auto home-based work and auto home-based non-work trip distances (airline).[2]

then multiplied by the average trip length computed from Step 3 to arrive at the external VMT. Then, this VMT owing to the external trips is added to the VMT calculated from Step 3 for the peripheral analysis area to obtain the total VMT.

Step 4: Computation of Vehicle-Miles of Travel on Freeways and Arterials

The vehicle-miles of travel computed through application of the previous steps must be accommodated by three levels of highway transportation systems; that is, freeways, arterials, and major collectors. The amount of travel that will need to be accommodated on the freeway system is a function of the spacing between freeways, the spacing of arterial and local routes, the average trip length, and the average vehicle-trip density.[3]

The relationship can be expressed as follows

$$V_1 = \frac{P\bar{r}}{2\left[\frac{1}{Z_1} + \frac{1}{\bar{r}} + \frac{Z_2}{\bar{r}(Z_1 - Z_3)}\right]} \qquad (11\text{-}1)$$

where

V_1 = average daily traffic on freeway;
P = average daily vehicle trip origins/square mile,
$\bar{r}$ = average vehicle trip distance (mi),
Z_1 = freeway spacing (mi),
Z_2 = arterial spacing (mi), and
Z_3 = local street spacing (mi).

This relationship can be used to solve for freeway spacing if desirable freeway traffic volumes are known. Then in solving for Z_1, and approximating Z_3 at 0 to simplify the solution

$$Z_1 = \frac{2V_1(\bar{r} + Z_2)}{P\bar{r}^2 - 2V_1} \qquad (11\text{-}2)$$

Figure 43 shows desirable freeway spacing based on this relationship for a 6-mile average trip length. Thus, for example, for a daily vehicle trip origin density of 14,000 trip ends/square mile, a six-lane freeway must be spaced at 4.6 mi, and an eight-lane freeway at 7.8 miles.

Given the information required[4] for the relationships previously described, either freeway volumes or spacing can

[2]Wilbur Smith and Associates, *Transportation and Parking for Tomorrow's Cities*, prepared under commission from the Automobile Manufacturers Association, New Haven, Connecticut (1969).

[3]M. Schneider, "A Direct Approach to Traffic Assignment," *Highway Research Record 6*, pp 71–75 (1963).

[4]Spacing, Z can easily be computed from the formula $Z = 2A \div L$, where L is the number of miles of route within an area A in square miles.

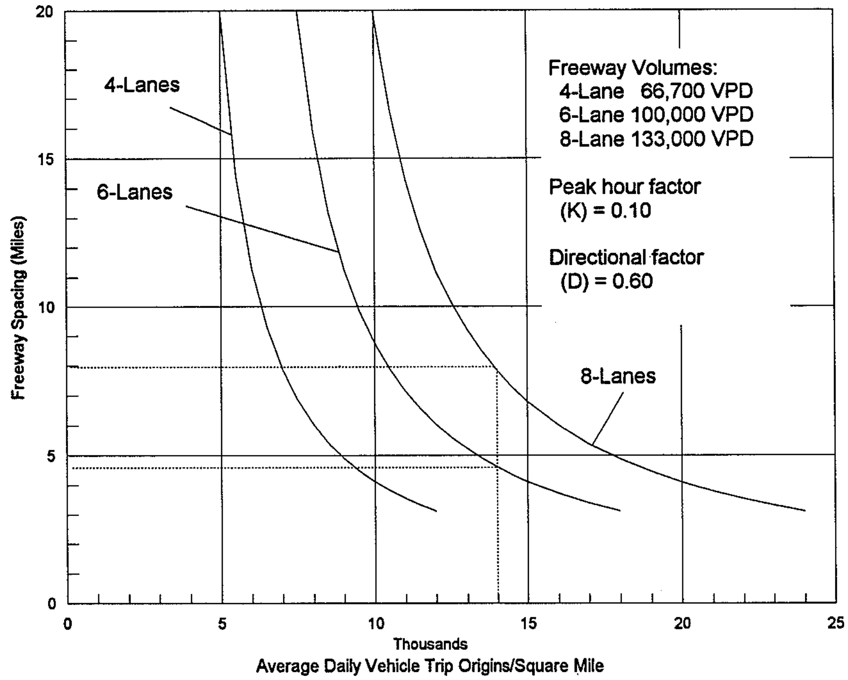


Figure 43. Freeway spacing vs. average daily vehicle trip origins per square mile.

be computed. If a specific level of service is desired, either freeway volumes, spacing, or miles of freeway can be computed. Similarly, if spacing is set (i.e., no new routes are contemplated), then the traffic volume on freeway facilities (and hence VMT) can be computed.

Subtracting this freeway VMT from the total gives the residual VMT that must be accommodated on arterial and local streets. After subtracting a percentage of the total VMT for local streets, the residual is the VMT on arterial routes.

Thus, for any analysis area other than a peripheral analysis area (i.e., not at the boundary of the metropolitan region), the arterial VMT is given by

$$\begin{aligned} \textit{Arterial VMT} &= (\textit{residential} + \textit{nonresidential})\ \textit{VMT} \\ &\quad - \textit{freeway VMT} - \textit{local VMT} \end{aligned}$$

For a peripheral analysis area (i.e., at the boundary of the metropolitan region), the arterial VMT is given by

$$\begin{aligned} \textit{Arterial VMT} &= (\textit{residential} + \textit{nonresidential})\ \textit{VMT} \\ &\quad + \textit{external VMT} - \textit{freeway VMT} \\ &\quad - \textit{local VMT} \end{aligned}$$

To compute freeway volumes or spacings, areas larger than the analysis areas (such as a subarea; i.e., a group of districts) used for arterials should be described. For example, areas on both sides of a freeway should be included.

Step 5: Computation of Average Arterial Volumes Per Lane and Level of Service

For uniform trip distributions and arterial loadings, traffic demand can be expressed as a function of arterial grid spacing and traffic volume. The relationship between traffic demand, arterial grid spacing, and traffic volume is given by the equation:

$$D = \frac{2}{S} V \tag{11-3}$$

where

D = the arterial vehicle-miles of travel per square mile,
V = the average daily traffic volume (VMT per mile of route), and
S = the distance between adjacent arterials in miles (spacing).

Volume (VMT per mile of route), although a useful indicator, is not as useful as volume per lane, because urban and suburban areas have a mix of two-, four-, and six-lane arterial facilities.

Table 65 gives the level-of-service volumes of different arterial facilities. It should be noted that two-lane arterials have a significantly lower service volume per lane than a multi-lane arterial at LOS C.

A better method, and one that is used in the example provided at the end of this chapter, is as follows:

- *The Equivalent-Lane Concept.* To relate traffic demands on different size arterial routes on an equal basis, each lane of a 4-lane arterial is set equal to 1.6 lanes of a 2-lane arterial, and each lane of a 6-lane arterial is set equal to 1.73 lanes of a 2-lane arterial. Average volumes per equivalent lane are then computed by analysis area (i.e., arterial VMT divided by equivalent lane-miles) and related to the level of service provided to the analysis area.
- *Arterial Level of Service.* Because it is not possible to calculate the traffic volume on each segment of each arterial (only an average volume can be calculated), a relationship was developed from traffic count data between the average equivalent-lane volume and the percentage of all VMT in the analysis area operating above levels of service C, D, and E. This relationship was derived from complete count data for Fairfax County, Virginia, and is displayed on Figure 44. In addition, another relationship was derived relating the percentage of route-miles over specified levels of service to the percentage of VMT over such levels of service as displayed on Figure 45. These relationships may be used to measure the level of arterial service provided.

Example:

If for an analysis area, the arterial VMT has been computed at 75,000 and the equivalent arterial lane-miles = 15, then equivalent lane volume = 75,000/15 = 5,000 VPD. Hence:

Percent VMT over Level of Service C = 93%
Percent VMT over Level of Service D = 80%
Percent VMT over Level of Service E = 66%

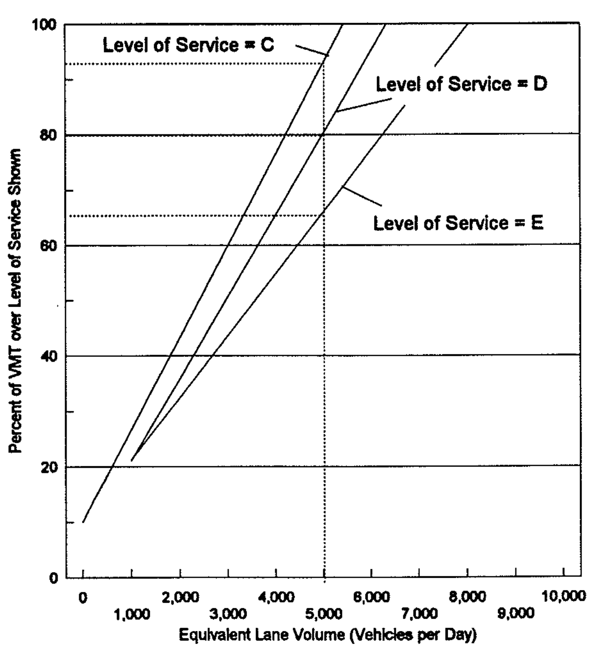


Figure 44. Arterial VMT level of service vs. equivalent lane volumes.

Determination of the number of equivalent arterial lane-miles of travel by district through the method illustrated can be used with these guidelines to aid in the design of an arterial highway system for an urbanized area. The next step is to convert the number of equivalent lanes to miles of 2-, 4-, or 6-lane facilities and space them as desired. Widening existing routes, providing HOV, or increasing transit should also be considered as appropriate.

Feedback

The process described also can be used to modify the lane-miles of arterial routes needed by subareas. The planner can reverse the process or "feedback" to prior steps by modifying inputs as desired. The following options are available:

1. Revise the level of service desired. By accepting a higher percentage of vehicle-miles of travel over a set level of service, the number of equivalent lanes can be reduced because a higher average volume per equivalent lane can be accommodated.
2. Add capacity on freeways. Adding high-type limited-access facilities or increasing capacity on such facilities in areas of high travel demands can reduce the volume on arterials.
3. Increase the use of transit or increase auto occupancy for the analysis area. See the discussion on TDM measures.

Example:

From Figure 44, percent VMT over Level of Service C = 93%.
Therefore, percent route miles over Level of Service C = 86%.

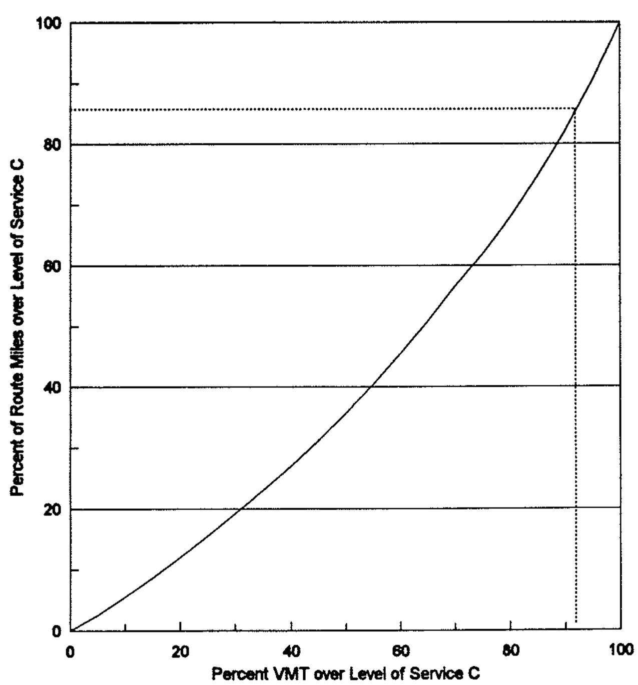


Figure 45. Relationship between level of service and route miles.

4. Reduce or reallocate land use. Reductions or reallocations of land use will reduce travel demands in areas that have low levels of service.

Testing of various options, singularly or in combination, is most useful in designing or evaluating a land use or transportation plan. This can be accomplished in a very short time using the relationships developed.

The following section provides an illustrative example to enable the user to apply the development density/highway spacing methodology described.

AN EXAMPLE APPLICATION

Suppose the transportation service in a subarea in the northeast quadrant of a hypothetical metropolitan region is to be analyzed for some future year. More specifically, given the projected land development density and the projected transportation supply in the subarea (and districts within the subarea), the objective is to determine the level of service at which the transportation system will operate for that future year. It is anticipated that improved transit and carpool programs are to be put in effect. Concurrently, the highway network itself will undergo traffic-flow improvements resulting in increased average speeds.

This example describes the use of the development-density/highway-spacing methodology. Computation steps similar to those outlined here must be executed for all districts of interest in a real application.

Input Information

Assume that the following input data are available for the metropolitan region, the study subarea, and the peripherally located study district 21. Except where noted (and where inappropriate), these input data represent the future condition.

1.	Existing population of the metropolitan region	1,200,000
2.	Area of the study subarea (sq mi)	55
3.	Area of study district 21 (sq mi)	8
4.	Residential development in district 21:	
	Single-family units (at 1 DU/acre)	5,100
	Townhouse units	2,000
	Apartment units	500
	Total number of dwelling units	7,600
5.	Nonresidential development in district 21:	
	General office (sq. ft. GFA)	100,000
	Industrial park (sq. ft. GFA)	100,000
6.	Transit use in district 21:	
	Existing (transit as a percent of total person trips)	10
	Future (transit as a percent of total person trips)	20
7.	Auto-occupancy rates in district 21:	
	Existing (persons/auto)	1.5
	Future (persons/auto)	1.6
8.	Average network speeds in metropolitan region:	
	Existing (mph)	26
	Future (mph)	29
9.	Daily through and external traffic volumes at the external count stations (excluding freeway volumes)	20,000 (vehicles)
10.	Facility mileage:	
	For district 21	
	2-lane arterials (mi)	8
	4-lane arterials (mi)	3
	6-lane arterials (mi)	12
	All arterials (mi)	23
	Freeways (mi)	6
	For study subarea	
	All arterials (including district 21) (mi)	86
	Freeways (including district 21) (mi)	18

Methodology

The density/spacing methodology is applied in a step-by-step manner as discussed in the preceding sections.

