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Model Validation and Reasonableness Checking Manual

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Travel Model Improvement Program

U.S. Department of Transportation
Federal Highway Administration
Federal Transit Administration
Assistant Secretary for Transportation Policy

U.S. Environmental Protection Agency

Travel Model Improvement Program

The Department of Transportation, in cooperation with the Environmental Protection Agency and the Department of Energy, has embarked on a research program to respond to the requirements of the Clean Air Act Amendments of 1990 and the Intermodal Surface Transportation Efficiency Act of 1991. This program addresses the linkage of transportation to air quality, energy, economic growth, land use and the overall quality of life. The program addresses both analytic tools and the integration of these tools into the planning process to better support decision makers. The program has the following objectives:

1. To increase the ability of existing travel forecasting procedures to respond to emerging issues including; environmental concerns, growth management, and lifestyles along with traditional transportation issues,

2. To redesign the travel forecasting process to reflect changes in behavior, to respond to greater information needs placed on the forecasting process and to take advantage of changes in data collection technology, and

3. To integrate the forecasting techniques into the decision making process, providing better understanding of the effects of transportation improvements and allowing decision makers in state governments, local governments, transit operators, metropolitan planning organizations and environmental agencies the capability of making improved transportation decisions.

This program was funded through the Travel Model Improvement Program.

Further information about the Travel Model Improvement Program may be obtained by writing to:

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Model Validation and Reasonableness Checking Manual

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1.0 Introduction

A major shortcoming of many travel demand models is the lack of attention and effort placed on the validation phase of model development. Validation involves testing the model's predictive capabilities. Travel models need to be able to replicate observed conditions within reason before being used to produce future-year forecasts. As metropolitan areas continue to refine and improve the travel demand forecasting process, the credibility of the process with decision makers will depend largely on the ability of analysts to properly validate procedures and models used.

The travel modeling process has undergone many changes in the past few years in order to evaluate more complex policy actions resulting from legislation such as ISTEA and the Clean Air Act. As travel models have become more complex, so have the procedures needed to validate them. Often there is a tradeoff between increasing confidence in the level of accuracy of the models and the cost of data collection and effort required to validate models. Tests or checks used to evaluate the reliability of models can range from a simple assessment of the reasonableness of model outputs to sophisticated statistical techniques.

1.1 Purpose of Manual

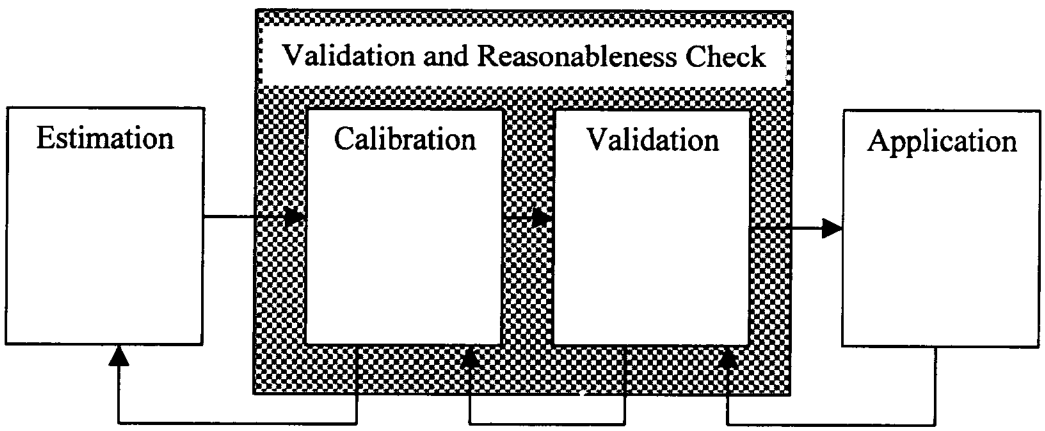
This manual builds upon the 1990 Federal Highway Administration publication *Calibration and Adjustment of System Planning Models* (FHWA-ED-90-015). That manual provided a set of simple procedures for calibrating travel models that reflected the limited number of regions with current household travel survey data available.

Since 1990, many regions have conducted, or are planning to conduct, new household travel surveys and other data collection efforts to improve their ability to develop and validate more detailed and rigorous models. In addition, the Travel Model Improvement Program has provided technical assistance, aiding planning organizations in implementing state-of-the-art modeling practices. This validation manual provides guidance on how to perform reasonableness checks on the latest generation of models commonly included in the four-step modeling process. While it is impossible to specify exact checks for every possible model, this manual will describe families of checks and provide concrete examples of validation checks. The manual also provides tips for regions with limited resources for model validation.

The manual should serve as a set of guidelines for best practice, not as a list of required steps. The process used to validate a travel model is dependent on the purpose of the model, available data resources, model structure, and desired level of accuracy. Improving the performance of travel models depends not only on the proper calibration of parameters, but also on careful review of exogenous inputs. Typical inputs include (1) zonal socioeconomic inputs such as population, households, employment, income or auto ownership, and school enrollment; and (2) transportation system characteristics such as highway and transit network definition and attributes. Therefore, this manual prescribes a number of reasonableness tests for model inputs, model parameters, and model outputs.

One difficulty in prescribing a set of procedures for validating models is that the concepts of model validation, calibration, and estimation have taken on different meanings and sometimes overlap in their objectives. In practice, travel model development usually involves all three steps, as well as model application, as shown in Figure 1-1. In this manual, the following definitions are used:

Figure 1-1
Role of Model Validation



- **Model Estimation**: Statistical estimation procedures are used to find the values of the model parameters (esp. coefficients) which maximize the likelihood of fitting observed travel data, such as a household travel survey or on-board transit survey. The focus is on correctly specifying the form of the model and determining the statistical significance of the variables. For example, the initial cross-classification of a trip production model or the logit estimation of level-of-service coefficients in a mode choice model are developed in the estimation phase. If local data are not available, then this initial step is often skipped and the coefficients are borrowed from another urban area.

- **Model Calibration:** After the model parameters have been estimated, calibration is used to adjust parameter values until predicted travel matches observed travel demand levels in the region. For example, calibration of the mode-specific constants in a mode choice model ensures that the estimated shares match the observed shares by mode (and often by mode of access).
- **Model Validation:** In order to test the ability of the model to predict future behavior, validation requires comparing the model predictions with information other than that used in estimating the model. This step is typically an iterative

process linked to model calibration. It involves checking the model results against observed data and adjusting parameters until model results fall within an acceptable range of error. If the only way that a model will replicate observed data is through the use of unusual parameters and procedures or localized "quick-fixes", then it is unlikely that the model can reliably forecast future conditions.

- **Model Application:** Although the model may replicate base year conditions, the application of the model to future year conditions and policy options requires checking the reasonableness of projections, so there is a link between application and validation as well. The sensitivity of the models in response to system or policy changes is often the main issue in model application.

The focus of this manual is on the iterative process shaded in the figure which links validation with calibration. It is not a manual on travel model development. While the estimation phase of model development does have a link to validation, this manual assumes that the final model structure, especially the inclusion of relevant variables and specification of initial parameters, has already been determined.

1.2 Target Audience

The model validation manual should prove to be a useful reference for the following persons:

- **Travel Forecasters**
  - responsible for model calibration and/or validation
  - responsible for model application
  - employees of metropolitan planning organizations (MPOs), states, municipalities and counties, and consultants;
- **Transportation Planners**
  - responsible for evaluation of plans
  - responsible for designing alternatives
  - employees of metropolitan planning organizations (MPOs), states, municipalities and counties, and consultants;
- **Decision-makers**
  - at overview level to know the questions to ask
  - employees of metropolitan planning organizations (MPOs), states, municipalities and counties;
- **Members of the public with an interest in travel forecasting.**

1.3 Overview of the Model Validation Process

Typically the calibration and validation processes focus only on the overall results of the travel model, especially highway volumes at screenline crossings. The models are run to obtain the necessary output such as mode shares, overall transit ridership, transit boardings for a specific line, or traffic volumes, without detailed checking of results from individual model components. This "all-too-common" approach to model validation might be used under the justification that traffic counts or transit boardings are the only historical data available or because time constraints preclude detailed checking of interim model steps.

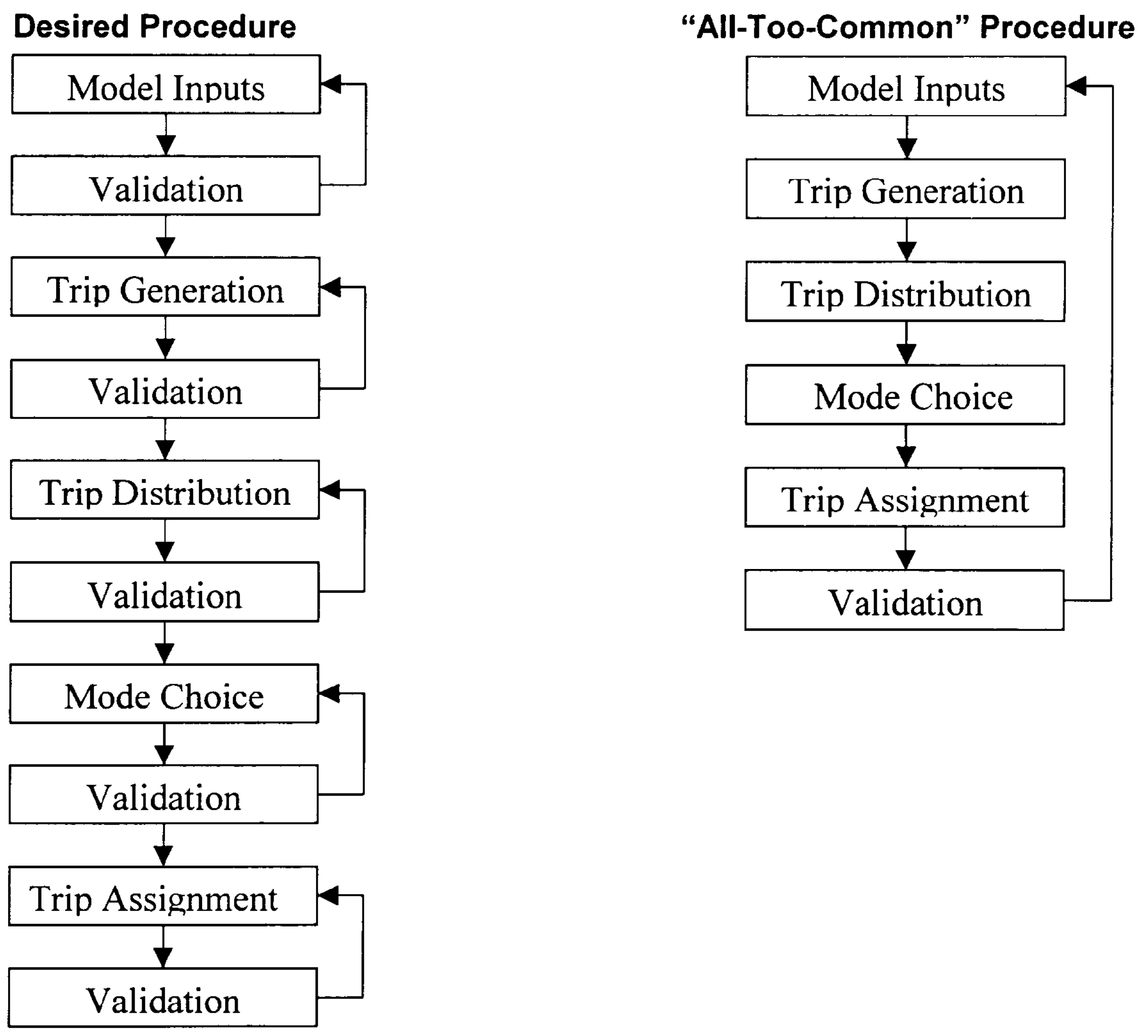
The approach advocated in this Validation Manual is to apply reasonableness checks during the processes of calibrating each individual model component. After each component has been validated, the overall set of models is validated to ensure that each is properly interfaced and that modeling error is not propagated by chaining the models together. Figure 1-2 presents an overview of the validation process contrasting the desired approach with the "all-too-common" approach.

Individual model validations are used as part of calibration to show that each component reasonably reproduces observed travel characteristics. For example, trip generation models should be checked to ensure that trip productions and attractions estimated on a district and regional basis are reasonably similar to the observed number of trips; trip distribution models are checked to ensure that they reasonably reproduce the observed average trip lengths by trip purpose; etc.

Validation of the overall set of models tests the effects of compounding errors. For example, suppose that the trip production model produced too few trips from a zone that was relatively close to a large attractor of trips. If these trip generation results are input to the trip distribution model, they would have a tendency to increase trip lengths because of the error in trip production modeling. Overall measures of model performance, such as regional VMT and screenline volumes, should be reviewed with the possibility of error propagation in mind.

Figure 1-2
Validation Process

Validation Overview (continued)



The following steps summarize the recommended overall model calibration and validation process:

1) *Estimate* model parameters and test the specification of the model structure using household travel survey data set.

2) *Calibrate* model parameters to reproduce desired regional control totals.

3) *Validate* each model component to ensure that reasonable results are produced, and that observed conditions are replicated. When available, use independent data sets to validate individual model components.

4) *Apply* travel model chain using initial calibrated parameters. Check overall aggregate measures (such as VMT by facility type and speed ranges, and screenline/cutline volumes). Compare modeled volumes with observed traffic counts.

5) *Evaluate* results from the steps above to determine whether systemwide and/or localized problems have occurred in the model application.

1.4 Validation Issues

Before presenting the validation checks in the following chapters, it is useful to consider a number of issues regarding the types of checks which are used, the level of aggregation, data sources, accuracy requirements, and sources of error.

1.4.1 Types of Validation Checks

As noted earlier in the Introduction, the approach used to validate travel models can vary a great deal depending on a variety of factors such as the types of policy options being tested and the availability of historical data. This Validation Manual provides a range of validation measures for both base year calibration and future year application of models.

Two major categories of validation checks are used in this report:

<u>Reasonableness Checks</u>: These include comparison of rates and parameters, total regional values, subregional values, logic tests, etc. Parameters should be checked against observed values, parameters estimated in other regions, or secondary data sources for consistency. The models should be evaluated in terms of acceptable levels of error, their ability to perform according to theoretical and logical expectations, and the consistency of model results with the assumptions used to generate them.

Sensitivity Tests: These include response to transportation system, socioeconomic, or policy changes. Sensitivity is often expressed as the elasticity of a variable. For example, one might examine the impact on travel demand if parking costs were to double or if bus headways were reduced dramatically. Sensitivity analysis should be used for all components of the modeling process, prior to application of the model for forecasting. It is important because projected policies (e.g. tolls) or conditions (e.g. high congestion levels) might not exist in the base year.

Throughout this manual, a number of validation tests will be described which compare observed and estimated values for a given model output (e.g. trips produced, daily link volumes) over a number of observations (e.g. TAZs, links with traffic counts).

There are four common approaches to evaluating how well the model estimates match the observed data:

1) Absolute difference: Calculated as the actual difference, i.e. Estimated - Observed. The sign (positive or negative) may be an important indicator of performance.

2) Relative difference: Values are normalized to remove scaling effects. Can be expressed as a percentage difference (e.g. acceptable range might be ±10%) or as a ratio (e.g. 0.9 to 1.1) and are calculated as follows:

$$\text{Percentage difference} = \frac{(\text{Estimated - Observed}) * 100}{\text{Observed}}$$

$$\text{Ratio} = \frac{\text{Estimated}}{\text{Observed}}$$

3) Correlation: In regression analysis, an equation is estimated which relates a dependent (or unknown) variable to one or more independent variables. Correlation analysis determines the degree to which the variables are related, i.e. how well the estimating equation actually describes the relationship. In the case of model validation, we determine the degree to which observed and estimated values are related. The most commonly used measure of correlation is the coefficient of determination R^2, which describes the amount of variation in the dependent variable which is explained by the regression equation. R^2 can range from 0 to 1, with a value of 0 for no correlation and 1 for perfect correlation. Acceptable values of R^2 can vary depending on the type of comparison being made, but it would ideally explain more than half of the variation ($R^2 > 0.5$). Note that as aggregation increases, the amount of correlation will increase.

4) Variance: Statistical measures can be calculated which measure the variance

between observed and estimated values. The most common measure for validation purposes is the Percent Root Mean Square Error (RMSE) which is described in section 7.1.3 *Highway Assignment*.

These validation tests can be easily calculated with a spreadsheet, database, or statistical package. For example, to estimate a regression line, most spreadsheet packages simply require that the observed and estimated values be placed in columns - the regression equation and R^2 are calculated using a simple command. For additional information, you may want to consult an introductory statistics textbook.

1.4.2 Level of Aggregation

Some researchers differentiate between the calibration procedures used for aggregate or first-generation models, such as zone-based regression models, and the disaggregate or second-generation models, such as individual-based choice models. With the first-generation models, calibration may involve trial-and-error adjustment of parameters which improve the overall goodness of fit between the model results and the observed data. With the second-generation models, much more attention is placed on the statistical properties of the parameters and the confidence limits of the estimated values.

Similar to calibration procedures, validation checks also vary by the level of aggregation. There is a continuum of checks ranging from validation using disaggregate data at the household level to aggregate results at the regional level. In the middle would be validation checks using the models applied to zonal data. For state-of-the-art disaggregate models, the entire range of checks is needed to ensure that the models can reproduce not only the travel behavior of individual households, but also the resulting performance of the transportation system when all of the individual trips are aggregated over the entire metropolitan area. The two ends of the continuum are defined below:

Disaggregate Validation provides a means of exploring how well a candidate model fits the observed data at the household or individual level. It involves defining subgroups of observations, based, for example, on household size and income or auto ownership levels. Model predictions are compared with observed data to reveal systematic biases. Note that disaggregate validation plays more of a role in the estimation phase of model development

Aggregate Validation provides a general overview of model performance through regional travel characteristics such as average trip rates, average trip lengths, average mode shares, and regional vehicle-miles of travel (VMT). Reasonable ranges for model parameter values have been included in the manual for comparative purposes. Travel models are applied to aggregate data at the regional, county, district, or zonal level. Traffic assignment results are validated at a regional level, using screenline volumes, and then at a local level, using cutline and individual link volumes.

1.4.3 Validation Data Sources

In order to sufficiently prove a model has been validated, the model should match observed data from an independent data source. Each chapter of this manual will discuss necessary validation data sources in detail.

While not an independent source, the calibration data set (typically from a household travel survey) is used in validation. Other travel surveys may be available for validation such as workplace/establishment, on-board transit, roadside origin-destination, and external cordon surveys. The Census Public Use Microdata Sample (PUMS) provides socioeconomic and travel behavior data at the household level.

For disaggregate models, particularly choice models with a large enough sample, a validation sample can be created by splitting the observed data set into two random groups. One sample is used for calibration, and the calibrated models are used to predict the second group's demand. A similar approach identifies stratification biases within the population by applying the models to a segment of the calibration data set. While this process does provide an independent set of observations, it lacks temporal variation.

The best estimate of socioeconomic data should be available locally, although these inputs should still be reviewed for reasonableness, particularly changes over time. Transportation system data can be compiled from other public agencies, such as the local highway administration or transit operator. Typical validation data includes daily and peak hour traffic volumes at screenlines, cutlines, critical links, and transit boardings by route.

A number of national data summaries provide comparative data including:

- FHWA's Highway Performance Monitoring System
- Census Transportation Planning Package
- Nationwide Personal Transportation Survey

Comparisons can also be made with observed data from other similar metropolitan areas. NCHRP Report 187 has recently been updated in the forthcoming report 365, *Travel Estimation Techniques for Urban Planning*. The transferable parameters contained in this report are useful for validation purposes.

Zonal socioeconomic input data and transportation system performance data should be collected for the same base year. Since virtually all transportation models have been based on cross-sectional survey data, there has been a tendency to view validation exclusively in terms of the ability of the model to match observed traffic volumes for a single base year. However, individual model components and the overall set of models should also be tested by predicting demand for a different historical time period than was used for calibration. When the models are applied to historical data, this is often referred to as backcasting. Unfortunately, consistent historical data for more than one time period are rarely available.

1.4.4 Sources of Error

Even when models reasonably reproduce their portions of regional travel, they are not without error. Error is inherent in all models since they are abstractions of real travel behavior; simplifications of reality are unavoidable in order to make the models usable and practical. Sources of error resulting from development and calibration of travel models include:

- *Measurement Errors* inherent in the process of measuring data in the base year, such as survey questions, network coding and digitizing errors, etc. resulting from poor data quality control.

- *Sampling Errors* such as bias introduced in the process of selecting the set of observations from the population.

- *Computational Errors* due to arithmetic mistakes, which are typically small for computer-based calculations

- *Specification Errors* due to improper structure of the model, such as omission of relevant variable.

- *Transfer Errors* when a model or parameters developed for one context or region is applied in a different one.

- *Aggregation Errors* arising from the need to forecast for groups of individuals (or households) while modeling needs to be done at the level of the individual.

A major concern for validation of travel models is error inherent in the collection of input data or historical data used for validation. Problems with input data or validation data can lead to erroneous corrections to models that, ultimately, will damage model performance, credibility, and results. For example, if daily traffic counts collected at screenlines are low due to incorrect collection methods, the analyst may attempt to increase auto occupancy rates or lower trip rates in order to match the screenlines. This suggests that a course of action for responding to models that do not validate is to check for errors first, then consider adjustments to parameters. Throughout the planning process, it is important to periodically perform a peer review of networks, socioeconomic inputs, and modeling procedures. Involving more than one person in the review process will often improve results and force the modeler to re-examine steps taken.

Figure 1-3 shows the possible effect of compounding error in model validation. Each step in the modeling process increases the overall error. While there is a potential for the errors to offset each other, there is no guarantee that they will.

1.4.5 Accuracy Requirements

There are no absolute measures or thresholds that can be achieved to declare a travel model or its components "validated." The level of accuracy expected of a model is somewhat subjective, and ultimately depends on the time and resources available, and on the intended application of the model. For example:

- Emissions estimates for air quality analysis require accurate summaries of VMT by speed range.
- Individual link volumes are not as critical in a long-range regional sketch plan as in a sub-area traffic impact study.
- Consideration of significant land-use changes introduces additional uncertainties and interactions into future year alternatives analysis.
- Transit contributions can vary considerably among metropolitan areas, as do the level of analysis and the complexity of representation of transit in various models.

Table 1-1 shows the estimated accuracy of some parameters in the travel modeling process. Accuracy tends to be greatest on higher volume links and screenlines. The confidence limits also show that, due to error propagation, assignment results tend to contain more error than earlier steps in the process such as trip distribution.

Figure 1-3
Effect of Compounding Error in Model Validation (from course materials)

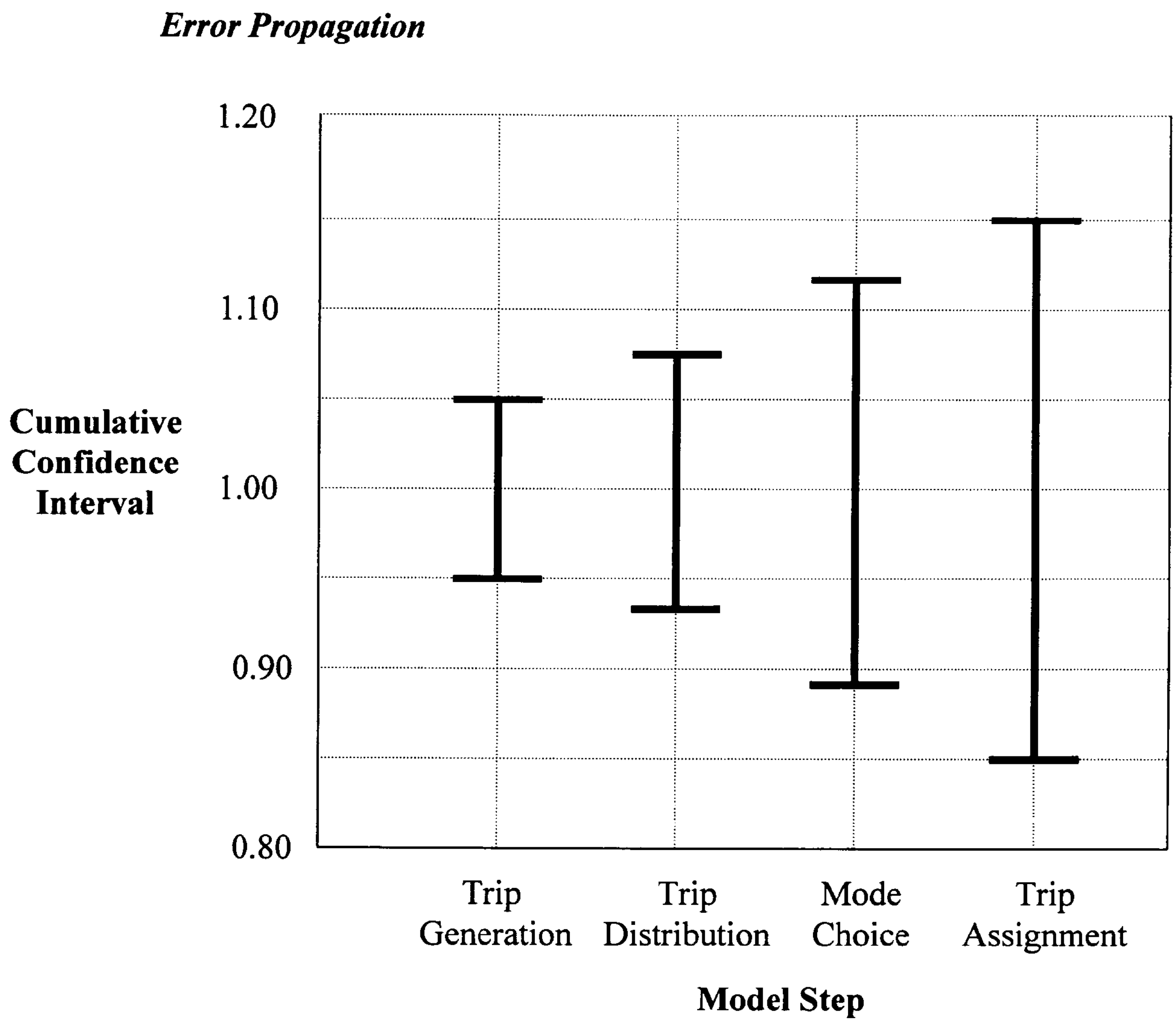


Table 1-1
Estimated Accuracy of Some Parameters in the Travel Modeling Process

Parameter	Typical Magnitude	95 Percent Confidence Limit
Zonal Generation	2,000 person trips	± 50%
Interzonal Movement	Small	Extremely Inaccurate
Major Trip Interchange	40,000 person trips	± 10%
Minor Trip Interchange	15,000 person trips	± 16%
Highway Link Loading:		
Minor Link	5,000 vehicles	± 55%
Average Link	20,000 vehicles	± 27%
Major Link	50,000 vehicles	± 17%
Public Transit Loading:		
Average Urban Link	5,000 passengers	> ± 46%
Major urban link	20,000 passengers	> ± 23%

Source: J. Robbins, "Mathematical Models - the Error of Our Ways," Traffic Engineering + Control, Vol. 18, No. 1, January 1978, p.33.