Step 1: Compute Vehicle-Trip Ends

Using the average daily vehicle-trip generation rates given in Table 3 (Chapter 3) and Method II described previously, the future one-way vehicle-trip ends for the residential and nonresidential development in district 21 are computed as follows for

$$\begin{aligned} \text{Single-family units} &= \tfrac{1}{2}(9.55 \times 5{,}100) &&= 24{,}353 \text{ trips} \\ \text{Townhouse units} &= \tfrac{1}{2}(5.86 \times 2{,}000) &&= 5{,}860 \text{ trips} \\ \text{Apartment units} &= \tfrac{1}{2}(6.47 \times 500) &&= 1{,}618 \text{ trips} \\ \text{General offices} &= \tfrac{1}{2}(11.85 \times 100) &&= 593 \text{ trips} \\ \text{Industrial park} &= \tfrac{1}{2}(6.97 \times 100) &&= 349 \text{ trips} \end{aligned}$$

Hence, the total one-way vehicle trips generated daily by the development in district 21 is given by 32,771 vehicle trips. Note that Table 3 provides vehicle trips to and from the generators (i.e., vehicle-trip ends); consequently, such trips must be halved as shown previously to obtain the one-way trips.

Step 2: Compute Transit-Use and Auto-Occupancy Adjustments

Figure 38 can be used to adjust the daily vehicle trips output from Step 1 for future improvements in transit and carpooling programs. Thus

For the existing condition, at 10 percent transit use and 1.5 persons/auto, auto-driver trips as a percent of total person-trips = 60%

For the future condition, at 20 percent transit use and 1.6 persons/auto, auto driver trips as a percent of total person-trips = 50%

Therefore, percent reduction in auto-driver trips =

$$\frac{50 - 60}{60} \times 100 = -16.7\%$$

Therefore, adjusted daily vehicle-trips = 32,771 (1 – 0.167) = 27,309

These trips represent the future internal-internal daily vehicle trips in district 21.

Step 3: Compute Vehicle-Miles of Travel

Before computing VMT, the average over-the-road trip distance must be calculated. Figure 40 enables the estimation of the average airline trip distance with respect to urbanized area population; that is, if such a measure is not available from local information. For an urbanized area of 1,200,000 existing population, Figure 40 shows that an average vehicle-trip distance of approximately 4.0 airline miles is the current measure of trip length.

Because it is expected that average network speeds will change in the future (in the ratio 29/26; i.e., 1.12), Figure 41 provides the means for estimating the corresponding changes in HBW and HBO average airline trip distance.

From Figure 41:

Adjustment factor for HBW auto trips = 1.18

Therefore,

Adjusted HBW average auto airline-trip distance = 4 × 1.18 = 4.72 mi

Adjusted HBO average auto airline-trip distance = 3.11 mi (from Figure 42)

Assuming that work trips will constitute 25 percent of all trips, then:

Weighted auto airline trip distance = [(4.72 × 0.25) + (3.11 × 0.75)] mi = 3.51 mi

Assuming a circuity factor of 1.22:

Average auto over-the-road trip distance for the metropolitan region = 3.51 × 1.22 = 4.28 mi

Average daily internal-internal vehicle miles of travel for district 21 = 27,309 × 4.29 = 117,100 VMT

Step 3A: Compute External Vehicle-Miles of Travel Adjustment. District 21 is located at the periphery of the metropolitan region, and, therefore, a significant amount of traffic within its boundary can be attributed to the traffic that has origins or destinations external to that district. This external traffic contribution must be added to the VMT from Step 3. Note that this addition of external traffic is made to traffic in districts that are peripheral to the metropolitan region. It is assumed that, for the internally located districts, the external traffic contribution is small, because most of these trips will have "dropped off" in the peripheral districts.

For district 21, daily volume of traffic at the non-freeway external count stations is 20,000 vehicles. This volume includes through trips, which must first be accounted for. Table 16, Chapter 5, shows that for an urban area with a population of 1,200,000, approximately 13 percent of external vehicle trips are through trips. Reference to the example for the conversion of cordon counts to external trips shows that

$$\text{External trips} = \frac{\text{Cordon Count}}{(1 + \text{Proportion of Through Trips})}$$

Hence

$$\text{External trips} = \frac{20{,}000}{\left(1 + \frac{13}{100}\right)} = 17{,}700 \text{ vehicles}$$

Because many of these trips are accounted for by the population and employment trip estimates made for the districts, the external trips are reduced by one-half.

Therefore

Average daily external vehicle-miles of travel = ½(17,700) × 4.29 mi = 37,900 VMT

Average daily total VMT in district 21 = 117,100 + 37,900 = 155,000 VMT

At this point, the planner must be reminded that Steps 1 through 3 must be accomplished for all the eight study districts in the study subarea. For illustrative purposes, assume the following daily total VMTs have been calculated for the eight districts.

$$\textit{Arterial spacing } Z_2 = \frac{2 \times 55}{86} = 1.3 \textit{ mi}$$

Local spacing Z_2 =
0 *mi (assumption for ease of calculation)*

So, using equation 11-1, average daily traffic on the freeways, V_1, in the subarea is given by

$$V_1 = \frac{\frac{945{,}600}{55}}{\left[\frac{1}{6.1} + \frac{1}{4.4} + \frac{1.3}{4.4(6.1)}\right]} = 19{,}553 \textit{ vehicles}$$

Note that 953,700 ÷ 55 (i.e., average daily total VMT for subarea ÷ area of subarea) is the numerator $P\bar{r}$ in Equation 11-1. Also, 4.4 is the average auto over-the-road trip distance (miles) for the metropolitan region.

For the study subarea, then:

$$\textit{Freeway VMT} = V_1 \times \textit{freeway mileage} = 19{,}553 \times 18 = 352{,}000 \textit{ VMT}$$

Therefore, since

$$\textit{Arterial VMT} = \textit{subarea total VMT} - \textit{freeway VMT} - \textit{local VMT}$$

District Number	Calculated Average Daily Total VMT	Percent Subarea Total VMT
18 *	120,200	12.7%
19 *	135,700	14.4
20	96,800	10.2
21 *	155,000	16.4
22	110,900	11.7
23	80,100	8.5
24	95,000	10.0
25 *	151,900	16.1
Subarea total VMT	945,600	100%

* Peripheral districts requiring addition of external station VMT.

Step 4: Compute VMT on Freeways and Arterials

To calculate arterial VMT in district 21, first obtain the freeway VMT in the entire study subarea by employing Equation 11-2. This equation requires measures for freeway spacing (Z_1 mi), arterial spacing (Z_2 mi), and local spacing (Z_3 mi) as input. Thus, for the whole subarea:

Freeway spacing,

$$Z_1 = \frac{2A}{L}; \quad \textit{i.e.,} \quad \frac{2\ (\textit{study subarea})}{\textit{freeway mileage}} = \frac{2 \times 55}{18} = 6.1 \textit{ mi}$$

and if it is assumed that 10 percent of all subarea VMT is on local streets, then

$$\textit{Arterial VMT} = 945{,}600 - 352{,}000 - (0.10 \times 945{,}600 \textit{ VMT}) = 499{,}000$$

This subarea arterial VMT can then be distributed to each of the eight districts within the study subarea in proportion to the distribution of the total VMT (derived earlier). Then, the arterial VMT by district is as follows:

District Number	% Subarea Total VMT	Proportioned Arterial VMT
18	12.7%	63,400
19	14.4	71,600
20	10.2	51,100
21	16.4	81,800
22	11.7	58,500
23	8.5	42,300
24	10.0	50,100
25	16.1	80,200
Subarea Arterial VMT	100.0%	499,000

Thus for study district 21, the average daily arterial VMT that can be expected is 82,100 VMT.

Step 5: Compute Average Arterial Volumes Per Lane and Level of Service

To determine the level of service provided by the arterial network in district 21, the equivalent lane-miles must first be calculated. (See previous section in this chapter, The Equivalent Lane Concept.) Now,

$$\textit{Equivalent lane-miles} = 1.00\ (2\textit{-lane arterial mileage}) + 1.60\ (4\textit{-lane arterial mileage}) + 1.73\ (6\textit{-lane arterial mileage})$$

Therefore

$$\textit{Equivalent lane-miles} = 1.00(8) + 1.60(3) + 1.73(12) = 33.56\ \textit{lane-miles}$$

Therefore

$$\textit{Equivalent arterial lane volume} = \frac{\textit{Average daily arterial VMT}}{\textit{Equivalent arterial lane-miles}}$$

$$= \frac{81,800}{33.56} = 2,437\ \textit{vehicles/day}$$

For 2,437 average daily vehicles per equivalent lane, the following level-of-service results can be obtained (for district 21):

- VMT over Level-of-Service C = 51%
- VMT over Level-of-Service D = 42%
- VMT over Level-of-Service E = 36%

Next, Figure 45 can be entered to determine the percent of arterial route-miles operating over level-of-service C. Hence, 37 percent of the arterial mileage in District 21 can be expected to operate over level-of-service C.

Output Information

It can be seen that the development density/highway spacing methodology, as applied previously, yields the freeway VMT, the arterial VMT, and the level of service provided by the transportation network in district 21 for some future year. The remaining seven districts in this study subarea can be similarly analyzed.

CHAPTER **12**

CASE STUDY APPLICATION OF DEFAULT PARAMETERS

INTRODUCTION

Throughout this report we have used a case study to illustrate the application of the parameters and techniques described in various chapters of the report. The data included in this case study were provided by the State of North Carolina for the City of Asheville, North Carolina. The applications of the study parameters and techniques introduced in Chapters 1 through 9 have been applied to this case study and presented at the conclusions of the chapters. The case study has allowed the user to follow the development and application of the travel forecasting model beginning with the data collection phase. Subsequent chapters followed the model development process through trip generation, trip distribution, and, ultimately, the final traffic assignment.

This final chapter of the report presents the case study in its entirety, from data collection through traffic assignment. The material in this chapter is presented in the order in which it should be collected, processed, and analyzed.

TRANSPORTATION DATABASE

In Chapter 2, we introduced the transportation database for the Asheville, North Carolina, test case. The Asheville Metropolitan Statistical Area (MSA) lies in the western quarter of the state of North Carolina, roughly 230 miles west of the state capital in Raleigh and 110 miles east of Knoxville, Tennessee. As defined by the U.S. Census Bureau, the region consists of the City of Asheville and surrounding Buncombe County. In 1990, the entire MSA had a population of 174,821, and the City of Asheville had a population of 110,429.

Figure 46 displays a base map for the Asheville region. Asheville's transportation network consists primarily of its roadway system and the City Coach bus service, a twelve route transit system operated by the Asheville Transit Authority. Two U.S. Interstate routes meet just south of the City of Asheville: I-40, running east to west, and I-26, which connects Asheville to Atlanta. A belt-line, I-240, makes a half-circle around the City to its northern side. As of 1991, City Coach carried fewer than 4,000 daily passengers, approximately 1 percent of the daily person trips made in the Asheville area. The remainder of the daily person trips on the transportation network were made in private vehicles.

Socioeconomic Data

The trip generation equations require socioeconomic and land-use data to describe the quantity and type of travel activity in the region. Required land-use data include the following: number of households by size; household income or auto ownership; and employment by type. These data should be allocated throughout the region according to a traffic analysis zone (TAZ) structure that is appropriate for the level of analysis and the detail in the selected network.

The North Carolina Department of Transportation (NCDOT) originally developed the Asheville TAZs. Their zone system contains 353 internal zones and 36 external stations. NCDOT compiled household and employment data for the MSA at the 353 TAZ level of detail. A review of the NCDOT zone structure revealed that it provided more detail than was needed for the case study example, which is intended to forecast traffic volumes only on the major roadways. The 353 zones were aggregated into 107 internal zones and 16 external stations for the case study. Figure 47 displays the revised zone structure with 107 internal TAZs. This zone system is somewhat coarse but should be sufficient for forecasting traffic volumes on the major roadways.

The socioeconomic data for this case study were extracted from the 1990 U.S. Census. Serial Tape File (STF) 3-A was downloaded from the North Carolina State Library. These data included the following summary information:

- Household income by household size,
- Median household income,
- Number of persons in household,
- Mode of travel to work,
- Time of departure from work, and
- Private vehicle occupancy for work trips.

These census data revealed that the study area contains a population of approximately 110,000 persons in 46,492 households. The household data for the 107 internal zones of the Asheville study area are tabulated in Appendix B-1.