The reliability of a model validation effort is always constrained by the quality and quantity of validation data available. There is some error inherent in even the best data. Traffic counts alone can vary by 10 percent or more due to daily and seasonal variation (FHWA Guide to Urban Traffic Volume Counting, 1980). Other sources of count error include improper count location, variation in the portion of multi-axle vehicles, special events, accidents, mechanical count failure, and personnel mistakes.

Sources of significant uncertainty or potential error should be identified early in an effective validation process. Thorough knowledge of a model's design, inputs, and applications is needed to recognize if a point-of-diminishing-returns has been reached. It is important to recognize that uncertainty is inevitable, and to avoid confusing precision with accuracy.

1.5 Organization of Manual

The remainder of the Validation Manual is divided into the following chapters:

Chapter 2 discusses reasonableness checks for input data, including zonal socioeconomic data and network inputs. While these checks are not actually model validation checks, a tremendous amount of time can be wasted testing and adjusting models when the problem is with input data. Thus, a separate chapter has been devoted to this subject.

Chapters 3 through 7 discuss validation techniques and reasonableness checks for model parameters and outputs for each of the following travel model elements:

- Trip Generation
  - Socioeconomic Disaggregation
  - Trip Production
  - Trip Attraction
  - External Travel

- Trip Distribution
  - Estimating Travel Impedances
  - Gravity Model

- Mode Choice
  - Nested Logit Model
  - Auto Occupancy

- Time-of-Day/Direction Split Factors

- Traffic Assignment
  - Highway Assignment
  - Transit Assignment

Chapters 3 through 7 focus on standard four-step models. However, concepts presented in these chapters should lead the reader to reasonable validation checks for non-traditional modeling processes. Each chapter discusses strategies for systematic troubleshooting of validation problems. The highway assignment section also includes examples of validation targets used to validate the overall modeling process after the initial calibration of each component.

Appendices are included at the end of the manual which provide specific examples of parameters and travel characteristics for a number of metropolitan areas.

2.0 Model Inputs

There are two major types of data which are used as inputs to travel models. The first are socioeconomic data, which describe population, households, employment, and land use characteristics of the region by transportation analysis zone (TAZ). The second are transportation network data, which describe the region's transportation system.

It is critical that socioeconomic and transportation network data be checked prior to other steps in validation. If these data are accurate, the level of effort needed to perform other validation steps is greatly reduced. Usually the most common causes of error in travel models are inaccuracies in socioeconomic and transportation network data.

2.1 Land Use and Socioeconomic Data

Current travel demand models are based on the concept that travel is derived from the need to participate in a number of daily activities which are distributed spatially such as work, school, shopping, entertainment, etc. Travel models use zonal socioeconomic or land use data in order to reflect the underlying activity in the study area. The process by which socioeconomic data are estimated in the base year and forecast for future years has a significant impact on model results.

Regional planning agencies often provide input socioeconomic data for base-year validation of travel models. These data are nearly always based on census data, but are often revised for any year other than the decennial census year. These data and measures calculated from the data should be compared to census data from previous years to check for reasonable rates of change. Base year model input data are not actually validated against an independent data source. However, reviewing the socioeconomic inputs for reasonableness is still an important step to ensure that changes are not made to models to improve validation results when, in fact, the problems have been caused by the exogenous data used for the validation.

2.1.1 Sources of Data

In the base year, estimates of zonal population and employment should be based on the best available estimates. Primary data sources provide the information necessary for aggregate travel model validation. The decennial United States Census is an excellent source of socioeconomic data for input into models. Data from both Summary Tape File 3 (STF3) and the Census Transportation Planning Package (CTPP) can be used. STF3 provides univariate distributions of household and population data such as households by household size, households by income group, households by structure type, households by auto ownership, and population in households. The CTPP data provide multivariate distributions of household and population data such as households by auto ownership and household size, and households by income group and auto ownership.

Another source of socioeconomic data available for validation is the 1990 U.S. Census Public Use Microdata Sample (PUMS). This dataset contains individual records of responses to full Census questionaires, but with unique identifiers (names, addresses, etc.) removed to protect the confidentiality of the respondent. PUMS is available for the entire United States for areas that meet a 100,000 minimum population threshold. The standard PUMS datasets include the 5% sample county level file and 1% sample metropolitan area file. Households are geocoded to a Public Use Microdata Area (PUMA), each with population in the range from 100,000 to 200,000.

The state employment/unemployment department can usually provide information on existing numbers of jobs and employed residents, by industry sector. *County Business Patterns* provides estimates of employment by type of industry and employer size. This information is also available through the U.S. Department of Labor's Employment, Wages, and Contributions file ES-202 (Employment Securities Manual) with employment classified by Standard Industrial Codes (SIC). Employment data are often difficult to obtain because the reported employment location may not reflect the true work location of an employee. For example, franchises may list all of the employees at one single location for the purpose of the Labor Department file.

After regional totals of population and employment have been estimated, the next step is to allocate jobs and households to each traffic analysis zone. This process, often referred to as land use forecasting, occurs outside of the typical travel modeling process. Three techniques used to allocate socioeconomic data include negotiated estimates, scenario approaches, and formal mathematical land use models. Errors in allocation of data can affect both the quantity of trips generated and the distribution of those trips around the region.

2.1.2 Types of Checks

Typically regional and county control totals for socioeconomic data can be easily matched and verified. However, the allocation of regional totals to the subregional level is a process involving both technical and political challenges, particularly when developing forecasts for future year application of the model set. The main sources of error in estimating socioeconomic data for a validation year include:

- Collection (or reporting) of data, e.g. Census data collection problems, reporting all workers for an employer at a headquarters location.

- Retrieving data - data not at same geographic level as models require, e.g. Census tracts instead of traffic analysis zones.

- Specification errors - data needed are not exactly data available, e.g. auto ownership is forecasted regionally, but model is based on income level.

The first aggregate checks of model input data should involve summarizing data at the city/county/regional levels and comparing with control totals (if available). If local estimates or forecasts have not been developed, the data can be compared with other regions in terms of typical household characteristics or rates of growth. Comparisons to measures from previous models of the same region, models from other regions, and information provided in the forthcoming National Cooperative Highway Research Program (NCHRP) Report 365, *Travel Estimation Techniques for Urban Planning*, provide insight on reasonable values for these measures. Since socioeconomic characteristics do vary by region, they are best checked against local data sources.

Table 2-1 shows the national trends from the Nationwide Personal Transportation Survey (NPTS) for key demographic characteristics. Checks of these data are very straightforward and provide a simple overview of the reasonableness of the data. Basic checks include total population, total households, total employment, average household size (persons per household) and population/ employment ratio for the region. Appendix A includes summary statistics from the Census Journey-to-Work Data showing demographic statistics for some of the largest metropolitan areas.

Items that directly affect the travel models should be reviewed. For example, if trip generation models are based on workers per household and auto ownership, regional summaries of workers per household and average autos per household should be made. If the trip generation models include socioeconomic submodels to project some of the required socioeconomic data (e.g., accessibility to transit is used along with income and household size to estimate a distribution of households by auto ownership), the interim results of socioeconomic submodels at the regional level should be checked.

Some items that are not used directly by the models do provide a basis for checking input data. For example, resident labor force information is collected by the Census and Bureau of Labor Statistics and can be compared with employment (from establishments) at the regional level. That is,

$$\frac{\text{Employed Residents + External Residents Working in Region - Residents Working Outside the Region}}{\text{Total Employment (Jobs) in Region}}$$

should approximately equal 1.0.

Table 2-1

Summary of Demographic Trends from the NPTS

	1969	1977	1983	1990
Persons per household	3.16	2.83	2.69	2.56
Vehicles per household	1.16	1.59	1.68	1.77
Workers per household	1.21	1.23	1.21	1.27
Vehicles per worker	0.96	1.29	1.39	1.40
Vehicles per licensed driver	0.70	0.94	0.98	1.01

Source: 1969, 1977, 1983, and 1990 NPTS

Percent of Households by Vehicles Available (thousands)

Number of Vehicles Available	1969	1977	1983	1990
No vehicle	20.6%	15.3%	13.5%	9.2%
One vehicle	48.4%	34.6%	33.7%	32.8%
Two vehicles	26.4%	34.4%	33.5%	38.4%
Three or more vehicles	4.6%	15.7%	19.2%	19.5%

Source: 1969, 1977, 1983, and 1990 NPTS

Localized checks of socioeconomic data are used to review the allocation of regional totals to the subregional level. These levels can include districts (subregional aggregations of TAZs), individual TAZs, and TAZs or groups of TAZs which constitute major trip generators, such as CBDs, shopping malls, and suburban activity centers.

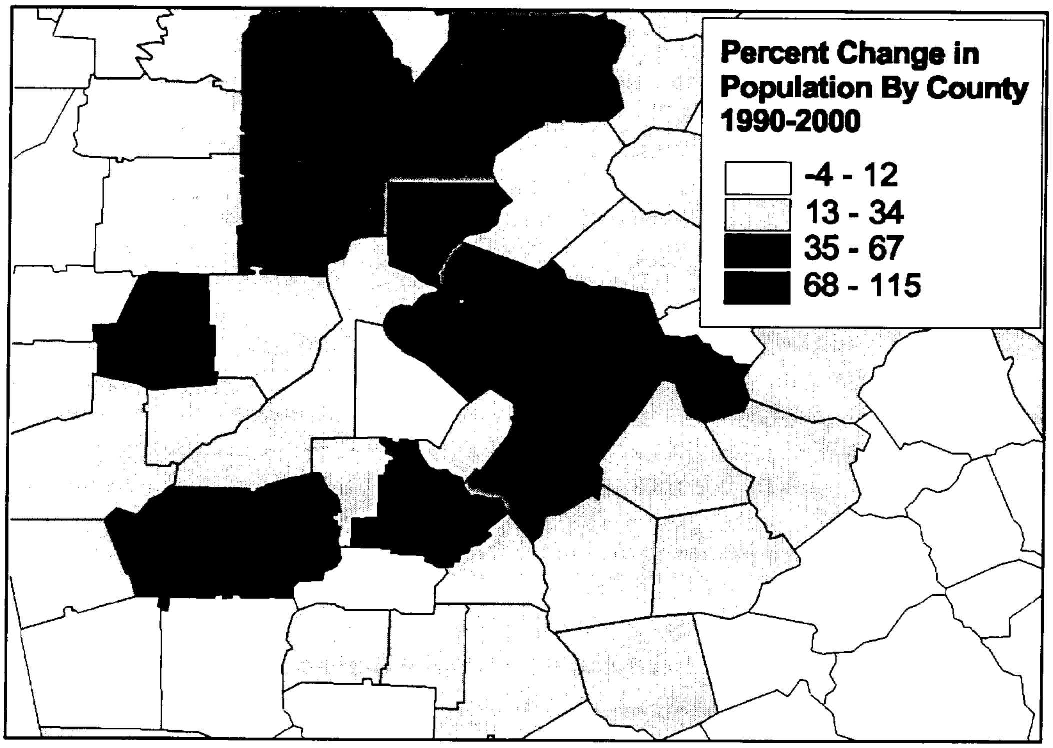
Almost any district-level or TAZ-level data can be effectively displayed using a geographic information system (GIS). Because of its graphic presentation capabilities, a GIS is an excellent tool for presenting the results of disaggregate data checks. Example zonal socioeconomic data which can be checked using a GIS include population, households, average household size, shares of households by socioeconomic stratum (e.g., income level or auto ownership), employment, and employment by category. An example plot is shown in Figure 2-1.

Two types of checks which can be performed with a GIS include:

- *Calculate densities and plot using thematic mapping.* Calculate population and employment density in persons per acre (or square mile). Densities should be grouped either using 4 or 5 equal area (or equal number of zones) categories. Color, shading, or bar symbols can be used to convey densities. Base year densities should be compared with forecasted densities.

- *Compare existing to forecasted totals by zone or district and plot changes.* Subtract existing totals from forecasted totals and plot so that positive and negative changes can be easily identified.

Figure 2-1
GIS Plot of Socioeconomic Data



2.2 Transportation Network Definition

The second type of input data to check are roadway and transit networks. Most regional planning agencies assemble data from state departments of transportation, local governments, and transit operators as major inputs to transportation network development. They also carry out primary data collection activities, such as verification of link characteristics, speed/delay studies, and transit wait time studies. These verification efforts are critical to the accuracy of the networks.

2.2.1 Highway Networks

The coded highway network represents the streets, roads, thoroughfares, and freeways that make up the regional highway system. The estimation of travel demand requires an accurate representation of the network. The most likely sources of error are from the coding process and error inherent in the base maps or digital files (i.e. TIGER files, highway attribute inventory) used to develop the network.

Centroids represent the center of activity of a TAZ. They should be located in the center of existing development for model validation. They should represent, as closely as possible, local streets within the TAZ, and the nodes connecting them with the roadway network should represent reasonable access points. Zones should not be split by any major physical barriers. The size and density of zones should correspond to the level of detail of the coded highway network.

Regional validation checks for roadway networks should include an overall visual inspection of the network, but focuses on checking ranges of speeds and capacities by facility type and area type, such as:

- Summarize route miles or lane miles by functional class, capacity, or speed.
- Calculate average speed or per-lane capacity by facility type and area type.

Detailed network checks should be made both in terms of network connectivity and network attributes.

Connectivity Checks

Visual roadway network inspections of individual links can be made using network editing and viewing routines or plotting routines provided with travel modeling software packages. Most travel modeling software packages have interactive network editors. These provide good network checking capabilities.

Network coding conventions have a significant impact on path building. Figure 2-2 gives examples of varying levels of coding detail. A simple network intersection, shown at the top, allows for unrestricted turns. In the other coding examples, freeway ramps are coded explicitly so that only permitted movements can be made. While many modeling software packages provide capabilities for adding turn prohibitors, good traffic assignments can be performed without heavy reliance on them.

Figure 2-3 displays an example of how *centroid connector coding* can impact travel paths and validation results. Ideally, connectors will be attached at the points at which local streets or driveways enter the coded highway network. In a typical urban setting, zones should be connected on all four sides roughly mid-block. If centroid connections are made on only one-side or at the intersection, assigned volumes can be over- or under-projected on the streets immediately adjacent to the zone.

Some network editors provide the capability to build and display shortest paths between pairs of centroids. This process is also known as skimming the network. *Skim trees* show the minimum path from one zone to multiple zones; *skim forests* show paths from multiple zones to multiple zones. An example plot of a network path tree is shown in Figure 2-4.

The construction and plotting of paths from one zone (or node) to other zones (or nodes) provides the capability to discover illogical travel paths. In network development, skim trees are used primarily to identify missing/incorrect links or test the coding of freeway interchanges. Typically, distance (miles) or freeflow times (e.g. based on posted speed limit) are used as the measure of network impedance. Zone pairs should be selected so that a majority of the network links are tested. At a minimum, paths should use all major facilities crossing network screenlines (see section 2.2.3). By using skim trees early in the process, network coding errors can be discovered before loading the vehicle trip table onto the network.

One of the most severe (and common) network connectivity problems is when a zone centroid is not connected to the highway network. An easy method for locating unconnected zones is by creating a skim matrix for all zones. Unconnected zones will either cause an error detected by the software, or else the matrix will contain a row of extremely large impedances (i.e. 99999) for that zone.

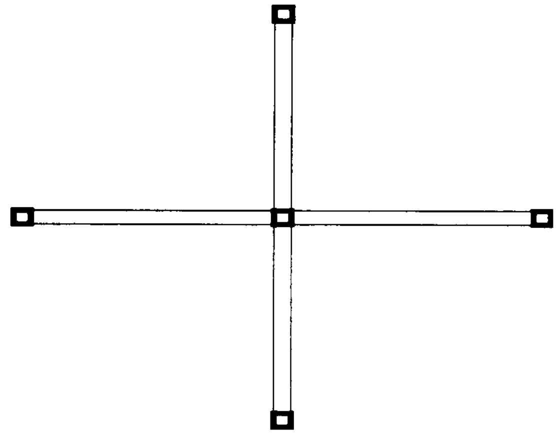
Similar path-building checks can be performed after highway assignment using paths based on congested travel times. Selected travel time paths can be compared to results from speed/delay studies.

Other network coding errors which affect path-building and assignment results include:

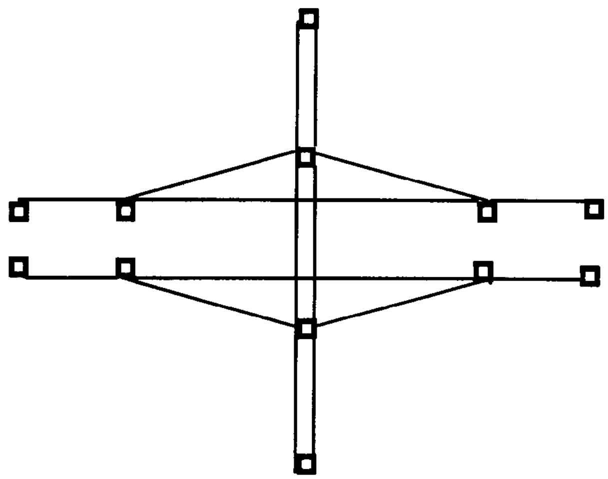
- missing nodes or links,
- one-way links going in the wrong direction, and
- trip passing through centroids instead of staying on highway links.

Figure 2-2
Network Coding Convention

Noncontrol Access Facilities Intersection



Control Access Interchange with Noncontrol Access (Freeway with 2-way arterial)



Control Access Interchange with Control Access (Freeway to Freeway)

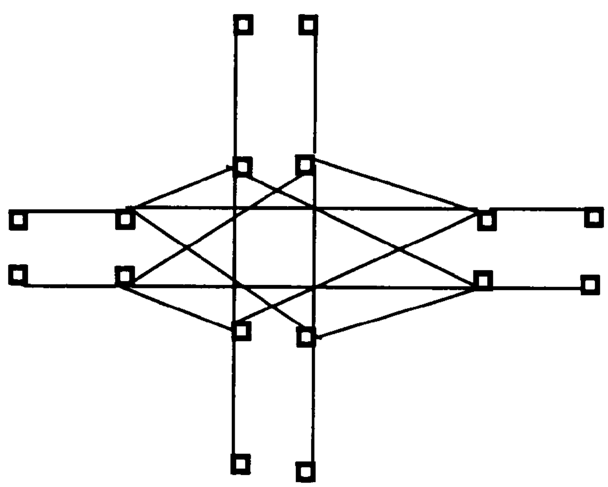


Figure 2-3
Coding of Centroid Connectors

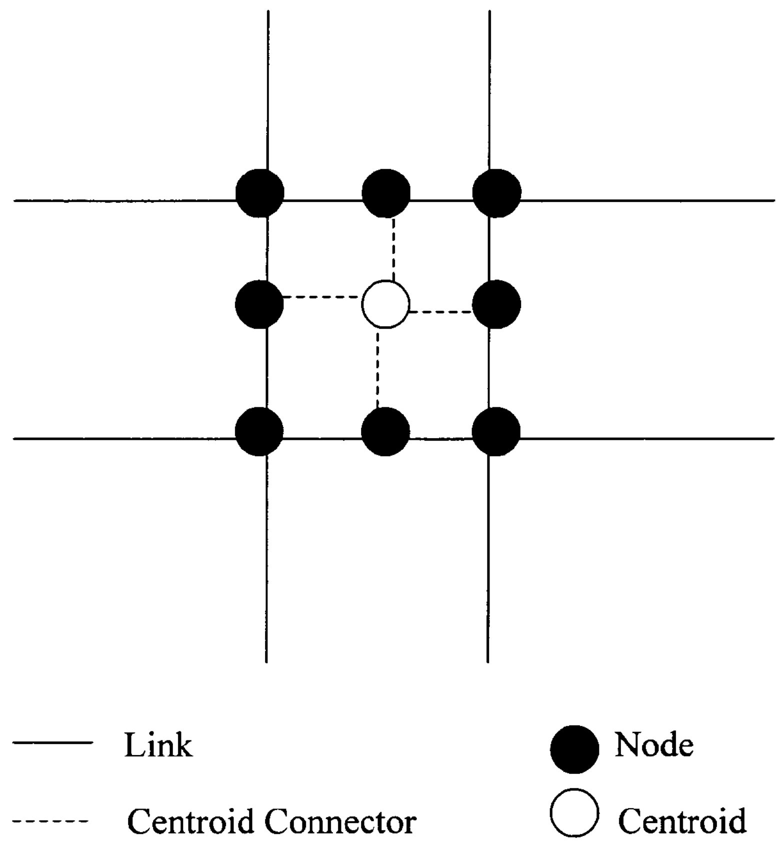
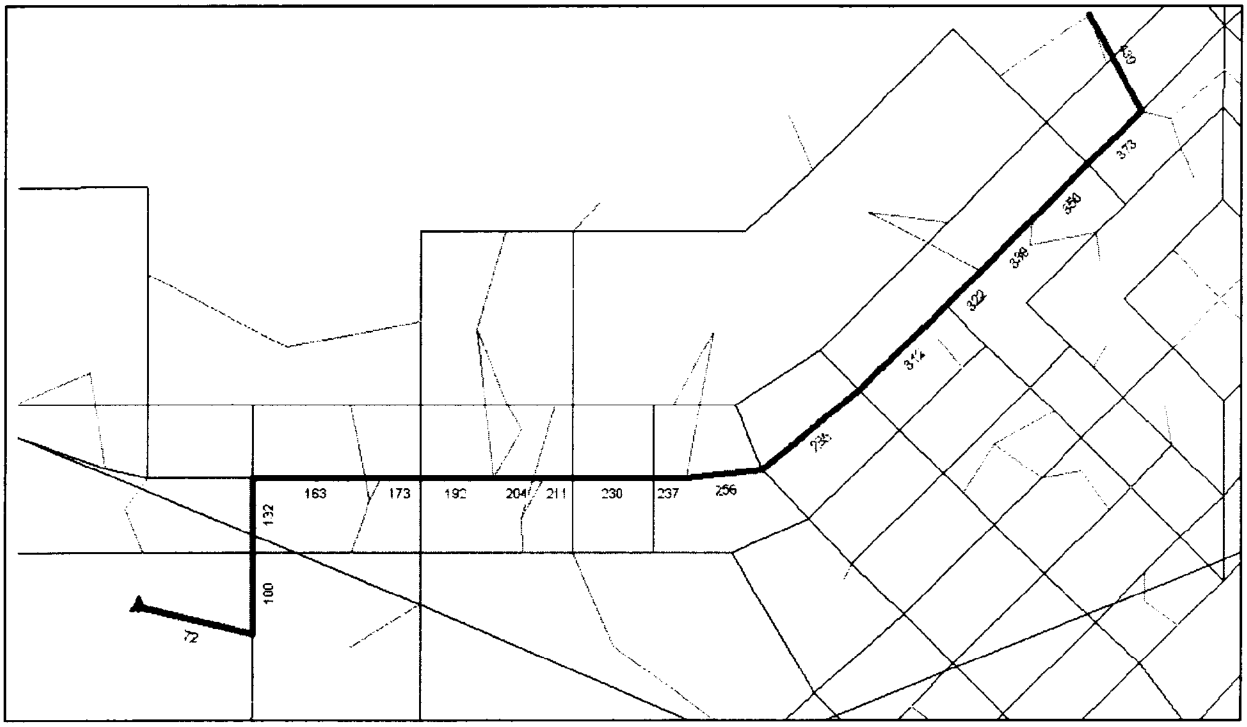


Figure 2-4
Shortest Path Between Two Nodes



Highway Attributes

Highway attribute data can be reviewed in one of two ways: range checking to verify valid ranges of input values, and color plotting using graphical capabilities of interactive network analysis programs or geographic information systems. Paper or screen plots of attributes are effective tools for verifying network accuracy. The plot displayed in Figure 2-5 shows this type of information graphically.