The household and income data were collected for use in the trip generation equations to calculate the person-trip *productions*. Person-trip *attractions*, on the other hand, are based on employment data, stratified by type of employment. The NCDOT data provided for this study were divided into several different sectors according to the Standard

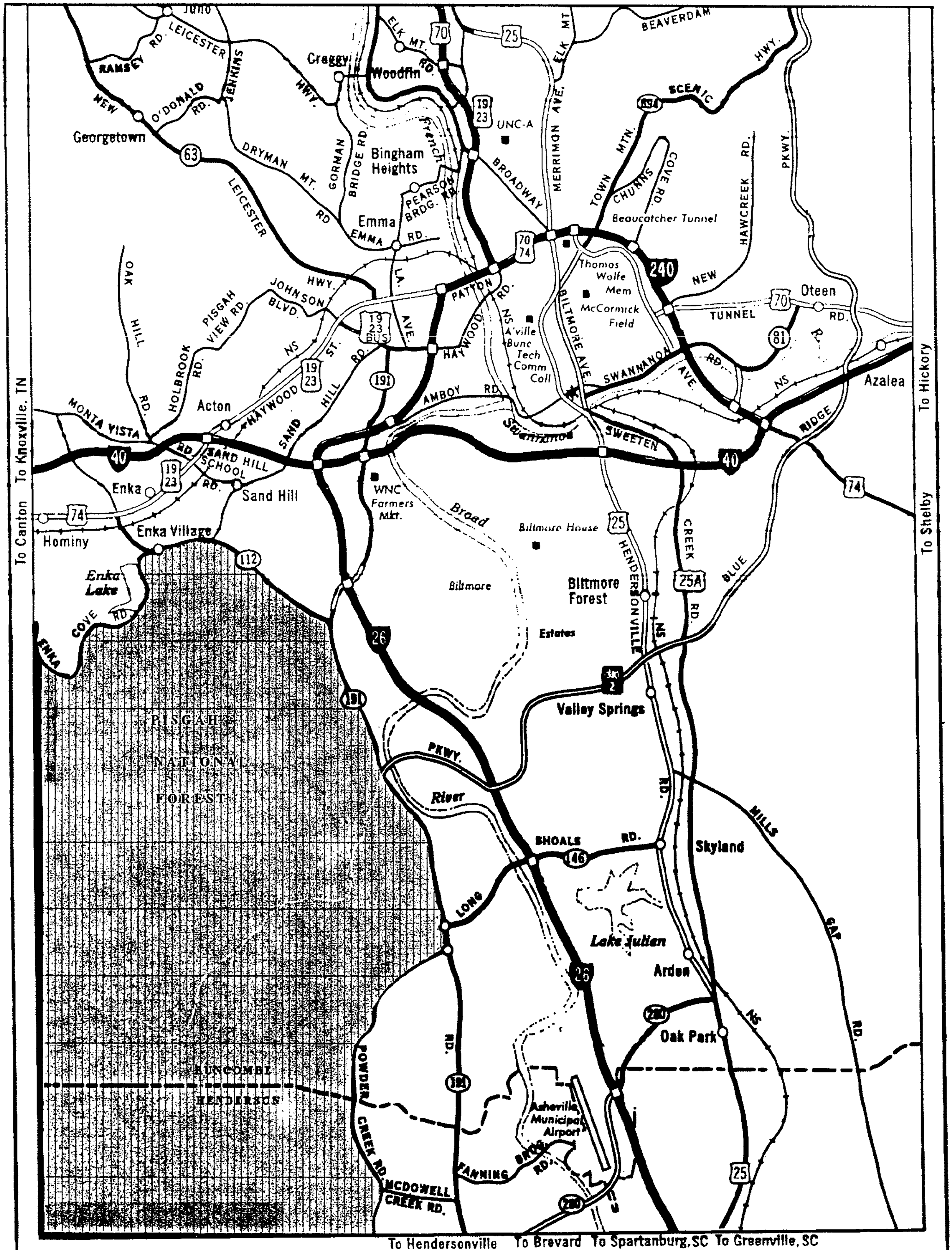


Figure 46. Asheville, North Carolina, map.

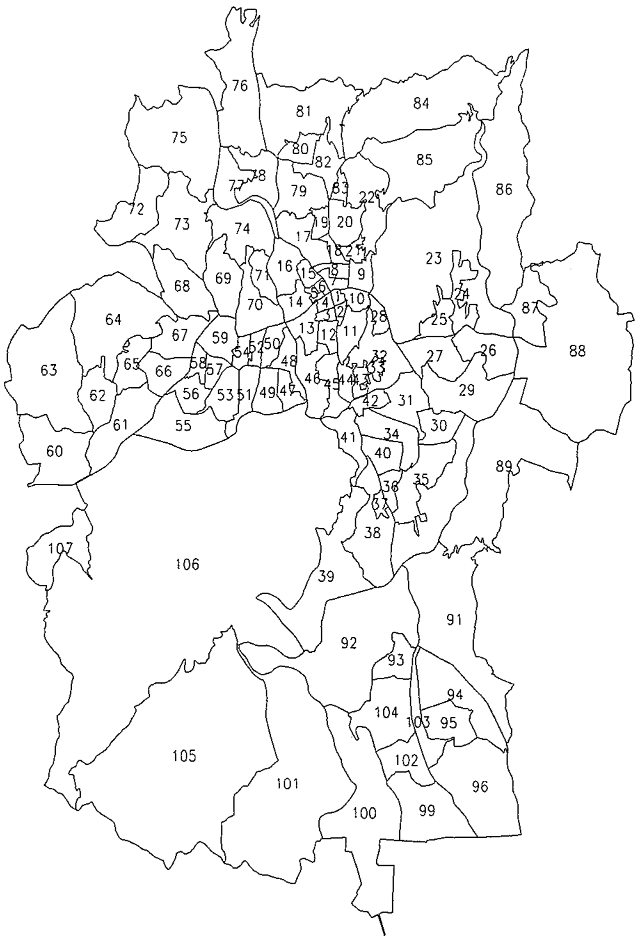


Figure 47. Asheville, North Carolina, TAZs.

Industrial Classification land use code. Total employment for the MSA is estimated at 59,037 by NCDOT's surveys. The employment data for the 107 internal zones of the Asheville study area are tabulated in Appendix B-2.

Network Description

The highway network for the region was acquired from NCDOT as a downloaded file on disk, which was then input directly into the transportation modeling software package. Each link in the network was then coded with a facility classification (freeway, major arterial, or minor arterial), number of exclusive lanes in the direction of travel, the free-flow speed, and the hourly per-lane capacity of the roadway.

As summarized in Table 66, the base highway network consists of 1,156 regular nodes connected by 168 freeway links, 922 major arterial links, and 1,550 minor arterial links. After the regular nodes were connected by links defined to represent actual highways, centroid connectors were added to allow the 107 internal centroids and the 16 external stations access to the highway network. (If we were planning to model the transit volumes on the local bus routes, we would have used the highway network as the base for building a transit network. However, given the fact that only 1 percent of the person trips in the Asheville MSA use transit, that component of the transportation network was ignored.)

Figure 48 is a plot of the coded base highway network, including all link types except centroid connectors.

Traffic Count Data

NCDOT also provided a selected count map, which displays total daily vehicle volumes for a variety of intersections and cordon points. These counts, summarized in Table 67, were used to provide average daily traffic (ADT) at the 16 facilities crossing the external cordon around the Asheville region. These ADT counts were collected at all locations where significant traffic volumes flow into or out of the region.

TRIP GENERATION

The techniques described in Chapter 3 were followed to obtain trip productions and attractions.

Trip Productions

The estimation of trip productions using disaggregate travel demand models typically uses a cross-classification of household size data with a measure of wealth, such as income or the number of automobiles available to the household. For this case study, however, no cross-tabulations were yet available from the Census Transportation Planning Package for the Asheville region. As a result, trip production rates were calculated by using the average values for the region, stratified only by household size. The average daily vehicle trips per household were calculated using the rates shown in Table 68.

Since the trip productions are classified according to trip purpose, the information regarding trip purpose by household size was also used. Table 69 lists the percent of trips by purpose and household size.

The calculation of trip productions was performed using a computer spreadsheet. The input data were arranged in five columns reflecting the household size groupings from one-person households through five-plus-person households. The output data are the three columns reflecting the trip purposes—home-based work, home-based other, and non-home-based. The person trip calculations are expressed by the following formulas:

Home-Based Work Productions =

$$0.20 \times 3.7 \times HH(1) + 0.22 \times 7.6 \times HH(2) + 0.19 \times 10.6 \times HH(3) + 0.19 \times 13.6 \times HH(4) + 0.17 \times 16.6 \times HH(5)$$

TABLE 66 Base network summary

Nodes		Quantity		
Zone Centroids (Internal)		107		
Zone Centroids (External)		16		
Regular Nodes		1,156		
Total Nodes		1,279		
Link Type	**Description**	**Quantity**	**Free-Flow Speed (mph)**	**Capacity Veh. per Hr.**
1	Freeway	168	55	1350
2	Major Arterial	922	45	825
3	Minor Arterial	1,550	35	825
4	Centroid Collector	632	20	-
Total Links		3,272		

$$\textit{Home-Based Other Productions} = 0.54 \times 3.7 \times HH(1) + 0.54 \times 7.6 \times HH(2) + 0.56 \times 0.6 \times HH(3) + 0.58 \times 13.6 \times HH(4) + 0.62 \times 16.6 \times HH(5)$$

$$\textit{Non-Home Based Work Productions} = 0.26 \times 3.7 \times HH(1) + 0.24 \times 7.6 \times HH(2) + 0.25 \times 10.6 \times HH(3) + 0.23 \times 13.6 \times HH(4) + 0.21 \times 6.6 \times HH(5+)$$

where

$HH(n)$ = the number of households with n occupants.

These equations were used to calculate the trip productions for each of the 107 internal zones in the Asheville MSA. The total number of trip productions estimated for the region is 383,006, which includes 76,033 HBW productions, 215,407 HBO productions, and 91,566 NHB productions.

Trip Attractions

Trip attractions were also calculated on a spreadsheet using the parameters from Table 8.

The input data for these calculations include the employment by type—specifically retail, service, and other employment—and the total households for each of the 107 TAZs within the study area.

The home-based work trip attractions for all 107 internal zones were calculated using the following equation:

$$\textit{Home-Based Work Attractions} = 1.45 \times \textit{Total Employment}$$

For the other two trip purposes, home-based other and non-home-based, two different equations were used for calculating the number of attractions for each TAZ, depending on whether the zone is within the CBD. In the City of Asheville, zones 1 through 15 are considered to be within the CBD, and the remaining zones (from 16 through 107) are considered to be in the non-CBD category.

The trip attraction rates for CBD zones 1 through 15 were calculated using the following equations:

$$\textit{Home-Based Other Attractions} = 2.0 \times RE + 1.7 \times SE + 0.5 \times OE + 0.9 \times TH$$

$$\textit{Non-Home Based Attractions} = 1.4 \times RE + 1.2 \times SE + 0.5 \times OE + 0.5 \times TH$$

The trip attraction rates for non-CBD zones 16 through 107 were calculated using the following equations:

$$\textit{Home-Based Other Attractions} = 9.0 \times RE + 1.7 \times SE + 0.5 \times OE + 0.9 \times TH$$

$$\textit{Non-Home Based Attractions} = 4.1 \times RE + 1.2 \times SE + 0.5 \times OE + 0.5 \times TH$$

where

RE = retail employment;
SE = service employment;
OE = other employment; and
TH = total households.

For all internal zones, the trip attractions in the region totaled 383,741, of which 85,604 were HBW trips, 188,806 were HBO trips, and 109,331 were NHB trips. These totals reflect the unbalanced attractions before they are matched to the productions in the region. Appendix Table B-3 lists the productions and attractions for the three trip purposes for each of the 107 internal TAZs.

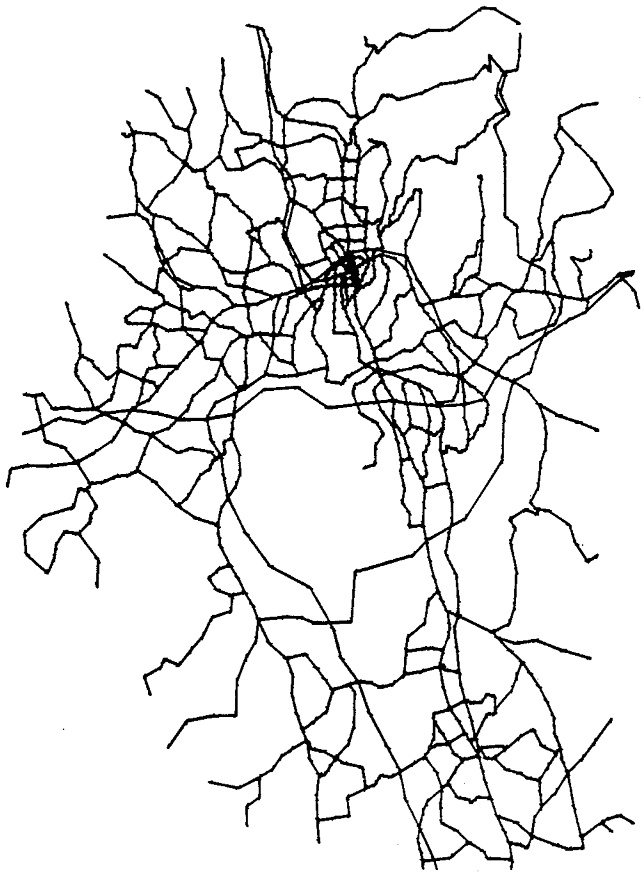


Figure 48. Base highway network.

EXTERNAL TRAVEL

As was discussed in Chapter 5, external trips can be divided into two categories: (1) external-external or through trips, which pass completely through the region without having a trip-end within the region; and (2) external-internal trips, which have one trip-end within the region and one trip-end outside of the region. The external-internal trips were converted to person trip-ends and incorporated into the regional trip generation model, while the external-external trips were expressed as a separate vehicle-trip table that was added to the other vehicle-trip tables before assignment.

The procedures used to estimate external travel for the Asheville case study are listed below. All of the calculations were performed with the aid of a computer spreadsheet program.

Classification of External Stations

ADT counts were collected at all locations where significant traffic volumes flow into or out of the Asheville region. Each of the 16 external stations selected were classified as either a minor arterial, a principal arterial, or an interstate facility. In addition, continuous facilities were noted for pairs of external stations that would be expected to carry a statistically significant share of external-external traffic. The most notable continuous pairs in the Asheville region are between stations 109 and 117, which connect the Route 19/23 bypass in the north to Interstate 26 in the south, and stations 114 and 121, which connect the eastern and western extremes of Interstate 40.