The following attributes should be checked and plotted where appropriate:

- **Link Distance (length):** Roadway link distances should be compared to straight-line distances calculated from node locations and coordinate geometry. Minimum and maximum link distances should be checked for reasonableness. Straight-line, or air-line, distances are calculated using the formula:

$$length = \sqrt{(x_a - x_b)^2 + (y_a - y_b)^2}$$

where

x_a = x-coordinate of the a-node
x_b = x-coordinate of the b-node
y_a = y-coordinate of the a-node
y_b = y-coordinate of the b-node

  The ratio of coded length versus straight-line length can be plotted so that links falling outside of an acceptable range (e.g. 0.9 to 1.1) can be identified.

- **Posted Speed Limit (in m.p.h.):** Speed limits may be used as inputs to a trip distribution model. However, motorists typically will travel faster than posted speeds under free-flow conditions.

- **Facility Class:** Roadways are typically classified by type such as freeway/expressway, principal arterial, minor arterial, collector, and local-access streets. High-occupancy lanes may be designated as a separate facility type.

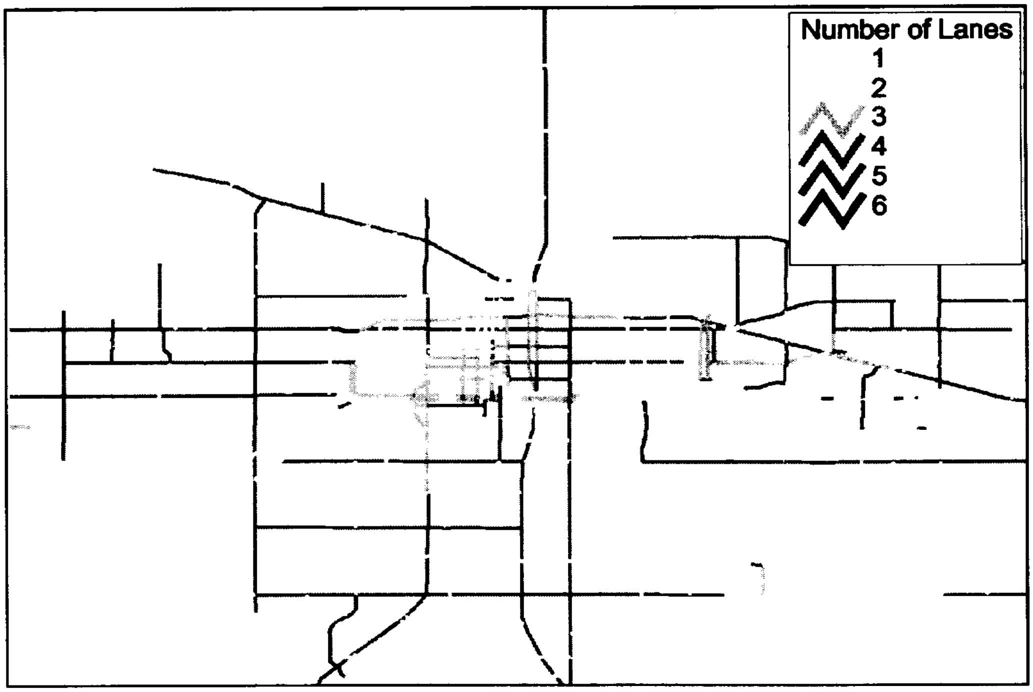
- **Area Type:** e.g. urban, suburban, and rural. If area type and facility type are used to determine default speeds and capacities, the combined code should be checked.

- **Number of Lanes:** The number of functional lanes by direction is most important, but parking and turn lanes may also be used.

- **Tolls or parking costs:** May be coded either in dollars or minutes.

- **Intersection Type**

Figure 2-5
Color-Coding of Network Attributes



2.2.2 Transit Networks

Public transportation system networks and data should be reviewed. Network plots color-coded by mode can be used to help verify access links, transfer points, stop locations, station connectivity, parking lots, fare coding, etc. If possible, the route itineraries should be plotted so that they can be compared with the transit operator's system map.

System level checks for transit networks include checks on minimum and maximum headways and range checks of walk or auto access times to stations/bus stops. Walk links often have associated walk percentages by zone which can be reviewed by looking at the zone structure along a transit route. Transit system characteristics can be listed by mode, type of vehicle, company, or route.

In addition to hard coded transit speeds, most travel modeling software packages provide the means to directly relate bus speeds to highway (auto) speeds. The relationship between transit speed and highway speed is not the same for all highway links. For example, buses on a freeway operate at speeds that approximate auto speeds, while buses on downtown streets may operate much more slowly than auto traffic. Checks should be made to ensure that bus speeds are less than or equal to, and not greater than, auto speeds (except for bus express lanes).

In some transit modeling software, it may be possible to trace shortest transit paths and compare differences between competing routes in a corridor. For example, routes coded over the same roadway section should have the same stop nodes (unless explicitly different as between a local and express route).

One typical source of error with transit modeling occurs when bus routes traverse local streets not coded in highway networks. It may be desirable to code special transit-only links to allow for routes that deviate significantly from the coded network in order to account for additional travel time on local streets.

2.2.3 System Performance and Validation Data

In adddition to the data collected as inputs to the travel models, it is important to collect and review system performance data which will be used in the validation process. The most common types of validation data include highway traffic volumes, highway speeds and travel times, and transit ridership.

Traffic Volumes

Average daily traffic (ADT) and peak hour traffic volumes are collected at a number of locations throughout the region. Two methods are commonly used: 1) using an automatic traffic counter (either in one or both directions), and 2) manually counting vehicles. ADT is typically collected using automatic counters, while counts classifying vehicles by type (e.g. automobile, light truck, heavy truck, motorcycle) are typically done manually. Manual counts can also be used to collect vehicle occupancy data.

Sufficient coverage of traffic counts may be available already at permanent count locations. Additional counts may be needed at critical links, especially along imaginary lines that are used to assess model validation. These are described below and shown in Figures 2-6 and 2-7:

- *Screenlines* typically extend completely across the modelled area and go from boundary cordon to boundary cordon. For example, a river that passes completely through the area makes an excellent screenline. Travel demand that goes from one side of the river to the other must cross this river screenline within the study area boundary. Screenlines are often associated with physical barriers such as rivers or railroads, however jurisdictional boundaries such as county lines that extend through the study area make excellent screenlines.

- *Cutlines* extend across a corridor containing multiple facilities. They should be used to intercept travel along only one axis.

- *Cordon lines* completely encompass a designated area. Cordon lines are typically associated with the boundary of the area being modelled. However, for model validation purposes, it is also helpful to develop internal cordon lines or boundaries. For example, a cordon around the central business district is useful in validating the "ins and outs" of the CBD related traffic demand. Over or under estimates of trips bound for the CBD could indicate errors in the socioeconomic data (employment data for the CBD) or errors in the trip distribution or mode choice model.

Figure 2-6
Example of Screenline Locations

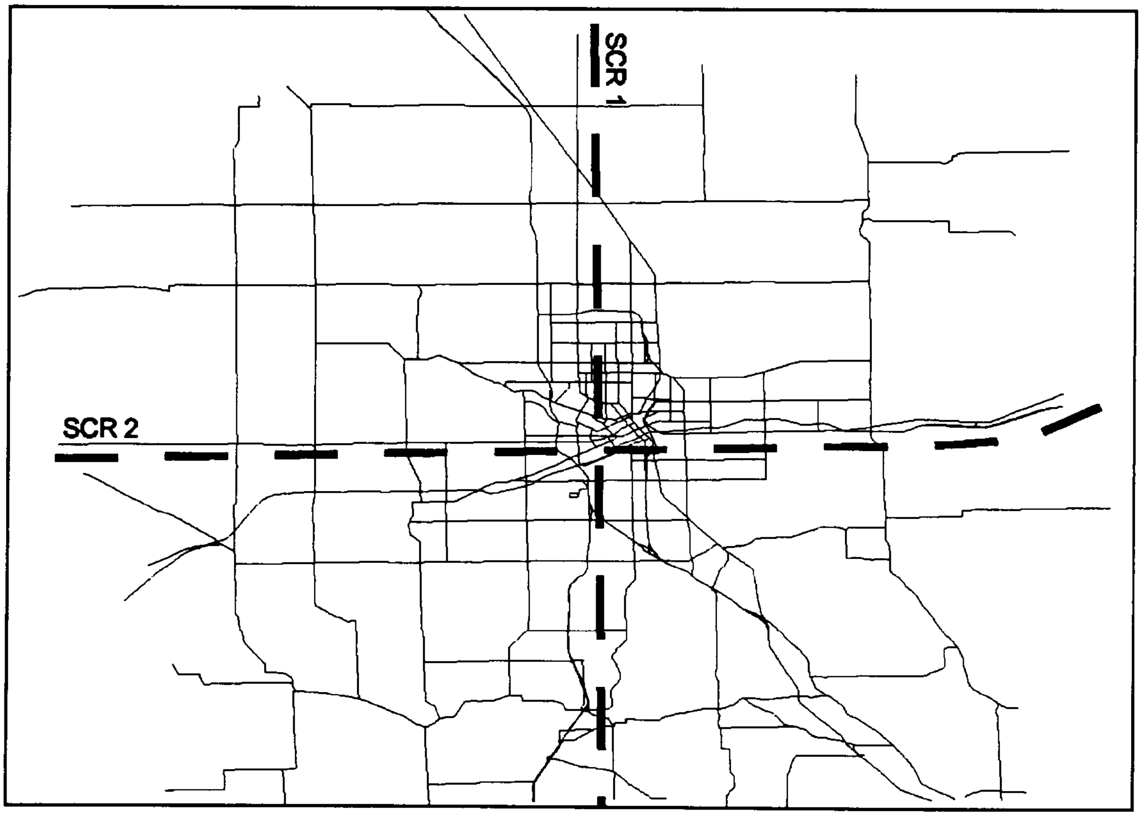
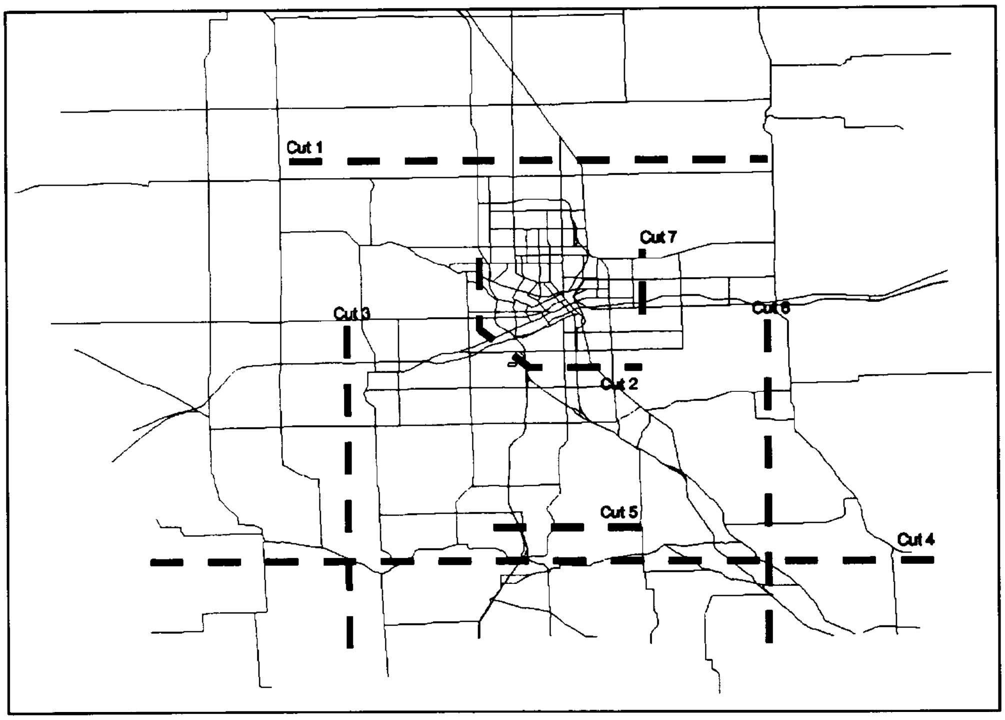


Figure 2-7
Example of Cutline Locations



If multiple counties are included in the modelled area, then each county boundary can form either a cordon or screenline, dependent upon its location within the area. Using county boundaries as cordon and screenlines allow the use of the Census data for validating the home based work trip distribution. The Census data provides summaries, by county, of place of residence versus place of employment. This county-to-county distribution of home and work place can be used as a surrogate for the observed work trips.

Each roadway that crosses a screenline must be taken into account. Roadways which carry significant traffic volumes should be coded into the roadway network and traffic count data should be included. Minor roadways which carry very low traffic volumes may be omitted from the network and from the traffic count database, but their volumes should be estimated and accounted for in the validation analysis.

The traffic counts should be collected during the same year for which the model is being validated. In order to obtain the most typical estimate of ADT, FHWA recommends that a minimum of one midweek 24-hour count be taken at least every two years. Three-day counts can be averaged to improve reliability. Factors can also be applied to the count to relate weekday to average week traffic, and to relate a given month to average monthly conditions. Peak and off-peak traffic volumes can be taken directly from automatic tube counters or from hourly classification counts.

Counts should be reviewed for reasonableness using measures such as volume per lane (e.g. 4,000 vehicles/lane-hour might be unreasonable, etc.).

Speed (or Travel Time)

Speed measurements are particularly important for validating modeled speeds which are used as inputs to air quality emissions models. Observed speed data can be posted on network links with other attribute data Speeds can be collected for peak and/or off-peak time periods using floating car runs or radar detection. Due to the cost of collecting speed data, many areas have very limited information for the highway network. Ideally, speed data should be collected for as many locations as possible for a given area type and facility type (e.g. urban-freeway, suburban-principal arterial, etc.)

Transit Ridership

Three sources of public transportation data include onboard origin-destination surveys, load point checks, and ride checks. Onboard surveys are typically used in the calibration process and should be used to validate total transit trips, trips by route, and trip interchanges made on public transportation. Passenger load checks are performed at location selected for proximity to the maximum load point of a route. Typical information would include headways and schedule, passenger loads compared with seats available, and boarding/alighting activity at that particular location. Ride checks involve having an individual ride a transit vehicle and monitor the number of passengers boarding and alighting at each bus stop.

2.3 Forecasting and Monitoring Model Inputs

Checking the reasonabless of model inputs for the validation base year is only the first step in the process. In order to produce projections of future travel, the models must be applied to forecasts of future population, employment, and other socioeconomic variables. Monitoring is used to determine if development trends and transportation system characteristics are evolving as forecasted.

Socioeconomic Inputs

There is more uncertainty (and potential for error) in predicting socioeconomic inputs to TAZ's. Forecasts are typically made at the traffic analysis zone level for population and households, mean or median income, auto ownership or availability, and employment by type (retail vs. non-retail). Demographic relationships (persons/household, workers/ household, employment/population ratios, etc.) and growth rates should be checked for consistency with expectations, assumptions, and policies. Significant changes in land use must also be carefully evaluated for reasonableness with respect to regional and local growth rates, in both absolute and relative terms.

Care must also be taken to maintain constant dollars with respect to income, parking and operating costs, transit fares, etc.

Transportation Networks

The transportation networks (infrastructure and operational characteristics) for future alternatives are typically well-defined in long-range transportation plans and other documents. They are essentially treated like base networks, although capacities and speeds may be adjusted to reflect more advanced signal coordination systems or ITS strategies.

For future year analyses which involve updates to the base network, once the existing base (or "no-build") highway network has already been checked, the simplest check of the accuracy of coding highway network changes is to overlay the build network over the no-build network to check the differences.

3.0 Trip Generation

The trip generation model estimates the number of motorized person trips to and from each TAZ in the study area. In this step of the travel forecasting process, socioeconomic data are used to estimate the number of daily motorized person trips within the study area, i.e. internal-internal, and with origins or destinations outside the study area, i.e. external-internal or internal-external.

The trip generation model estimates trip productions and trip attractions. For transportation planning purposes, a trip production is a trip end made at the home location for home-based trips and the origin location for non-home-based trips. For example, if a person travels from home to work and then from work to home on a certain day, that person would be considered to have two home-based work trip productions at his or her home and two home-based work trip attractions at his or her work location.

In most metropolitan area transportation models, trips are stratified by purpose. Typical trip purposes can include: home-based work; home-based non-work such as shopping, school, other; and non-home-based.

The trip generation model typically has a number of components including the following:

- Socioeconomic Disaggregation Submodels -- These models provide data in sufficient detail to apply disaggregate trip production models. For example, one may need to estimate households by income group and household size given zonal households, populations, and median household income. Other models can be used to project auto ownership for households.

- Trip Production Models -- These models estimate trip productions on a traffic analysis zone level. Productions are typically a function of population or number of households (or both) along with a measure of wealth such as income or autos. Other explanatory variables might be used (e.g. number of workers, life-cycle, etc.)

- Trip Attraction Models -- These models estimate trip attractions on a traffic analysis zone level. Attractions are typically a function of socioeconomic activity - households, employment by type, school enrollment - but can also be land-use based (e.g. gross floor area for manufacturing, retail, government, open space, etc.).

Two other components of trip generation include:

- Estimation of external trip ends

- Procedure for balancing trip productions and attractions

3.1 Socioeconomic Disaggregation Submodels

<u>Model Description</u>

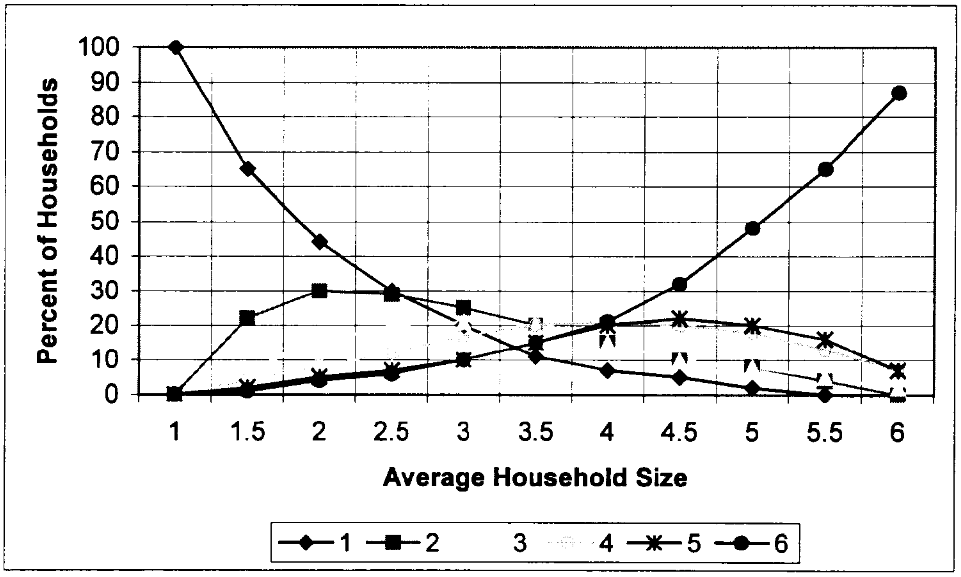
The socioeconomic submodels play an important role in forecasting the inputs to disaggregate trip generation models. While the detailed demographic data required for trip generation is available for the base year from the Census, land use forecasting procedures will typically only produce aggregate zone level estimates of households, population, median income, and vehicles. As a result, socioeconomic submodels are needed to develop disaggregate zonal estimates.

It has been ascertained in a number of other studies that the mix of disaggregated households is fairly similar for any spatial grouping given the average values. For example, if the average household size in a zone is 1.5 persons per household, it is logical to anticipate that there will be large numbers of one- and two-person households and fewer households with more than three persons. In order to develop a model, household data are summarized for small ranges of the zonal average, whether it be household size, income, or autos owned, to provide average aggregate estimates of the mix of households.

The primary data source used for calibration is typically the Census Transportation Planning Package (CTPP) at either the TAZ or Census tract level. For example, CTPP Table 1-17 lists the number of households by household size and vehicles available. A household travel survey may be used as a secondary source for verifying the distributions since it is not as robust as the Census data. The CTPP provides a breakdown of households by zone for the households size, auto ownership, and income group classifications.

An example of a household size disaggregation model is shown in Figure 3-1. A similar set of curves can be developed for other socioeconomic variables.

Figure 3-1
Household Size Disaggregation Model



Another type of procedure used by regions are disaggregate vehicle ownership (or availability) models which predict the number of vehicles available to households for each traffic analysis zone. These models typically incorporate a number of socioeconomic variables, the most important of which is income level. The model structure can vary from empirical curves to discrete choice models, but the type of aggregate validation checks used is roughly the same for all procedures.

Table 3-1 displays typical percentages of households by autos owned and income level.

Table 3-1
Percent of Households by Autos Owned and Income

Urbanized Area Size = 200,000 - 499,999				
INCOME	AUTOS OWNED			
	0	1	2	3+
Low	17	51	24	8
Medium	2	32	53	13
High	0	13	53	34
Weighted Avg.	7	32	42	19

Source: NCHRP 365

Note: In 1990 dollars, Low Income = less than $20,000; Medium Income = $20-39,999; and High Income = $40,000 and up.

Validation Tests

The models can be validated against the zonal level Census data used to develop them. The models would first be applied using the calibration data (e.g., for a household size submodel, using the observed average household size). The result of this step would be observed and estimated households by household size for each zone.

Several possible validation tests are described below:

- *Compare observed and estimated households by socioeconomic subgroups.* The differences can be examined in absolute terms and the coefficient of determination (R^2) can be calculated over all strata (e.g. 0-1 Avg. Household Size, 1-2 AHHS, 2-3 AHHS,...). Look for systematic biases. An example of the socioeconomic subgroups is shown in Table 3-2.

- *Calculate correlation (or coefficient of determination R^2) of shares of observed and estimated households by subgroups.* R^2 can be inflated since it also measures "zone size effects", i.e. zones with a lot of households result in a lot of households while zones with few households result in few households by group. Using the shares instead of absolute values helps to factor out "zone size effects."

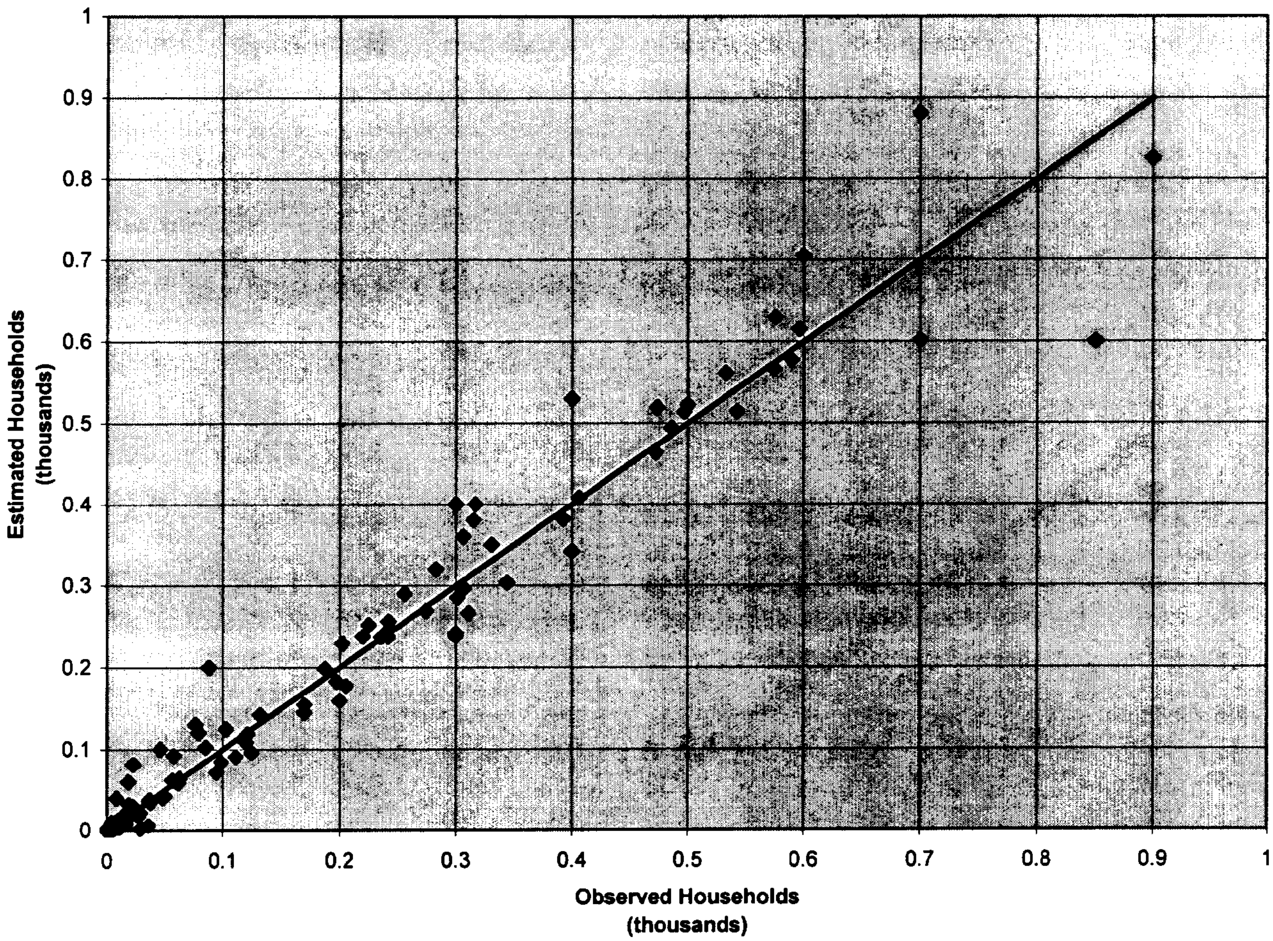
- *Calculate correlation (or coefficient of determination R^2) and plot the relationship between the observed and estimated households for each household size group at the district or census tract level.* Look for geographic biases. An example scatterplot is shown in Figure 3-2.