Estimation of Through-Trip Percentages

The synthetic procedures outlined in Chapter 5 for estimating the share of external cordon trips that are likely to be through trips are appropriate only for urbanized areas with less than 50,000 in population. Therefore, local experience was relied upon to estimate the through-trip making potential for the Asheville region. This experience was used to classify four facilities, each carrying ADT volumes of greater

TABLE 67 External stations

Station No.	Description	1989 ADT	Classification
108	Route 251	1,800	Minor
109	Routes 19 & 23 Bypass	27,700	Principal
110	Routes 19 & 23 Business	7,000	Minor
111	BRP (N)	2,850	Minor
112	Snope Creek Road	2,000	Minor
113	Route 70	16,100	Principal
114	I-40 (E)	24,700	Interstate
115	Route 74	11,000	Minor
116	Route 25	12,450	Minor
117	I-26	33,100	Interstate
118	Routes 191 & 280	7,400	Minor
119	BRP (S)	970	Minor
120	Route 151	1,550	Minor
121	I-40 (W)	27,500	Interstate
122	Leicester Highway	14,000	Principal
123	Bear Creek Road	3,940	Minor

TABLE 68 Trip productions by household size

Household Size	Average Person-Trips per Household
One Person	3.7
Two Person	7.6
Three Person	10.6
Four Person	13.6
Five+ Person	16.6
Weighted Average	9.2

than 20,000, as interstate facilities which were estimated to contribute 30 percent of their traffic to the external-external trip table. Two other facilities, designated as principal arterials, were estimated to have a 10 percent through-trip share. The remainder of the external stations were designated as minor arterials and were assumed to contribute a negligible share of their ADT volumes to the through-trip table.

Table 70 displays the external station volumes, including the estimated number of through trips and internal-external trips. All of the data in this table reflect vehicle trips, since they are based upon existing traffic count data.

Distribution of Through Trips to External-External Trip Table

The distribution of through trips between stations was estimated using Equations 5-2, 5-3, and 5-4. The relative shares were first calculated as in the following example for the interchange between external stations 109 and 117, which represent the eastern and western extremities of I-40 within the study area:

$$Y_{ij} = -2.70 + 0.21 \times PTTDES_j + 67.86 \times RTECON_{ij}$$
$$= -2.70 + 0.21 \times 30 + 67.86 \times 1 = 71.46$$

where $i = 109$ and $j = 117$. The calculations for the other external station pairs are displayed in Appendix B-4.

The relative shares for each of the possible destinations from a cordon station were added together, and the result was used to adjust, or normalize, the raw shares. Table 71 displays the raw shares and the normalized shares for each of the potential destinations for through trips entering the region at each of the six interstate and principal external stations.

Next, the normalized shares were used to distribute the through trips entering the study area at these stations to the other five external stations that contribute a significant number of through trips to the external-external trip table. For station 109, the adjusted shares were used to distribute the 8,310 through trips originating at that station to the other five stations. The same procedure was used to distribute the through trips originating at those other five interstate and principal external stations. The results of this process are displayed in Table 72. Note that, for intuitive reasons, there are no *intrazonal* trips within the external zones. Similarly, there are no trips allowed between stations 113 and 114, which are proximate parallel facilities unlikely to attract trips from one another.

Since the values arrived at in Table 72 are not symmetrical (i.e., the number of trips from station *i* to station *j* is not equal to the number of trips from *j* to *i*) the next step was to average the *ij* and *ji* values to produce a symmetrical trip table. For example, since the estimated value from station 109 to station 117 is 7,031, and the value from station 117 to 109 is 8,402, the average value between stations 109 and 117 is 7,717. The result of this exercise is displayed in Table 73, the symmetrical trip table.

Unfortunately, the symmetrical through-trip table in Table 73 is a trip table in which the row totals and column totals are not equal to the through volumes estimated in Table 70. The recommended solution to this problem was to apply the Fratar technique to the symmetric trip table, using the through-trip volumes in Table 70 as the row and column

TABLE 69 Percentage of trips by purpose and household size

Household Size	Percent of Average Daily Person Trips HBW	HBO	NHB
One Person	20	54	26
Two Person	22	54	24
Three Person	19	56	25
Four Person	19	58	23
Five+ Person	17	62	21
Weighted Average	20	57	23

TABLE 70 External station through-trip summary

Station Number	Description	1989 ADT	Classification	Percent Through	External-External	Internal-External
108	Route 251	1,800	Minor	0	0	1,800
109	Routes 19 & 23 Bypass	27,700	Interstate	30	8,310	19,390
110	Routes 19 & 23 Business	7,000	Minor	0	0	7,000
111	BRP (N)	2,850	Minor	0	0	2,850
112	Snope Creek Road	2,000	Minor	0	0	2,000
113	Route 70	16,100	Principal	10	1,610	14,490
114	I-40 (E)	24,700	Interstate	30	7,410	17,290
115	Route 74	11,000	Minor	0	0	11,000
116	Route 25	12,450	Minor	0	0	12,450
117	I-26	33,100	Interstate	30	9,930	23,170
118	Routes 191 & 280	7,400	Minor	0	0	7,400
119	BRP (S)	970	Minor	0	0	970
120	Route 151	1,550	Minor	0	0	1,550
121	I-40 (W)	27,500	Interstate	30	8,250	19,250
122	Leicester Highway	14,000	Principal	10	1,400	12,600
123	Bear Creek Road	3,940	Minor	0	0	3,940

targets. The ultimate result of the FRATAR process is the final external-external vehicle-trip table, as displayed in Table 74.

Conversion of Internal-External Trips to Person-Trip Productions and Attractions

In order to estimate the internal-external vehicle-trip totals, the through-trip totals were subtracted from the external station totals as shown previously in Table 70. Next, the external trip purpose factors were applied to the external-internal totals. Local experience in the region was used to estimate that the traffic crossing the external cordon is composed of 40 percent home-based work trips, 40 percent home-based other trips, and 20 percent non-home-based trips. Local experience was then used to further estimate that the Asheville area is a net importer of work trips, by a ratio of 70 to 30 and that the region is a net importer of other home-based trips by a ratio of 60 to 40. As usual, non-home-based trips were assumed to be balanced between productions and attractions.

Finally, auto-occupancy factors (from Chapter 7) of 1.11 persons per vehicle for home-based work trips, 1.67 persons per vehicle for home-based other trips, and 1.66 persons per vehicle for non-home-based trips were used to convert the vehicle trips into person trips. The resulting estimates of trip productions and attractions for external stations in the Asheville region are summarized in Table 75. This table shows that the estimated 157,150 external-internal vehicle trips crossing the cordon around the Asheville region carried 226,925 person trips, including 137,915 productions (trips from locations outside the region) and 89,010 attractions (trips to locations outside the region).

BALANCING PRODUCTIONS AND ATTRACTIONS

The final step in the trip generation phase of travel demand forecasting is the balancing of regional trip productions and attractions. The trip distribution phase of the travel demand forecasting process requires that the total number of regional trip productions equals the total number of regional trip attractions for each of the trip purposes. Table 76 summarizes the internal-trip and external-trip totals before balancing.

The regional control totals for productions and attractions of all three trip purposes were set to equal the combined internal plus external trip productions. For example, the control total for home-based work trips was set at 124,875 trips. The balancing process was accomplished by applying a balancing factor to the attraction trips for all internal TAZs. The balancing factor is intended to change the total number of internal attractions so that the total number of attractions, including external stations, equals the total number of productions. Following the example for home-based work trips, the goal was to factor the 85,604 internal HBW trips so that the total number of attractions equalled the total number of productions. In order to factor the 106,536 total HBW attractions to equal the 124,875 productions, the internal HBW attractions had to be factored to equal 124,875 minus the number of external HBW attractions (since external trips are based on existing traffic volumes, they were not factored). The balancing factor for HBW trips was therefore calculated as

$$HBW\ Factor = \frac{124{,}875 - 20{,}932}{85{,}604} = 1.2142$$

Similarly, balancing factors were calculated for the other trip purposes as follows:

TABLE 71 Through-trip distribution—raw and normalized percentages

Destination Station	Origin Station 109	113	114	117	121	122
Raw Percentages						
109	—	3.60	3.60	71.46	3.60	3.60
113	3.23	—	—	3.23	3.23	3.23
114	3.60	—	—	3.60	71.46	3.60
117	71.46	3.60	3.60	—	3.60	3.60
121	3.60	3.60	71.46	3.60	—	3.60
122	2.56	2.56	2.56	2.56	2.56	—
Total	84.46	13.36	81.22	84.46	84.46	17.63
Norm. Factor	1.184	7.483	1.231	1.184	1.184	5.671
Normalized Percentages						
109	—	26.94	4.43	84.61	4.26	20.42
113	3.83	—	—	3.83	3.83	18.33
114	4.26	—	—	4.26	84.61	20.42
117	84.61	26.94	4.43	—	4.26	20.42
121	4.26	26.94	87.98	4.26	—	20.42
122	3.03	19.18	3.16	3.03	3.03	—
Total	100.00	100.00	100.00	100.00	100.00	100.00

$$HBO\ Factor = \frac{278{,}393 - 41{,}990}{188{,}806} = 1.2521$$

$$NHB\ Factor = \frac{117{,}652 - 26{,}087}{109{,}331} = 0.8375$$

After the balancing factors were applied, the total numbers of productions were calculated as summarized in Table 77. The total number of attractions calculated for the internal and external zones is 520,920, which matches the total productions for the region.

The final step in trip balancing involved updating the non-home-based productions. Remembering that the NHB trips that are made by the residents of a household do not have either trip-end at the household (that is why they are called non-home-based trips), the non-home-based trip productions were replaced by the distribution associated with the non-home-based attractions. In other words, the calculation of the number of non-home-based productions was performed for the sole purpose of calculating the total number of non-home-based trips for the region. The distribution of trip-end locations is best estimated for both productions and attractions using the NHB attraction equations.

TABLE 72 Through-trip table—asymmetrical

Destination Station	Origin Station 109	113	114	117	121	122	Total
109	—	434	328	8,402	352	286	9,802
113	318	—	—	380	316	257	1,271
114	354	—	—	423	6,981	286	8,044
117	7,031	434	328	—	352	286	8,431
121	354	434	6,519	423	—	286	8,016
122	252	309	234	301	250	—	1,347
Total	8,310	1,610	7,410	9,930	8,250	1,400	36,910

TABLE 73 **Through-trip table—symmetrical**

Destination Station	Origin Station 109	113	114	117	121	122	Total
109	—	376	341	7,717	353	269	9,056
113	376	—	—	407	375	283	1,440
114	341	—	—	376	6,750	260	7,727
117	7,717	407	376	—	387	294	9,180
121	353	375	6,750	387	—	268	8,133
122	269	283	260	294	268	—	1,373
Total	9,056	1,440	7,727	9,180	8,133	1,373	36,910
Target	8,310	1,610	7,410	9,930	8,250	1,400	36,910
Adj. Factor	0.918	1.118	0.959	1.082	1.014	1.019	

The balanced productions and attractions for the three trip purposes are listed in Appendix B-5. At this point, these values for the productions and attractions were ready to be used in the trip distribution phase of model development in order to prepare the person-trip tables. Therefore, the production and attraction data were imported into the travel demand forecasting software and saved in three origin vectors for the production data for the three trip purposes and three destination vectors for the attraction data for those same trip purposes.

TRIP DISTRIBUTION

The trip distribution process and subsequent steps were performed twice during the course of the Asheville case study. The first time through the process was intended to estimate baseline traffic volumes that result from the assignment of a trip table based on free-flow speeds on the highway network. The second run was designed to use congested travel times resulting from the first run as the measure of impedance for the second application of the trip distribution model.

Free-flow times, or impedances, were used to perform the first distribution of trips for the three trip purposes. The resulting person-trip tables were then converted to vehicle trips, which in turn were combined to build a daily vehicle-trip table. This table was then assigned to the highway network using an equilibrium assignment. The result of this assignment was a set of traffic volumes and congested speeds for each link in the highway network. These congested speeds were subsequently used to produce a second matrix of congested travel times, which were used to perform a second application of the trip distribution model, which resulted in the ultimate trip distribution and traffic assignment.

Estimation of Free-Flow Travel Times

The free-flow zone-to-zone travel time matrix was constructed using the default speeds posted on each link in the Asheville highway network. Speeds were set at 55 mph on freeways, 45 mph on major arterials, and 35 mph on minor arterials. Travel time was calculated using the simple relationship:

TABLE 74 **Through-trip table—Fratared**

Destination Station	Origin Station 109	113	114	117	121	122	Total
109	—	222	167	7,526	243	152	8,310
113	222	—	—	676	439	273	1,610
114	167	—	—	515	6,521	207	7,410
117	7,526	676	515	—	746	467	9,930
121	243	439	6,521	746	—	301	8,250
122	152	273	207	467	301	—	1,400
Total	8,310	1,610	7,410	9,930	8,250	1,400	36,910

TABLE 75 External-internal person-trip productions and attractions

Station Number	Productions			Attractions		
	HBW	HBO	NHB	HBW	HBO	NHB
108	559	721	299	240	481	299
109	6,026	7,772	3,219	2,583	5,181	3,219
110	2,176	2,806	1,162	932	1,870	1,162
111	886	1,142	473	380	762	473
112	622	802	332	266	534	332
113	4,503	5,808	2,405	1,930	3,872	2,405
114	5,374	6,930	2,870	2,303	4,620	2,870
115	3,419	4,409	1,826	1,465	2,939	1,826
116	3,869	4,990	2,067	1,658	3,327	2,067
117	7,201	9,287	3,846	3,086	6,191	3,846
118	2,300	2,966	1,228	986	1,977	1,228
119	301	389	161	129	259	161
120	482	621	257	206	414	257
121	5,983	7,715	3,196	2,564	5,144	3,196
122	3,916	5,050	2,092	1,678	3,367	2,092
123	1,225	1,579	654	525	1,053	654
Total Person Trips	48,842	62,986	26,087	20,932	41,990	26,087

$$\textit{Travel Time (in minutes)} = \textit{Link Length (in Miles)} \times \frac{60}{\textit{Speed (in mph)}}$$

The transportation planning software was used to produce the matrix of travel times, or highway skims, based on the minimum time path between each pair of zones. These free-flow travel times were based on speed and distance only; no volume delay was included.

Intrazonal Times

The free-flow matrix, as produced in the previous step, did not contain any intrazonal travel times, which represent the travel time required to make a trip wholly within a single TAZ. An intrazonal travel time matrix, which is represented by the diagonal of the 107 by 107 matrix of internal zones, was produced using the nearest-neighbor method. This consisted of identifying the zones adjacent to each of the 107 internal zones, taking the free-flow travel time from the zone of interest to all adjacent zones, calculating a mean for that set of times, and halving that value to arrive at the assumed intrazonal travel time. These steps resulted in intrazonal times ranging from 0.54 minute to 4.33 minutes, with an average value of 1.85 minutes.

Terminal Times

Terminal times represent impedances at both the origin and destination ends of a trip, such as the time required to park or access a car, parking cost, and so forth. For the Asheville case study, the study area was assumed to have

TABLE 76 Unbalanced trips

	Productions			Attractions		
	HBW	HBO	NHB	NBW	HBO	NHB
Internal	76,033	215,407	91,566	85,604	188,806	109,331
External	48,842	62,986	26,087	20,932	41,990	26,087
Total	124,875	278,393	117,652	106,536	230,796	135,418

TABLE 77 Balanced trips

	Productions			Attractions		
	HBW	HBO	NHB	NBW	HBO	NHB
Internal	76,033	215,407	91,566	103,943	236,402	91,566
External	48,842	62,986	26,087	20,932	41,990	26,087
Total	124,875	278,393	117,652	124,875	278,393	117,652

three distinct area types: CBD, suburban, and rural. Zones 1 through 15 were designated as CBD zones and all trip-ends at those zones have a terminal time of 5 minutes. Zones 16 through 59, 61, 62, 65 through 71, 74, 77 through 80, 82, and 83 were designated as suburban zones and have terminal times of 2 minutes for each trip-end. The remainder of the internal zones were designated as rural zones and have a 1-minute terminal time associated with all trip-ends. The average terminal time for the 107 internal TAZs is 2.2 minutes.

The total travel time for each zone-to-zone pair was calculated by adding the terminal times at both the origin and destination ends of the trip to the free-flow travel time (or to the intrazonal travel time in the case of intrazonal zone pairs). This process was used within the matrix calculator to produce a matrix of zone-to-zone impedances between all 123 zones in the Asheville region.

Choice of Friction Factors

The gamma function was used to calculate the friction factors that represent the travel impedances between zones in the trip distribution gravity model. The calculation of friction factors for each zone pair was performed within the travel demand model software by using a matrix calculator. The preliminary friction factors used in this case study were calculated using the gamma function coefficients listed below for the three trip purposes:

The final step in the calculation of the friction factors was to set the friction factors for the external-external zone pairs to zero. This adjustment was performed in order to prevent the gravity model from distributing any trips to external-external zone pairs. (Otherwise, the distribution model and the through traffic model would combine to overestimate the number of through trips made in the region.) A friction factor value of zero was used to replace the calculated value for trips with both origin and destination zones between 108 and 123.

Creation of Free-Flow Trip Tables

After the friction factor matrices were created for the three trip purposes, the trips were distributed using the gravity model component of the travel demand modeling software. The balanced productions and attractions by trip purpose were set as the row and column control totals. The Fratar method was then applied to the trip ends so that the row and column totals matched the total productions and attractions in each zone.

The output of the distribution process was a set of three person-trip tables. These matrices contain the same number of trips as the trip generation control totals: 124,875 home-based work trips, 278,393 home-based other trips, and 117,652 non-home based trips. However, unlike the production and attraction vectors, the person-trip tables are two-dimensional and reflect the movement of trips between zones.

Trip Purpose	a	b	c
Home-Based Work	100	-0.020	-0.125
Home-Based Non-Work	100	-1.300	-0.100
Non-Home-Based	100	-1.350	-0.100

For example, the home-based work friction factors were calculated using the equation:

$$HBW\ Friction\ Factor(i,j) = 100 \times t_{ij}^{-0.020} \times e^{t_{ij} \times (-0.125)}$$

where t_{ij} = the impedance for all interchanges between origin zone i (from 1 to 123) and destination zone j (from 1 to 123).

Since the distribution of trips is calibrated to the trip length in minutes for each trip purpose, it is useful at this point to review the trip lengths after applying the gravity model. Average trip length was obtained by weighting the free-flow travel time matrix, including intrazonal times and terminal times, with the person-trip tables. The average trip lengths for the initial application of the gravity model are as follows:

home-based work—16.9 minutes; home-based other—14.4 minutes; and non-home based—14.8 minutes.

Two reasonableness checks were performed on these results. First, the average trip length for home-based work trips resulting from the gravity model was compared with the average home-based work trip length derived from the 1990 census data. The *1990 Journey-To-Work* statistics show that residents of the Asheville MSA reported an average home-based work trip length of 18.7 minutes. The average trip length produced by the gravity model, using free-flow speeds to build the impedances, should be slightly less than the average trip length reported by actual commuters, who tend to experience congested traffic during their home-based work trips. The average modeled free-flow travel time of 16.9 minutes, achieved with the use of the default parameters, passes this reasonableness check.

The second reasonableness check suggests that the average trip length for home-based other trips and non-home-based trips should be approximately 80 percent of the home-based work trip length. For the Asheville MSA, this corresponds to 15.0 minutes for home-based non-work and non-home-based trips. The modeled results, using the default coefficients for the gamma function, produced average trip lengths of 14.4 minutes and 14.8 minutes for home-based non-work and non-home-based trips respectively. Since these values are based on free-flow speeds, they are well within the range of reasonableness.

Later, after the assignment of the vehicle-trip table to the congested highway network, the average travel time was recalculated to ensure that the average travel time remained reasonably close to the average travel times reported in the *Journey-To-Work* statistics.

Aside from trip lengths, another way to check the reasonableness of the trip distribution results is by comparing the trip table data with any data regarding observed travel patterns. These data, if they existed, would usually come in the form of trip movements between districts or groups of zones, which could be compared with the model estimated interchanges. Unfortunately, such data do not exist for the Asheville MSA.

MODE-CHOICE ANALYSIS

Because transit usage in the Asheville region is so small, representing less than 1 percent of the average daily person trips made in the region, we did not use a mode-choice model component in this case study.

If we had done so, however, we would have needed to build a transit network and transit travel time matrices (transit skims) and to apply one of the mode-choice models described in Chapter 6.

AUTOMOBILE-OCCUPANCY CHARACTERISTICS

The estimation of vehicle trips for the purposes of the Asheville, North Carolina, case study was based on the auto-occupancy factors found in Table 37 of Chapter 7. The average values by trip purpose for urban areas with under 200,000 population were applied to convert the 520,921 total person trips into 350,077 vehicle trips, as shown in the following equations:

$$\begin{aligned} \textit{HBW Vehicle Trips} &= \frac{124{,}875 \textit{ HBW Person Trips}}{1.11} \\ &= 112{,}500 \textit{ HBW Vehicle Trips} \\ \textit{HBO Vehicle Trips} &= \frac{278{,}393 \textit{ HBO Person Trips}}{1.67} \\ &= 166{,}702 \textit{ HBO Vehicle Trips} \\ \textit{NHB Vehicle Trips} &= \frac{117{,}652 \textit{ NHB Person Trips}}{1.66} \\ &= 70{,}875 \textit{ NHB Vehicle Trips} \end{aligned}$$

TIME-OF-DAY CHARACTERISTICS

This is the point during the travel-demand modeling process at which the daily trip tables, which had been maintained in production-attraction format (P-A) were converted to origin-destination format (O-D) for the time periods to be analyzed. For the Asheville case study, we wished to use the model only to estimate ADT volumes. Conversion of the three P-A trip tables and the through-trip table into one daily vehicle-trip table was accomplished using the following equation:

$$\begin{aligned} \textit{Daily Vehicle Trips (O-D)} = {} & 0.5 \times (HBW_{PA} + HBW_{AP} \\ & + HBO_{PA} + HBO_{AP}) \\ & + NHB + \textit{Through Trips} \end{aligned}$$

where HBW_{AP} is the transpose of HBW_{PA}. The non-home-based and through trips were not factored since they were already balanced in origin-destination format.

The time-of-day characteristics presented in Chapter 8 provide the ability to factor a daily trip table to create peak period and off-peak period trip tables. Assigning traffic by time-of-day considers the relative levels of congestion and the alternate optimal travel paths between zone pairs that vary by time period. By adding traffic volumes from each of the time periods together, an estimate of the daily volume on a link was produced.

The results of trip distribution for Asheville indicated that the difference between free-flow and congested conditions is minimal. As a result, assigning the trips by time period would not necessarily produce a better assignment. For the purposes of this example problem, the daily trip table was converted to a peak-hour trip table by factoring the daily trip table by a 10 percent factor. The trip table assigned to the network was calculated by applying the 10 percent factor to all trips such that:

Hourly Vehicle Trips (O-D) =
0.10 × *Daily Vehicle Trips (O-D)*

TRAFFIC ASSIGNMENT OF FREE-FLOW TRIP TABLE

The hourly vehicle-trip table from the previous step was assigned to the base highway network using an equilibrium assignment. The travel-demand modeling software package used for the case study included algorithms for an equilibrium assignment using parameters from Chapter 9.

Delay on the roads caused by congestion was calculated using the Bureau of Public Roads (BPR) curve shown in Chapter 9. Coefficients for the formula were also obtained from that chapter. Freeway links used values of 0.83 for α and 5.5 for β that correspond to a design speed of 60 mph. Arterial links used values of 0.71 for α and 2.1 for β that correspond to a design speed of 50 mph on multi-lane roads. Congested travel time was calculated using the following formulas:

Trip Purpose	a	b	c
Home-Based Work	100	-0.300	-0.070
Home-Based Non-Work	100	-1.250	-0.100
Non-Home-Based	100	-1.350	-0.100

$$\textit{Freeway Travel Time} = \left(\frac{length}{speed} \times 60\right) \times \left(1 + 0.83 \times \left(\frac{volume}{capacity} \times lanes\right)^{5.5}\right)$$

$$\textit{Arterial Travel Time} = \left(\frac{length}{speed} \times 60\right) \times \left(1 + 0.71 \times \left(\frac{volume}{capacity} \times lanes\right)^{2.1}\right)$$

The equilibrium traffic assignment used several iterations to assign the trip table to the shortest paths that would result in the least amount of overall congestion on the highway network. The end product of the equilibrium traffic assignment was a network of link volumes and congested speeds.

CREATION AND ASSIGNMENT OF CONGESTED TRIP TABLES

The estimation of a congested travel-time matrix is similar to the process used to estimate the free-flow travel-time matrix. The major difference between the two processes is that the travel times use the link speeds from the preceding equilibrium traffic assignment, which are subject to volume delay. The equilibrium assignment was used to estimate congested travel times between zones, which were then saved in a congested travel-time matrix. The congested travel-time matrix was completed by calculating the congested intrazonal times and adding the terminal times to the congested travel times. The revised friction factors were calculated using the same gamma function coefficients as before, and the gravity model was applied to create new person-trip tables based on the congested times.

In order to check the validity of the trip distribution model, the average trip lengths were calculated for the revised person-trip tables based on the congested travel time. Average trip lengths produced using congested travel times were home-based work—17.7 minutes, home-based other—14.9 minutes, and non-home-based—15.4 minutes.

The estimated travel time increased slightly for all three trip purposes as the result of the congested travel times. The Asheville region does not experience a great deal of traffic congestion, which can help explain the relatively small degree to which the average trip lengths changed.

Since the average trip length for home-based work trips was approximately 1 minute less than the target value, we performed two more iterations of the trip distribution model to achieve a more acceptable average travel time for this trip purpose. The coefficients listed below were the ultimate coefficients used in the gamma function for the three trip purposes:

The trip tables resulting from these model coefficients had average trip lengths of 18.7 minutes for HBW, 15.0 minutes for HBNW, and 15.4 minutes for NHB trips. The trip length frequency distribution curves for these three trip purposes are displayed in Figure 49.

After the calibration of the trip distribution model was completed and the congested person-trip tables were produced, the next step was to repeat the auto-occupancy and time-of-day steps to build a congested vehicle-trip table. These steps were followed by a final equilibrium traffic assignment of the vehicle-trip table. As with the assignment of the free-flow trip table, this assignment produced traffic volumes for each link in the highway network. These volumes were then factored by a value of 10.0 to reflect total daily traffic conditions. Figure 50 is a bandwidth plot of the volumes on the network.

MODEL VALIDATION AND SCREENLINE COMPARISONS

Traffic volumes were summarized at five screenlines in the Asheville region. Table 78 presents a comparison of the estimated and observed daily traffic volumes across these screenlines. These comparisons provide an indication of the accuracy of the travel models. Table 78 shows that the simulated volumes across the five screenlines range from 19 percent below the count volumes to 5 percent above. The overall trend seems to be that travel across these screenlines is underestimated by approximately 10 percent.