Other types of models might be used to estimate socioeconomic variables. For example, a few regions have developed disaggregate choice model to predict vehicle ownership (or availability). The methods outlined above can be used to validate these models. Other, more disaggregate, tests can also be performed (see discussion in Chapter 5.0 - Mode Choice).

Table 3-2
Observed and Estimated Households by Size Subgroups

Household Size Range	1 Person Households		2 Person Households		3 Person Households		4 Person Households		Total Households
	Obs.	Est.	Obs.	Est.	Obs.	Est.	Obs.	Est.	
1.00 - 1.04	181	181	0	0	0	0	0	0	181
1.05 - 1.14	0	0	0	0	0	0	0	0	0
1.15 - 1.24	0	0	0	0	0	0	0	0	0
1.25 - 1.34	308	293	28	33	5	15	8	8	349
1.35 - 1.44	29	35	17	7	0	3	0	2	46
1.45 - 1.54	382	391	115	119	38	34	33	23	568
1.55 - 1.64	1,531	1,452	515	622	183	190	144	109	2,373
1.65 - 1.74	987	912	425	512	114	150	136	88	1,662
1.75 - 1.84	1,656	1,749	1,211	1,232	472	357	231	232	3,570
1.85 - 1.94	1,208	1,187	938	991	313	320	250	211	2,709
1.95 - 2.04	1,126	1,259	1,263	1,207	555	452	283	310	3,227
2.05 - 2.14	1,178	1,185	1,211	1,280	600	542	396	379	3,385
2.15 - 2.24	2,714	2,569	2,981	3,074	1,279	1,450	1,312	1,193	8,286
2.25 - 2.34	1,373	1,346	1,562	1,710	1,028	886	775	796	4,738
2.35 - 2.44	1,962	1,908	2,570	2,648	1,534	1,481	1,415	1,444	7,481
2.45 - 2.54	2,948	2,886	4,465	4,405	2,367	2,595	2,877	2,772	12,657
2.55 - 2.64	2,431	2,469	4,172	4,124	2,486	2,567	3,076	3,005	12,165
2.65 - 2.74	2,362	2,316	4,251	4,221	2,664	2,805	3,591	3,526	12,868
2.75 - 2.84	1,506	1,425	2,871	2,832	2,030	2,040	2,500	2,610	8,907
2.85 - 2.94	659	708	1,722	1,518	1,102	1,189	1,577	1,645	5,060
2.95 - 3.04	605	590	1,554	1,332	1,013	1,146	1,585	1,689	4,757
3.05 - 3.14	242	201	622	478	289	460	708	722	1,861
3.15 - 3.24	188	172	492	420	439	449	693	770	1,812
3.25 - 3.34	58	19	22	52	45	62	121	113	246
3.35 - 3.44	0	0	0	0	0	0	0	0	0
3.45 - 3.54	17	14	83	42	64	60	93	141	257
3.55 - 3.64	0	9	56	25	42	39	79	104	177
3.65 - 3.74	6	2	12	6	8	10	27	34	53
3.75 - 3.84	0	0	0	0	0	0	0	0	0
3.85 - 3.94	28	6	47	18	49	34	94	160	218
3.95 or more	143	10	178	31	87	73	113	406	521
Total	25,828	25,296	33,383	32,940	18,806	19,408	22,117	22,490	100,134

Figure 3-2
Observed vs. Estimated Households by Census Tract



3.2 Trip Productions

Model Description

Trip production models have been based primarily on one of two basic structures: (1) regression equations, and (2) cross-classification trip rates. While earlier trip generation models were based on the regression method, most of the recently developed models are now based on the cross-classification method.

Regression models for trip generation were generally developed when origin-destination surveys were conducted for relatively large sample sizes. The large sample sizes provided enough samples of trips to cover most of the geographic area surveyed. This type of model is aggregate since the model is developed using data at the zonal level rather than the household level.

Regression equations explain the variation in a dependent variable, in this case, trips, based on one or more independent, or explanatory, variables. For example, a work trip production model may have the form:

*Home-Based Work Trips = a + b * (households) + c * (workers) + d * (autos)*

A distinct disadvantage with multivariate regression equations is that explanatory variables are often interrelated and correlated with each other. Interaction effects occur when one independent variable depends on the value of another independent variable. For example, zones with more households would also be expected to have more workers and more autos. Another weakness of regression models is that a large value for the constant *a* can distort the number of trips estimated for a zone.

Zonal models can only explain the variation in trip making behavior between zones, yet the main variations in person trips data occurs at the household level. In order to overcome this weakness, current state-of-the-practice models typically uses a set of trip production rates stratified by relevant characteristics of households for a given purpose. Trip rates can then be used to estimate trip productions by multiplying the rate by the total number of households in a category or cell.

While the use of a single category, such as auto ownership, will explain some of the variation in the number of trips, the use of multiple variables tends to improve the predictive ability of the model. Stratification of trip rates is often done with at least two independent variables such as income level, auto ownership, number of persons, household density range, and/or number of workers. These variables have been shown to be directly related to trip generation characteristics. Most models will use household size and a wealth variable, such as income or auto ownership, as the independent variables. Base data used for the calibration of trip production models is usually a regional household travel survey.

Cross-classification models are better than regression models in their ability to handle non-linear functions of variables. For example, a four-person household may not produce twice as many trips as a two-person household. Another advantage is that they are calibrated using disaggregate household data, which requires a smaller sample size than is required for more aggregate zone level calibration. The use of disaggregate data (i.e., households) reduces errors due to averaging. The main disadvantage of this approach is the need to forecast the number of households in each category.

There are a number of sources of error in the development of trip generation models. Sampling error and bias in the travel survey affect the trip generation rates. In some cases, the model may not be specified correctly with the relevant explanatory variables.

Validation Tests

The first validation checks which should be made for the trip production models involve examination of total and purpose-specific household trip rates. The most important of these regionwide checks are described below (from aggregate to disaggregate):

- *Calculate total person trip productions per household or per capita.* Examples of typical trip rates are available from the forthcoming publication *NCHRP 365 Travel Estimation Techniques for Urban Areas.* Table 3-3 shows trip estimation variables by urban size. Table 3-4 shows the average trips per household for a number of regions which was obtained from recent household travel surveys. Note that trip rates range from 8 to 14 trips per household on a typical day. The NCHRP 365 report concludes that urban size may not have a significant impact on variation in trip rates; geographical characteristics and level of service by mode may play a more important role. Variations in trip rates per household might be caused by variation in household sizes; trip rates per capita avoids this problem. A rule of thumb for models calibrated in the past decade is that the total person trips in motorized vehicles per capita should be over 3.0 and, very likely, in the range of 3.5 to 4.0. Note that comparisons of total trips should be consistent in terms of modes (motorized trips vs. all modes) and amount of trip linking.

- *Calculate total person trips by purpose.* Since trip generation models are stratified by purpose, the number of trips by purpose generated by the model is very important. Table 3-5 compares trips rates for a number of regions by purpose. Tables 3-3 and 3-6 compare the percentage of trips by purpose.

Table 3-3
Typical Trip Estimation Variables from NCHRP 365

Urban Area = 200,000 - 499,999

Income	Avg. Autos Per HH	Avg. Daily Pers Trips Per HH	Avg. Daily Veh. Trips Per HH	% Average Daily Person Trips by Purpose		
				HBW	HBO	NHB
Low	1.3	6.8	5.4	17	60	23
Medium	1.8	9.5	8.3	20	56	24
High	2.4	12.4	11.2	23	52	25
Wtd. Avg.	1.8	9.0	7.8	21	56	23
HH Size	**Avg. Autos Per HH**	**Avg. Daily Pers Trips Per HH**	**Avg. Daily Veh. Trips Per HH**	**% Average Daily Person Trips by Purpose**		
				HBW	HBO	NHB
1 Person	1.0	3.6	3.2	20	56	24
2 Person	1.9	7.0	6.3	23	53	24
3 Person	2.1	11.3	10.3	22	54	24
4 Person	2.2	13.4	11.2	18	61	21
5 Person+	2.4	16.8	13.5	19	59	22
Wtd. Avg.	1.8	9.0	7.8	21	56	23

Table 3-4
Average Motorized Person Trips per Household by Region

Region	Survey Year	Population	Person Trips/HH
Dallas-Ft.Worth	1984	1,000,000	8.68
Charlotte, NC	1985	511,433	9.29
Vancouver, WA	1985	259,000	5.83
San Diego, CA	1986	2,498,000	14.30
Northern NJ	1986	1,278,000	7.75
Austin, TX	1986	536,693	7.99
Reno,NV	1987	254,000	8.58
Phoenix, AZ	1989	840,000	8.98
Puget Sound	1989	2,559,000	12.20
St.Louis, MO	1990	2,444,000	9.05
Nashua, NH	1990	154,000	10.08
Pittsburg, PA	1990	2,323,000	10.72
Twin Cities, MN	1990	2,464,000	10.11
Atlanta, GA	1991	2,834,000	9.81

Source: FHWA Analysis of Survey Trip Rates (Unpublished)

Table 3-5
Comparison of Person Trips per Household

Purpose	Houston[1]	Dallas/Ft. Worth[2]	Denver[2]	San Francisco[2]	Atlanta[2]	Delaware Valley[3]
	1985 Models	1984 Trvl. Sur.	1985 Trvl Sur	1985 Trvl Sur.	1980 Trvl Sur.	1986 Trvl Sur.
HBW	1.71	2.29	1.96	1.89	1.95	2.27
HBNW	4.80	4.32	3.40	4.49	4.45	4.19
NHB	2.96	2.07	1.97	2.35	1.87	1.64
Total	9.47	8.68	7.33	8.71	8.27	8.10

Table 3-6
Comparison of Percentage of Person Trips by Purpose

Purpose	Houston[1]	Dallas/Ft. Worth[2]	Denver[2]	San Francisco[2]	Minn/St. Paul[4]	Atlanta[2]
	1985 Models	1984 Trvl. Sur.	1985 Trvl Sur	1985 Trvl Sur.	1982 Trvl Sur.	1980 Trvl Sur.
HBW	18.1%	27.0%	26.0%	23.6%	17.9%	23.6%
HBNW	50.6%	47.7%	47.0%	49.7%	53.7%	53.8%
NHB	31.3%	25.3%	27.0%	26.7%	28.4%	22.6%
Total	100%	100%	100%	100.0%	100.0%	100%

Sources:

1 - "Development, Update and Calibration of 1985 Travel Models for the Houston-Galveston Region", Prepared by the Houston-Galveston Area Council and Texas Transportation Institute, June 1991.

2 - "The 1984 Home Interview Survey in the Dallas-Ft. Worth Area: Changes in Travel Patterns, 1964-1984, Transportation Research Record 1134, Transportation Research Board, Washington, D.C., 1987.

3 - "Interregional Stability of Household Trip Generation Rates from the 1986 New Jersey Home Interview Survey", Transportation Research Record 1220, Transportation Research Board, Washington, D.C., 1989.

4 - "Calibration and Adjustment of System Planning Models", FHWA, December 1990.

- *Compare observed and estimated trips produced at the regional (aggregate) level.* Apply the model to base year zonal data to estimate trips produced by zone, and sum over all zones. The estimated number of trips are compared with the observed number of trips, which comes from weighted (expanded to the regional universe of households) trip records from the household travel survey. Comparisons of observed and estimated trips can be made for a number of different classifications including the following:

  - Trips by purpose (Home-Based Work, Home-Based Non-Work, etc.)
  - Trips by geographical area (region, county, district, zone)
  - Trips by income level or autos owned

  Differences between observed and estimated trip totals may be due to both error in the trip generation model, as well as sampling error in the household travel survey. In the example shown in Table 3-7, the effect of the sampling error has been explicitly shown by presenting a range for the observed trips by purpose. In most cases, the modeled trips were within the range of the sampling error. However, for some of the purposes, the final estimates of trips were substantially greater than would be expected due to sampling error. In the validation process, this was attributed to under-reporting of trips on the survey and justified as a method to match regional vehicle miles of travel (VMT).

- *Calculate the coefficient of determination (R^2) and plot the relationship between the observed and estimated trips (or trip rates) by districts.* An example scatterplot is shown in Figure 3-4. The geographic level at which this test is performed depends on the number of observations per district; comparisons at the TAZ level would not be possible unless the sample size was very large. The use of total trips by district is a "biased" validation measure in the sense that large zones produce a lot of trips, small zones produce fewer trips. Thus, the resulting R^2 is measuring zone size. A better measure would be to calculate the observed and estimated average household trip rates at the zonal or district level and compare these values. This comparison is a better indicator of model performance, even though it results in lower values for R^2.