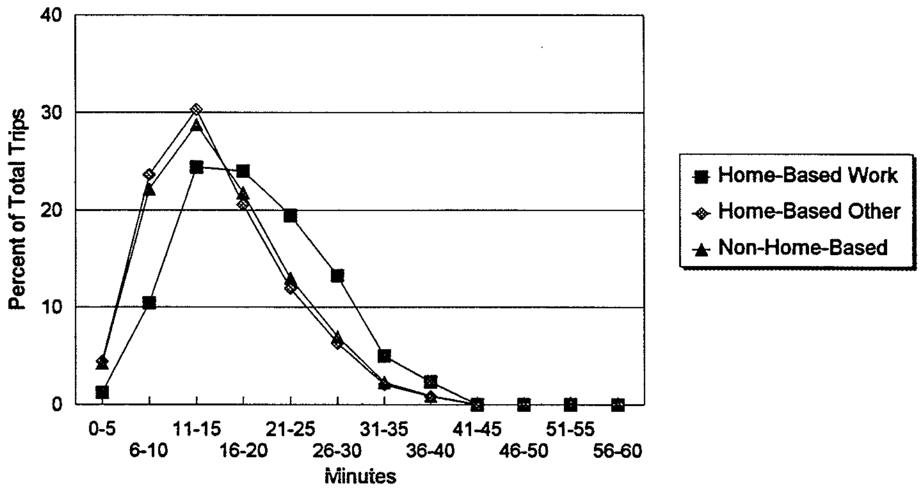


Figure 49. Model-generated trip-length distribution—by trip purpose.

The screenline comparisons have shown that the estimated traffic volumes match the observed traffic counts reasonably well. Another check of the reasonableness of the model results can be obtained by comparing the observed and estimated traffic counts for all facilities for which count data are available. The NCDOT provided a selected count map that displayed ADT count data for 386 links on the Asheville network. This database included counts on 48 freeway links, 176 major arterials, and 162 minor arterials or collector roads. The Federal Highway Administration's manual, *Calibration and Adjustment of System Planning Models* (1990) listed the following suggested limits by functional classification: freeways—less than 7 percent; principal arterials—less than 10 percent; minor arterials—less than 15 percent; and collector—less than 25 percent.

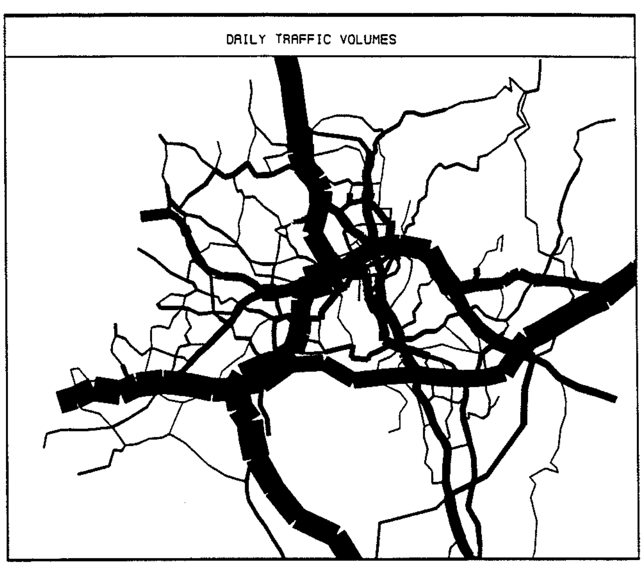


Figure 50. Traffic assignment bandwidths.

As displayed in Table 79, the model-generated traffic assignments were very reasonable for the freeway facilities, where the average link volume was 1.016 times the count volume, with a standard deviation of 0.222. The average traffic assignment on major arterials was also reasonably close to the count data, with an average ratio of 0.945; however, the standard deviation for these counts was a rather large 0.969. Average traffic assignments on minor arterials and collector facilities were far less respectable, with an average ratio of 0.567 and a standard deviation of 0.635. These results are consistent with the original intent of the case study, which was intended to forecast traffic volumes on the major roadways. The traffic assignments on the minor facilities could be improved by disaggregating the zone structure. Disaggregation would improve the ability to forecast traffic on minor facilities by increasing the accuracy with which trips from each TAZ access the coded highway network via centroid connectors and by decreasing the number of trips that are distributed to intrazonal cells in the trip tables given that these trips are not assigned to the highway network.

Model validation is usually performed at different levels. First, systemwide performance is reviewed to determine if regional inputs or parameters should be changed. For example, given that the assignment volumes appear to be slightly lower than the observed volumes, changes in the socioeconomic data, trip generation rates, auto-occupancy factors, or trip length could be used to increase volumes throughout the region. Second, if the assigned volumes on different facility types are estimated less accurately than on others, the default speeds or capacities on the various facilities could be modified in order to balance the results. Third, problems on specific links confined to a small area of the network could indicate network coding errors.

For this case study, no further actions were performed. The initial results provide an indication of the ability of the parameters to match observed volumes without extensive adjust-

TABLE 78 Traffic volumes at major screenlines

	Observed	Estimated	Difference
East Screenline			
U.S. 70	26,000	19,850	-23.7%
Swannanoa Road	8,500	2,380	-72.0
I-240	27,800	24,630	-11.4
U.S. 74	11,500	9,290	-19.2
I-40	22,400	26,970	20.4
Total	96,200	83,120	-13.6%
South Screenline			
U.S. 25-A	10,200	7,530	-26.2%
U.S. 25	19,600	14,700	-25.0
I-26	36,000	36,200	0.6
NC 191	8,400	4,810	-42.7
Total	74,200	63,240	-14.8%
West Screenline			
I-40	24,000	25,490	6.2%
I-240	40,200	42,710	6.2
U.S. 19-23 Haywood	17,600	9,770	-44.5
NC 63 Leicester Highway	18,800	12,200	-35.1
Total	100,600	90,170	-10.4%
North Screenline			
NC 251 Riverside Drive	6,700	3,980	-40.6%
I-70	30,300	31,060	2.5
Broadway Street	7,100	13,660	92.3
U.S. 25 Merrimon Avenue	17,000	13,110	-22.9
NC 694 Town Mountain	500	2,820	464.0
Total	61,600	64,630	4.9%
Inside Loop			
Swannanoa River	8,500	7,380	-13.2%
Baltimore Avenue	19,500	16,270	-16.6
McDowell Street	14,600	9,130	-37.5
Meadow Road	8,000	8,090	1.1
Total	50,600	40,870	-19.2%

ments. If observed data other than traffic counts, such as occupancy rates, were available, these could have been used in conjunction with the default parameters to improve model results.

CONCLUSIONS

This case study has presented one application of the procedures in the manual. The Asheville region provides a good example of an urbanized area with less than 200,000 in population. The ability to replicate observed traffic volumes in a small region with minimal transit ridership was seen as a likely use for the default parameters.

Few resources were used to complete the case study. Inputs to the process included socioeconomic and network data which were already available. Software requirements were limited to a standard computer spreadsheet for the trip

Table 79 Assignment validation by facility type

Facility Type	Observations	Average Ratio (Est./Obs.)	Standard Deviation
Freeway	48	1.016	0.222
Major Arterial	176	0.945	0.969
Minor Arterial and Collector	162	0.567	0.635
Total	386	0.795	0.799

generation and external data calculations and a PC-based travel-demand modeling software for the distribution, matrix calculation, and assignment processes. Daily traffic counts had already been collected in the region.

Although the assignment results were not final, the default parameters were able to replicate observed traffic volumes on the major facilities within acceptable levels of error. Additional validation adjustments could have improved the model results.

Application of the calibrated travel models to produce forecasts of future travel would now be relatively easy. Projections of socioeconomic changes and network updates could be analyzed to plan the transportation system required to meet the demands of the future.

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APPENDIX A

NTPS AND HOME INTERVIEW SURVEY DATA

Number of Autos and Number of Sampled HouseHolds in Various Transportation Studies

Household Size	Number of Autos	Mean Number of Trips												
		Nashua	Charlotte	Reno	Austin	Vancouver	Phoenix	Pittsburgh	Seattle	St. Louis	San Diego	Atlanta	New Jersey	NPTS
One Person	Zero Cars	4	58	19	34	7	133	22	113	43	55	32	45	1,005
	One Car	55	231	166	30	107	446	22	54	213	355	278	205	2,909
	Two Cars	6	28	37	4	31	65	1	15	25	75	50	19	408
	Three Cars Plus	0	5	9	5	13	19	0	7	5	16	118	2	111
Two Person	Zero Cars	1	14	12	126	3	64	7	612	36	17	15	15	403
	One Car	55	93	106	90	70	351	22	346	102	250	112	201	2,038
	Two Cars	211	284	193	26	121	205	44	132	326	577	549	210	3,915
	Three Cars Plus	35	40	58	48	76	208	4	119	49	173	176	31	1,075
Three Person	Zero Cars	3	7	3	6	1	24	5	137	23	15	8	12	213
	One Car	33	31	38	230	50	100	31	873	35	82	45	64	875
	Two Cars	117	128	84	86	76	159	58	317	126	212	213	166	1,802
	Three Cars Plus	88	89	68	117	47	169	42	520	84	191	230	101	1,375
Four Person Plus	Zero Cars	3	4	0	2	1	24	5	52	28	12	4	9	219
	One Car	51	22	34	46	62	120	14	470	40	101	23	55	895
	Two Cars	442	171	122	66	152	322	61	329	204	328	242	210	2,831
	Three Cars Plus	199	117	105	91	79	584	48	474	107	295	198	182	2,243
Total		1,303	1,322	1,054	1,007	896	2,993	386	4,570	1,446	2,754	2,433	1,527	22,317

Appendix A-1

Average Daily Person Trips per Household by Number of Autos and Persons per Household in Various Transportation Studies

Household Size	Number of Autos	Mean Number of Trips												
		Nashua	Charlotte	Reno	Austin	Vancouver	Phoenix	Pittsburgh	Seattle	St. Louis	San Diego	Atlanta	New Jersey	NPTS
One Person	Zero Cars	1.00	1.55	1.79	2.12	3.29	1.56	3.32	4.08	1.70	3.27	0.78	1.38	1.47
	One Car	5.04	4.36	4.42	4.48	3.20	4.09	5.27	4.73	4.10	5.91	3.92	3.57	3.16
	Two Cars	4.00	4.43	4.97	5.33	3.52	5.22	5.00	4.34	4.16	5.79	3.62	3.84	3.51
	Three Cars Plus	0.00	3.60	3.89	4.00	4.23	4.58	0.00	4.88	6.20	8.38	4.72	2.00	3.82
Two Person	Zero Cars	0.00	2.29	2.75	2.80	2.00	3.03	4.43	4.37	5.08	7.35	2.47	3.33	3.29
	One Car	7.58	7.40	6.30	5.13	3.50	6.54	8.86	4.50	6.48	10.24	6.44	5.68	4.63
	Two Cars	7.26	7.64	7.22	7.18	4.72	7.37	7.66	4.49	7.60	10.88	7.10	6.62	5.53
	Three Cars Plus	7.60	9.43	8.21	7.96	4.87	7.39	6.75	4.77	8.02	12.31	8.61	8.29	6.00
Three Person	Zero Cars	2.67	5.43	3.67	7.25	5.00	5.75	6.40	5.60	6.09	11.40	5.62	4.50	4.82
	One Car	7.18	8.29	8.29	6.73	5.40	7.21	10.10	5.27	9.46	14.23	10.33	6.00	6.66
	Two Cars	10.02	10.45	8.38	9.19	5.82	10.21	10.88	4.76	9.52	15.80	10.08	7.76	7.53
	Three Cars Plus	10.28	11.15	11.01	10.09	7.40	10.73	11.43	4.81	12.05	16.46	10.74	10.02	8.20
Four Person Plus	Zero Cars	0.00	7.75	0.00	6.40	14.00	4.79	7.40	3.86	12.86	12.25	10.78	4.56	6.85
	One Car	10.20	12.82	10.62	10.58	7.19	10.38	12.86	4.94	10.40	20.42	14.28	7.20	9.10
	Two Cars	12.27	16.26	14.32	11.42	7.70	13.26	14.75	4.75	14.98	24.41	15.76	11.33	11.07
	Three Cars Plus	11.81	17.62	15.26	13.91	10.16	15.33	16.25	4.93	16.63	25.09	16.28	14.16	11.37
Average Rate		10.08	9.29	8.58	7.99	5.82	8.98	10.72	4.69	9.05	14.30	8.22	7.75	6.70

Appendix A-2

APPENDIX B

ASHEVILLE, NORTH CAROLINA, CASE STUDY

Appendix B-1
Household Size Data - Asheville, NC MSA (Source: 1990 U.S. Census)

TAZ	Size of Household in Persons					Total Households
	1	2	3	4	5+	
1	71	8	0	0	0	79
2	61	33	4	6	0	104
3	0	0	0	0	0	0
4	242	23	0	0	0	265
5	113	43	33	9	0	198
6	75	28	30	13	8	154
7	131	110	45	24	4	314
8	114	119	59	29	26	347
9	324	80	39	6	8	457
10	39	33	15	11	11	109
11	97	189	54	57	59	456
12	65	43	24	14	34	180
13	302	88	20	13	14	437
14	62	82	66	45	60	315
15	117	123	42	43	24	349
16	152	112	75	52	67	458
17	244	220	100	52	15	631
18	106	90	63	36	37	332
19	268	195	38	34	4	539
20	228	162	51	60	45	546
21	132	105	39	41	8	325
22	135	310	75	64	8	592
23	815	699	300	214	134	2,162
24	52	224	51	21	7	355
25	147	90	28	35	13	313
26	180	289	111	115	19	714
27	254	252	65	0	20	591
28	93	46	27	8	0	174
29	91	121	64	27	19	322
30	156	174	103	51	14	498
31	228	192	86	113	78	697
32	167	184	52	66	23	492
33	57	54	19	11	20	161
34	58	70	43	30	20	221
35	177	300	144	105	72	798
36	119	148	53	11	18	349
37	20	39	13	18	7	97
38	90	170	56	49	29	394
39	3	20	6	0	7	36

Appendix B-1
Household Size Data - Asheville, NC MSA (Source: 1990 U.S. Census)

TAZ	Size of Household in Persons					Total Households
	1	2	3	4	5+	
40	111	168	90	55	23	447
41	3	3	2	3	0	11
42	36	9	28	10	0	83
43	119	101	27	30	9	286
44	123	99	54	6	16	298
45	72	66	57	23	45	263
46	84	93	74	52	42	345
47	63	134	50	40	9	296
48	93	82	39	19	44	277
49	202	146	110	48	33	539
50	78	87	29	32	15	241
51	183	140	88	43	31	485
52	58	90	31	23	0	202
53	199	275	132	73	61	740
54	129	104	52	76	16	377
55	17	107	9	21	29	183
56	251	241	74	89	26	681
57	93	125	79	62	8	367
58	149	132	37	28	9	355
59	144	170	101	16	35	466
60	52	255	106	88	0	501
61	146	192	61	30	60	489
62	66	126	42	64	29	327
63	101	122	103	77	35	438
64	107	120	83	112	43	465
65	97	120	105	30	18	370
66	136	124	103	74	51	488
67	127	212	130	65	66	600
68	146	166	136	104	45	597
69	86	100	127	71	8	392
70	86	217	92	66	23	484
71	98	83	90	29	49	349
72	11	168	114	93	48	434
73	134	165	122	88	32	541
74	65	152	48	24	6	295
75	82	202	65	59	44	452
76	47	160	77	49	0	333
77	65	70	15	27	18	195
78	185	290	154	74	14	717

Appendix B-1
Household Size Data - Asheville, NC MSA (Source: 1990 U.S. Census)

TAZ	Size of Household in Persons					Total Households
	1	2	3	4	5+	
79	200	255	126	94	51	726
80	37	77	48	29	17	208
81	123	194	47	54	39	457
82	95	113	7	33	23	271
83	150	71	42	0	11	274
84	85	236	64	29	35	449
85	97	129	79	75	23	403
86	74	218	49	50	60	451
87	139	161	109	88	16	513
88	99	132	60	82	10	383
89	103	389	150	103	58	803
90	109	160	84	34	23	410
91	225	343	67	76	53	764
92	476	305	86	34	2	903
93	68	215	15	59	33	390
94	136	320	110	35	45	646
95	93	219	164	171	55	702
96	134	206	112	147	29	628
97	89	115	57	30	18	309
98	116	245	143	93	30	627
99	223	241	150	95	62	771
100	59	62	72	87	14	294
101	75	248	195	122	58	698
102	63	50	43	14	8	178
103	154	91	115	25	12	397
104	185	134	106	65	12	502
105	95	63	52	28	33	271
106	448	561	457	373	112	1,951
107	8	76	48	11	0	143
Total	13,787	16,313	7,886	5,592	2,914	46,492

Appendix B-2
Study Area Employment by Zone - Asheville, NC MSA (Source: NCDOT, 1990)

TAZ	Employment Type: Basic	Retail	Service	Total Employment
1	390	791	226	1,407
2	1,171	120	170	1,461
3	52	421	224	697
4	1,764	409	327	2,500
5	17	29	9	55
6	76	8	17	101
7	358	208	106	672
8	196	183	89	468
9	69	43	28	140
10	614	820	61	1,495
11	271	505	120	896
12	388	624	238	1,250
13	807	535	246	1,588
14	19	85	33	137
15	64	22	12	98
16	71	255	22	348
17	156	234	2,560	2,950
18	50	145	47	242
19	44	48	33	125
20	82	126	82	290
21	43	20	7	70
22	35	14	4	53
23	77	1,222	510	1,809
24	18	75	32	125
25	50	37	83	170
26	38	13	103	154
27	493	153	455	1,101
28	28	40	197	265
29	708	79	393	1,180
30	52	69	23	144
31	485	89	81	655
32	113	216	578	907
33	0	0	0	0
34	1,074	430	204	1,708
35	815	98	87	1,000
36	43	79	64	186
37	20	24	0	44
38	44	162	7	213
39	0	26	4	30

Appendix B-2
Study Area Employment by Zone - Asheville, NC MSA (Source: NCDOT, 1990)

TAZ	Employment Type: Basic	Retail	Service	Total Employment
40	29	185	77	291
41	29	96	63	188
42	275	247	356	878
43	8	143	25	176
44	27	667	94	788
45	157	1,444	127	1,728
46	365	273	89	727
47	27	19	21	67
48	123	52	58	233
49	38	95	91	224
50	68	35	55	158
51	61	150	33	244
52	28	26	56	110
53	44	121	19	184
54	60	58	110	228
55	80	3	33	116
56	65	31	67	163
57	38	132	46	216
58	33	77	71	181
59	215	158	338	711
60	241	178	198	617
61	37	133	425	595
62	4	3	5	12
63	19	124	14	157
64	15	28	81	124
65	59	59	58	176
66	255	37	136	428
67	511	31	177	719
68	142	47	124	313
69	233	42	120	395
70	257	349	341	947
71	1,026	4	0	1,030
72	617	111	230	958
73	14	99	15	128
74	208	12	3	223
75	70	22	66	158
76	492	31	30	553
77	345	89	559	993
78	134	36	25	195

Appendix B-2
Study Area Employment by Zone - Asheville, NC MSA (Source: NCDOT, 1990)

TAZ	Employment Type Basic	Retail	Service	Total Employment
79	88	58	258	404
80	9	6	10	25
81	25	51	104	180
82	30	131	124	285
83	56	78	79	213
84	2	61	0	63
85	32	31	30	93
86	2	3	4	9
87	54	35	115	204
88	48	119	95	262
89	46	11	17	74
90	313	156	241	710
91	334	55	28	417
92	732	346	406	1,484
93	219	129	123	471
94	121	23	36	180
95	23	10	34	67
96	591	58	54	703
97	798	104	87	989
98	79	124	163	366
99	306	64	261	631
100	615	158	286	1,059
101	348	8	92	448
102	1,222	50	100	1,372
103	44	9	25	78
104	1,457	131	106	1,694
105	17	9	36	62
106	2,488	285	535	3,308
107	0	120	0	120
Total	27,343	16,327	15,367	59,037

Appendix B-3
Unbalanced Productions and Attractions - Asheville, NC MSA

	Trip Productions				Trip Attractions			
TAZ	HBW	HBO	NHB	TOTAL	HBW	HBO	NHB	TOTAL
1	66	175	83	324	2,040	2,388	1,613	6,042
2	124	328	148	601	2,118	1,677	1,010	4,804
3	0	0	0	0	1,011	1,270	884	3,164
4	218	578	275	1,070	3,625	3,200	1,980	8,805
5	245	669	303	1,217	80	267	159	505
6	219	628	271	1,118	146	252	147	545
7	445	1,211	535	2,191	974	1,201	754	2,930
8	550	1,563	664	2,778	679	1,006	635	2,319
9	490	1,337	608	2,435	203	607	357	1,167
10	174	502	210	886	2,168	2,394	1,583	6,145
11	810	2,347	965	4,122	1,299	1,868	1,215	4,382
12	300	909	367	1,577	1,813	2,164	1,443	5,420
13	484	1,330	594	2,407	2,303	2,608	1,666	6,577
14	602	1,825	734	3,160	199	527	326	1,051
15	556	1,574	666	2,796	142	436	252	830
16	774	2,308	945	4,028	505	2,625	1,336	4,466
17	926	2,549	1,116	4,591	4,278	6,914	4,425	15,616
18	553	1,620	675	2,848	351	1,596	842	2,789
19	700	1,871	834	3,405	181	797	528	1,506
20	824	2,360	995	4,178	421	1,620	929	2,970
21	480	1,332	578	2,390	102	393	274	769
22	957	2,574	1,122	4,654	77	460	376	913
23	3,307	9,345	3,991	16,643	2,623	13,015	6,742	22,380
24	590	1,564	684	2,837	181	923	532	1,637
25	443	1,239	535	2,217	247	676	433	1,355
26	1,191	3,307	1,420	5,918	223	683	553	1,460
27	797	2,133	946	3,876	1,596	2,890	1,715	6,201
28	221	598	270	1,089	384	807	501	1,693
29	522	1,467	629	2,617	1,711	2,177	1,311	5,199
30	785	2,184	949	3,917	209	956	586	1,750
31	1,175	3,448	1,423	6,046	950	1,724	1,053	3,727
32	771	2,155	921	3,847	1,315	3,274	1,882	6,471
33	256	741	308	1,304	0	81	81	161
34	381	1,101	461	1,942	2,477	5,294	2,655	10,426
35	1,397	4,009	1,679	7,085	1,450	2,162	1,313	4,925
36	521	1,432	622	2,575	270	1,033	597	1,899
37	172	491	206	869	64	283	157	503
38	672	1,895	799	3,366	309	1,707	892	2,907
39	67	196	80	343	44	259	129	432
40	751	2,116	904	3,771	422	2,046	1,089	3,556
41	19	54	23	96	273	1,003	489	1,765
42	124	354	157	634	1,273	3,117	1,619	6,009
43	414	1,142	495	2,052	255	1,480	763	2,498
44	426	1,185	517	2,127	1,143	6,336	3,010	10,489
45	465	1,398	570	2,432	2,506	13,485	6,283	22,273

Appendix B-3
Unbalanced Productions and Attractions - Asheville, NC MSA

	Trip Productions				Trip Attractions			
TAZ	HBW	HBO	NHB	TOTAL	HBW	HBO	NHB	TOTAL
46	620	1,831	756	3,206	1,054	3,109	1,581	5,745
47	500	1,381	594	2,475	97	379	265	741
48	458	1,357	555	2,370	338	816	483	1,636
49	832	2,374	1,017	4,224	325	1,313	787	2,425
50	387	1,092	463	1,941	229	590	364	1,183
51	745	2,121	907	3,773	354	1,704	928	2,985
52	315	851	374	1,540	160	455	289	904
53	1,234	3,513	1,484	6,231	267	1,531	911	2,709
54	616	1,757	745	3,118	331	952	588	1,870
55	346	991	402	1,739	168	247	183	598
56	1,041	2,899	1,246	5,187	236	792	581	1,609
57	620	1,739	749	3,108	313	1,484	799	2,596
58	503	1,373	601	2,477	262	1,021	595	1,878
59	734	2,071	888	3,694	1,031	2,423	1,394	4,848
60	906	2,474	1,071	4,451	895	2,406	1,338	4,639
61	799	2,296	955	4,050	863	2,197	1,318	4,378
62	591	1,702	706	2,999	17	203	184	404
63	784	2,281	956	4,021	228	1,376	754	2,357
64	858	2,525	1,042	4,425	180	636	452	1,268
65	612	1,731	747	3,091	255	868	526	1,649
66	851	2,501	1,039	4,390	621	1,038	686	2,345
67	1,064	3,087	1,287	5,439	1,043	1,340	895	3,277
68	1,055	3,064	1,286	5,405	454	1,060	711	2,225
69	693	1,978	852	3,523	573	988	629	2,189
70	847	2,366	1,009	4,222	1,373	4,194	2,211	7,778
71	606	1,804	746	3,155	1,494	1,134	704	3,331
72	894	2,616	1,077	4,588	1,389	2,162	1,257	4,808
73	938	2,693	1,140	4,771	186	1,200	701	2,087
74	478	1,290	563	2,331	323	448	304	1,075
75	806	2,297	958	4,060	229	599	430	1,259
76	584	1,594	694	2,873	802	939	576	2,317
77	316	904	377	1,598	1,440	2,159	1,306	4,905
78	1,163	3,202	1,395	5,760	283	846	603	1,731
79	1,215	3,460	1,463	6,139	586	1,403	954	2,943
80	376	1,079	453	1,908	36	183	145	364
81	760	2,148	902	3,810	261	887	575	1,723
82	424	1,192	499	2,115	413	1,552	836	2,802
83	345	954	423	1,722	309	1,024	580	1,912
84	760	2,107	895	3,762	91	775	476	1,342
85	705	2,020	853	3,579	135	560	381	1,076
86	816	2,345	964	4,126	13	261	244	518
87	864	2,444	1,047	4,356	296	816	565	1,676
88	655	1,845	786	3,287	380	1,467	817	2,665
89	1,459	4,102	1,730	7,291	107	571	490	1,168
90	670	1,878	806	3,354	1,030	2,300	1,290	4,620

Appendix B-3
Unbalanced Productions and Attractions - Asheville, NC MSA

	Trip Productions				Trip Attractions			
TAZ	HBW	HBO	NHB	TOTAL	HBW	HBO	NHB	TOTAL
91	1,221	3,400	1,442	6,063	605	1,225	808	2,638
92	1,129	3,002	1,355	5,486	2,152	4,915	2,723	9,790
93	686	1,912	797	3,395	683	1,762	981	3,426
94	1,075	2,977	1,272	5,324	261	700	521	1,482
95	1,362	3,973	1,650	6,986	97	520	444	1,061
96	1,131	3,236	1,362	5,729	1,019	1,460	912	3,391
97	501	1,410	603	2,514	1,434	1,957	1,084	4,475
98	1,108	3,128	1,333	5,570	531	1,778	1,057	3,365
99	1,291	3,712	1,565	6,568	915	1,681	1,114	3,710
100	557	1,630	682	2,868	1,536	2,609	1,446	5,590
101	1,342	3,884	1,625	6,851	650	891	666	2,206
102	276	779	337	1,392	1,989	1,809	1,025	4,823
103	596	1,685	739	3,020	113	362	287	762
104	776	2,185	948	3,910	2,456	2,922	1,644	7,022
105	446	1,318	547	2,310	90	293	224	607
106	3,470	10,005	4,222	17,697	4,797	6,689	4,030	15,516
107	258	700	308	1,266	174	1,152	564	1,889
Internal	76,033	215,407	91,566	383,006	85,604	188,806	109,331	383,740
108	559	721	299	1,580	240	481	299	1,020
109	6,026	7,772	3,219	17,017	2,583	5,181	3,219	10,982
110	2,176	2,806	1,162	6,143	932	1,870	1,162	3,965
111	886	1,142	473	2,501	380	762	473	1,614
112	622	802	332	1,755	266	534	332	1,133
113	4,503	5,808	2,405	12,716	1,930	3,872	2,405	8,207
114	5,374	6,930	2,870	15,174	2,303	4,620	2,870	9,793
115	3,419	4,409	1,826	9,654	1,465	2,939	1,826	6,230
116	3,869	4,990	2,067	10,926	1,658	3,327	2,067	7,052
117	7,201	9,287	3,846	20,334	3,086	6,191	3,846	13,123
118	2,300	2,966	1,228	6,494	986	1,977	1,228	4,191
119	301	389	161	851	129	259	161	549
120	482	621	257	1,360	206	414	257	878
121	5,983	7,715	3,196	16,894	2,564	5,144	3,196	10,903
122	3,916	5,050	2,092	11,058	1,678	3,367	2,092	7,137
123	1,225	1,579	654	3,458	525	1,053	654	2,232
External	48,842	62,986	26,087	137,915	20,932	41,990	26,087	89,010
Total	124,875	278,393	117,653	520,921	106,536	230,797	135,417	472,750

Appendix B-4
Distribution of Through Trips - Asheville, NC MSA

From External Station Number	To External Station Number									
109	113	Y = -7.40 +	0.55 x	10 +	24.68 x	0 +	45.62 x	16,100 /	143,100 =	3.23
	114	Y = -2.70 +	0.21 x	30 +	67.86 x	0			=	3.60
	117	Y = -2.70 +	0.21 x	30 +	67.86 x	1			=	71.46
	121	Y = -2.70 +	0.21 x	30 +	67.86 x	0			=	3.60
	122	Y = -7.40 +	0.55 x	10 +	24.68 x	0 +	45.62 x	14,000 /	143,100 =	2.56
113	109	Y = -2.70 +	0.21 x	30 +	67.86 x	0			=	3.60
	117	Y = -2.70 +	0.21 x	30 +	67.86 x	0			=	3.60
	121	Y = -2.70 +	0.21 x	30 +	67.86 x	0			=	3.60
	122	Y = -7.40 +	0.55 x	10 +	24.68 x	0 +	45.62 x	14,000 /	143,100 =	2.56
114	109	Y = -2.70 +	0.21 x	30 +	67.86 x	0			=	3.60
	117	Y = -2.70 +	0.21 x	30 +	67.86 x	0			=	3.60
	121	Y = -2.70 +	0.21 x	30 +	67.86 x	1			=	71.46
	122	Y = -7.40 +	0.55 x	10 +	24.68 x	0 +	45.62 x	14,000 /	143,100 =	2.56
117	109	Y = -2.70 +	0.21 x	30 +	67.86 x	1			=	71.46
	113	Y = -7.40 +	0.55 x	10 +	24.68 x	0 +	45.62 x	16,100 /	143,100 =	3.23
	114	Y = -2.70 +	0.21 x	30 +	67.86 x	0			=	3.60
	121	Y = -2.70 +	0.21 x	30 +	67.86 x	0			=	3.60
	122	Y = -7.40 +	0.55 x	10 +	24.68 x	0 +	45.62 x	14,000 /	143,100 =	2.56
121	109	Y = -2.70 +	0.21 x	30 +	67.86 x	0			=	3.60
	113	Y = -7.40 +	0.55 x	10 +	24.68 x	0 +	45.62 x	16,100 /	143,100 =	3.23
	114	Y = -2.70 +	0.21 x	30 +	67.86 x	1			=	71.46
	117	Y = -2.70 +	0.21 x	30 +	67.86 x	0			=	3.60
	122	Y = -7.40 +	0.55 x	10 +	24.68 x	0 +	45.62 x	14,000 /	143,100 =	2.56
122	109	Y = -2.70 +	0.21 x	30 +	67.86 x	0			=	3.60
	113	Y = -7.40 +	0.55 x	10 +	24.68 x	0 +	45.62 x	16,100 /	143,100 =	3.23
	114	Y = -2.70 +	0.21 x	30 +	67.86 x	0			=	3.60
	117	Y = -2.70 +	0.21 x	30 +	67.86 x	0			=	3.60
	121	Y = -2.70 +	0.21 x	30 +	67.86 x	0			=	3.60

Appendix B-5
Balanced Productions and Attractions - Asheville, NC MSA

	Trip Productions				Trip Attractions			
TAZ	HBW	HBO	NHB	TOTAL	HBW	HBO	NHB	TOTAL
1	66	175	1,351	1,592	2,477	2,990	1,351	6,818
2	124	328	845	1,297	2,572	2,099	845	5,516
3	0	0	741	741	1,227	1,590	741	3,558
4	218	578	1,658	2,454	4,402	4,007	1,658	10,067
5	245	669	133	1,047	97	334	133	564
6	219	628	123	970	178	315	123	616
7	445	1,211	632	2,288	1,183	1,504	632	3,319
8	550	1,563	531	2,644	824	1,260	531	2,615
9	490	1,337	299	2,126	246	760	299	1,305
10	174	502	1,326	2,002	2,632	2,998	1,326	6,956
11	810	2,347	1,017	4,174	1,578	2,339	1,017	4,934
12	300	909	1,209	2,418	2,201	2,709	1,209	6,119
13	484	1,330	1,395	3,209	2,796	3,265	1,395	7,456
14	602	1,825	273	2,700	241	659	273	1,173
15	556	1,574	211	2,341	173	546	211	930
16	774	2,308	1,119	4,201	613	3,287	1,119	5,019
17	926	2,549	3,706	7,181	5,194	8,657	3,706	17,557
18	553	1,620	705	2,878	426	1,998	705	3,129
19	700	1,871	442	3,013	220	998	442	1,660
20	824	2,360	778	3,962	511	2,029	778	3,318
21	480	1,332	230	2,042	123	492	230	845
22	957	2,574	315	3,846	93	576	315	984
23	3,307	9,345	5,646	18,298	3,185	16,296	5,646	25,127
24	590	1,564	446	2,600	220	1,156	446	1,822
25	443	1,239	362	2,044	299	846	362	1,507
26	1,191	3,307	463	4,961	271	856	463	1,590
27	797	2,133	1,437	4,367	1,938	3,618	1,437	6,993
28	221	598	420	1,239	467	1,011	420	1,898
29	522	1,467	1,098	3,087	2,078	2,726	1,098	5,902
30	785	2,184	490	3,459	254	1,197	490	1,941
31	1,175	3,448	882	5,505	1,153	2,158	882	4,193
32	771	2,155	1,576	4,502	1,597	4,100	1,576	7,273
33	256	741	67	1,064	0	101	67	168
34	381	1,101	2,224	3,706	3,007	6,628	2,224	11,859
35	1,397	4,009	1,099	6,505	1,761	2,708	1,099	5,568
36	521	1,432	500	2,453	327	1,293	500	2,120
37	172	491	131	794	77	354	131	562
38	672	1,895	747	3,314	375	2,137	747	3,259
39	67	196	108	371	53	324	108	485
40	751	2,116	912	3,779	512	2,561	912	3,985
41	19	54	410	483	331	1,255	410	1,996
42	124	354	1,356	1,834	1,546	3,903	1,356	6,805
43	414	1,142	639	2,195	310	1,853	639	2,802
44	426	1,185	2,521	4,132	1,387	7,933	2,521	11,841
45	465	1,398	5,262	7,125	3,042	16,884	5,262	25,188

Appendix B-5
Balanced Productions and Attractions - Asheville, NC MSA

	Trip Productions				Trip Attractions			
TAZ	HBW	HBO	NHB	TOTAL	HBW	HBO	NHB	TOTAL
46	620	1,831	1,324	3,775	1,280	3,893	1,324	6,497
47	500	1,381	222	2,103	118	475	222	815
48	458	1,357	404	2,219	410	1,021	404	1,835
49	832	2,374	659	3,865	394	1,644	659	2,697
50	387	1,092	305	1,784	278	739	305	1,322
51	745	2,121	777	3,643	430	2,133	777	3,340
52	315	851	242	1,408	194	570	242	1,006
53	1,234	3,513	763	5,510	324	1,917	763	3,004
54	616	1,757	493	2,866	401	1,191	493	2,085
55	346	991	154	1,491	204	309	154	667
56	1,041	2,899	486	4,426	287	992	486	1,765
57	620	1,739	669	3,028	380	1,858	669	2,907
58	503	1,373	498	2,374	319	1,278	498	2,095
59	734	2,071	1,167	3,972	1,252	3,034	1,167	5,453
60	906	2,474	1,121	4,501	1,086	3,013	1,121	5,220
61	799	2,296	1,104	4,199	1,048	2,751	1,104	4,903
62	591	1,702	154	2,447	21	254	154	429
63	784	2,281	631	3,696	276	1,723	631	2,630
64	858	2,525	379	3,762	218	796	379	1,393
65	612	1,731	441	2,784	310	1,086	441	1,837
66	851	2,501	575	3,927	754	1,299	575	2,628
67	1,064	3,087	750	4,901	1,266	1,678	750	3,694
68	1,055	3,064	595	4,714	551	1,327	595	2,473
69	693	1,978	527	3,198	695	1,237	527	2,459
70	847	2,366	1,851	5,064	1,667	5,251	1,851	8,769
71	606	1,804	590	3,000	1,813	1,420	590	3,823
72	894	2,616	1,052	4,562	1,687	2,707	1,052	5,446
73	938	2,693	587	4,218	225	1,502	587	2,314
74	478	1,290	255	2,023	393	561	255	1,209
75	806	2,297	360	3,463	278	750	360	1,388
76	584	1,594	482	2,660	974	1,176	482	2,632
77	316	904	1,094	2,314	1,748	2,704	1,094	5,546
78	1,163	3,202	505	4,870	343	1,059	505	1,907
79	1,215	3,460	799	5,474	711	1,756	799	3,266
80	376	1,079	122	1,577	44	229	122	395
81	760	2,148	481	3,389	317	1,110	481	1,908
82	424	1,192	700	2,316	502	1,944	700	3,146
83	345	954	485	1,784	375	1,282	485	2,142
84	760	2,107	398	3,265	111	971	398	1,480
85	705	2,020	319	3,044	164	702	319	1,185
86	816	2,345	204	3,365	16	327	204	547
87	864	2,444	473	3,781	359	1,021	473	1,853
88	655	1,845	685	3,185	461	1,837	685	2,983
89	1,459	4,102	410	5,971	130	715	410	1,255
90	670	1,878	1,081	3,629	1,250	2,880	1,081	5,211

Appendix B-5
Balanced Productions and Attractions - Asheville, NC MSA

	Trip Productions				Trip Attractions			
TAZ	HBW	HBO	NHB	TOTAL	HBW	HBO	NHB	TOTAL
91	1,221	3,400	677	5,298	734	1,534	677	2,945
92	1,129	3,002	2,281	6,412	2,613	6,153	2,281	11,047
93	686	1,912	822	3,420	829	2,206	822	3,857
94	1,075	2,977	436	4,488	317	877	436	1,630
95	1,362	3,973	372	5,707	118	650	372	1,140
96	1,131	3,236	764	5,131	1,238	1,828	764	3,830
97	501	1,410	908	2,819	1,741	2,450	908	5,099
98	1,108	3,128	885	5,121	644	2,226	885	3,755
99	1,291	3,712	933	5,936	1,111	2,104	933	4,148
100	557	1,630	1,211	3,398	1,865	3,266	1,211	6,342
101	1,342	3,884	558	5,784	789	1,115	558	2,462
102	276	779	858	1,913	2,416	2,265	858	5,539
103	596	1,685	241	2,522	137	453	241	831
104	776	2,185	1,377	4,338	2,983	3,658	1,377	8,018
105	446	1,318	188	1,952	109	367	188	664
106	3,470	10,005	3,375	16,850	5,824	8,375	3,375	17,574
107	258	700	472	1,430	211	1,442	472	2,125
Internal	76,034	215,409	91,566	383,009	103,940	236,401	91,566	431,907
108	559	721	299	1,579	240	481	299	1,020
109	6,026	7,772	3,219	17,017	2,583	5,181	3,219	10,983
110	2,176	2,806	1,162	6,144	932	1,870	1,162	3,964
111	886	1,142	473	2,501	380	762	473	1,615
112	622	802	332	1,756	266	534	332	1,132
113	4,503	5,808	2,405	12,716	1,930	3,872	2,405	8,207
114	5,374	6,930	2,870	15,174	2,303	4,620	2,870	9,793
115	3,419	4,409	1,826	9,654	1,465	2,939	1,826	6,230
116	3,869	4,990	2,067	10,926	1,658	3,327	2,067	7,052
117	7,201	9,287	3,846	20,334	3,086	6,191	3,846	13,123
118	2,300	2,966	1,228	6,494	986	1,977	1,228	4,191
119	301	389	161	851	129	259	161	549
120	482	621	257	1,360	206	414	257	877
121	5,983	7,715	3,196	16,894	2,564	5,144	3,196	10,904
122	3,916	5,050	2,092	11,058	1,678	3,367	2,092	7,137
123	1,225	1,579	654	3,458	525	1,053	654	2,232
External	48,842	62,987	26,087	137,916	20,931	41,991	26,087	89,009
Total	124,876	278,396	117,653	520,925	124,871	278,392	117,653	520,916