- *Compare observed and estimated trips produced at the household (disaggregate) level.* Apply the model for each household in the survey to estimate trips produced (e.g. each 1-person, low-income household will produce 0.57 HBW trips, etc.) Compare the estimated trips with the observed number of trips by household (e.g. HH#1 has 0 HBW trips, HH#2 has 2 trips, etc.),

Table 3-7
Aggregate Trip Generation Checks
Albuquerque Travel Model Summaries for 1992

Item	Surveyed Range of Values[1]	Modeled Value[2]
Home-Based Work	357,538-388,110	385,001
Home-Based School	230,658-250,382	232,441
Home-Based Shop	210,703-228,719	274,639
Home-Based Other	658,406-714,704	858,194
Non-home-Based Work-Related	197,819-220,845	272,132
Non-home-Based Other	368,079-410,925	506,352
Total Internal-Internal Trips	2,052,772-2,184,116	2,528,759
Total Trips per Person	3.64-3.87	4.49
HB Work Trips per Employee	1.29-1.40	1.39
HB Shop Trips per Retail Employee	4.15-4.50	5.40

1 Surveyed range of person trips based on measured sample error from 1992 household survey
2 Modeled person trips include increases to trips to match regional VMT

Source: Barton-Aschman Associates, Inc.

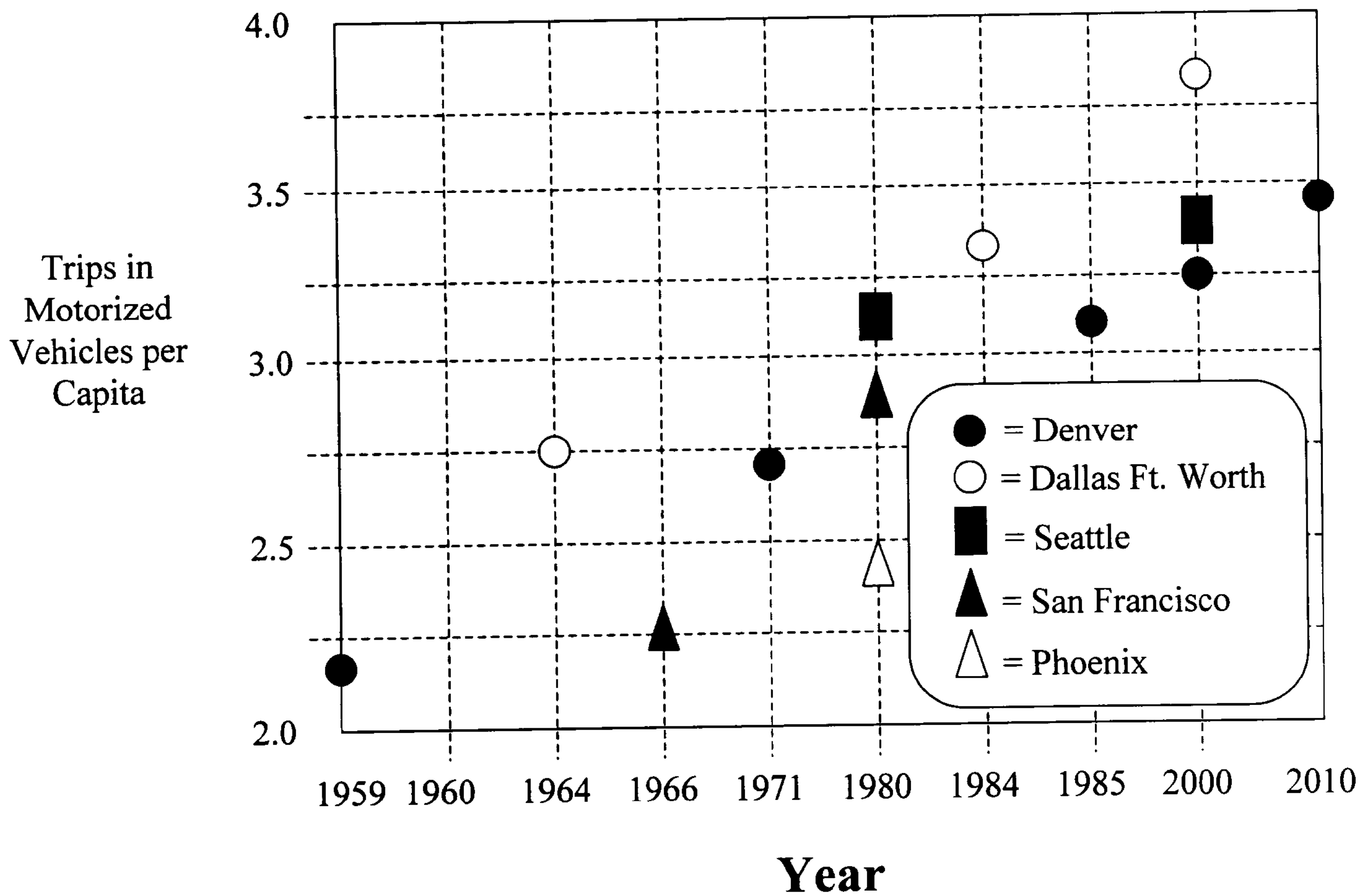
Sensitivity of trips per capita can be checked relative to changes in average household size, workers per household, income level, and auto ownership (not all of these variables would be included in a single model). Such an analysis involves relating variations in individual independent variables (inputs) to the resulting changes in the dependent variable (output).

Figure 3-3 shows the number of trips per capita that have been surveyed in several cities over a number of years. As can be seen, there is a general trend that the number of trips per capita is increasing over time, albeit at a decreasing rate. One factor to consider is that surveys may also have improved (or changed) over the same time period in terms of capturing more of trips made by each household. The use of activity-based surveys may further increase the portion of trips recorded by the survey respondent.

While examination of trip rate trends might be considered an aggregate data check, it can also form the basis for a sensitivity check. For example, if the trip generation model for a future year results in static or decreasing trips per capita compared to the base year, concerns may be raised about the sensitivity of the trip generation model to the factors driving the increase in per capita trip-making.

Since observed data is not available for future years, validation of forecast models can rely as heavily on qualitative measures as quantitative ones. For example, are trip generation rates increasing, and is this trend consistent with household composition and income?

Figure 3-3
Trips per Capita - Selected U.S. Cities (from course materials)



3.3 Trip Attractions

Model Description

The trip attraction model is used to predict the trip ends which are associated with the non-home end of the trip. The same trip purposes that are used for the trip production models are used for the trip attraction models. Two different approaches can be used to calibrate trip attraction models similar to those used for trip production models. The first method is to develop regression equations which relate the trip attractions to a number of explanatory variables such as population, households, employment, density, and school enrollment. A second method is to estimate regional trip-attraction rates, stratified by land use or employment category.

Attraction models are typically developed from the same household travel survey used to calibrate the trip production model. Data limitations are often a problem with trip attraction models. While household travel surveys provide excellent data for production models on the location, nature, and trip-making characteristics of households, much less information is available on activity locations. Nearly all household surveys are too small to provide stable zone level attraction data. As a result, attraction models are typically developed with regression equations using data aggregated to large districts. Zone-level calibration is more realistic if an establishment survey of major trip attractors has been conducted.

Validation Tests

Validation of trip attraction models should use the same basic procedures as for the trip production models. Trip attraction rates should be reviewed for reasonable relationships and compared with other areas. The following rates should be reviewed:

- Home-based work person trip attractions per total employment
- Home-based school trips per school enrollment
- Home-based shop trips per retail employment

The trip attraction models can be applied to zonal input data to estimate trip attractions in the base year. A comparison of observed and estimated trips should be made at either the district or county level.

3.4 Special Generators

Special attention should be paid to identifying the location and magnitude of activity associated with major trip generators, including CBDs, shopping malls, suburban activity centers, hospitals, government installations such as military bases, airports, and colleges and universities. It is likely that some of these should be represented in the modeling system as special generators, particularly military bases, airports, and colleges and universities. These are major land uses for which the standard trip generation and distribution models are not expected to provide reliable estimates of their travel patterns.

Two sources of data against which to check trips produced at activity centers include local trip generation surveys and ITE trip generation rates[1]. Local surveys, such as traffic impact studies, often provide detailed driveway traffic counts and may include occupancy information. ITE trip generation rates are classified by land use type. Since both of these sources give estimates of vehicle trips, these should be converted to person trips using an average auto occupancy.

3.5 Modeling Trips for Other Purposes

The previous sections have described trip generation for trips made internal to the study area by residents of the study area. In addition to those trips, trips for several other purposes need to be accounted for in the modeling of travel for the region. These trips include:

- truck trips or those trips made by commercial vehicles in the region,
- non-resident trips or trips made by non-residents of the modeling area while they are visiting the study area,
- internal-external trips or trips made by residents and non-residents of the study area with one end inside of the study area and one end outside of the study area, and
- external-external trips or those trips passing through the study area without stopping.

Truck Trips

Information on commercial vehicle travel within most regions is limited. In most regions where truck traffic is a minor component of the vehicular traffic, truck trips are estimated by simply factoring the auto trips. Classification counts which separate traffic volumes by type of vehicle are collected for a wide range of locations in the region. The percent of truck trips can be estimated and then applied to the auto vehicle trips before assignment. An alternative to simply factoring auto vehicles to obtain truck demand is to estimate truck trips separately using truck generation, distribution, and assignment models.

Internal Trips by Non-Residents

Non-residents of a region travel into the region for many purposes. Their trips into and out of the region are accounted for as internal-external trips (see below). However, while they are in the region, they make trips that are totally internal to the region before returning to their residences outside the region. In effect, these trips are non-home-based trips by non-residents of the region. In other areas with a great deal of travel made by tourists, a separate model is calibrated. However, for the most regions, a simple accounting of non-resident travel should be sufficient.

If overall trip generation appears low based on internal and external trip purposes, the non-home-

[1] **Institute of Transportation Engineers**, 1997. *Trip Generation Sixth Edition*. Publ. No. 1R-016D. Institute of Transportation Engineers, Washington, D.C.

based trips can be factored to reflect those trips made by non-residents. A simple factoring procedure is based on the assumption that the ratio of internal NHB trips to external-internal trips made by non-residents is equal to the ratio of NHB trips to home-based trips made by residents. This is expressed in the following equation where numerator should include the sum of all of the non-home based trips, both work-related and other purposes. The denominator should include the sum of all home-based trips for the residents of the region.

$$NHB_{ratio} = \frac{NHB}{HBW + HBSh + HBSc + HBO}$$

Non-residents of the region are assumed to behave like residents of the region for their non-home-based trip making. The non-home-based trip ratio for non-residents is set equal to the rate derived for residents shown above. Thus, the number of non-home-based trips made by non-residents of the region can be estimated using the following equation:

$$NHB_{nr} = NHB_{ratio} \ x \ IX_{nr} \ x \ IX$$

where: **NHB_{nr}** is the non-home-based trips made by non-residents
NHB_{rate} is the non-home-based ratio made by residents
IX_{nr} is the proportion of total internal-external trips attributed to non-residents
IX is the total number of internal-external trips

This procedure is best illustrated by an example. In typical urban area models, NHB trips made by residents equal about 25 percent of total trips. Percentages can be substituted for trips in the above equation for NHB_{ratio} without changing the results.

Therefore the ratio of NHB to HBNW would be:

$$NHB_{ratio} = \frac{\% NHB}{\% HBNW} = \frac{.25}{.75} = 0.33$$

The equation for NHB trips made by non-residents is factored to convert vehicle trips to person trips. Discounting the auto occupancy rates and assuming that the proportion of total internal-external, external-internal trips (IX_{nr}) made by non-residents is about 90%, then the following equation would be used to compute internal non-home based trips made by non-residents:

$$NHB_{nr} = NHB_{ratio} \ x \ 0.90 \ x \ IX = 0.33 \ x \ 0.90 \ x \ IX = 0.30 \ x \ IX$$

While this calculation estimates a rate of 0.30, the final factor will be based on the calibration of the entire model set and will be based on the match of assigned volumes to observed count data. If the overall assigned volumes are consistently below the count data then this factor can be adjusted upward. Conversely, it can be reduced if the model over-assigns travel.

External Trip Generation

Internal-external trips have one trip end outside of the cordon and are modeled as vehicle trips. For the base year, the control total for a given external station is the daily traffic volume after through traffic has been subtracted out.

External-external, or through, trips have both trip ends outside of the study area. These trips are also modeled as vehicle trips. There is no trip generation model for this purpose since both ends of the trip occur outside of the area being modeled. An origin-destination matrix for the through vehicle trips is developed using the external cordon survey and is added to the other internal-based vehicle trips before traffic assignment.

The total number of external-based trips comes directly from daily counts at the external cordon. However, in many metropolitan areas, limited data are available on the percentage of cordon traffic that are through trips and the origin-destination movements of external trips. As a result, through trip percentages may be adjusted during validation of the assignment results in order to match observed traffic count volumes.

3.6 Balancing Productions and Attractions

The last step in trip generation modeling is the balancing of regional trip productions and attractions. The regional total of trip productions must be equal to the total of trip attractions for each trip purpose in order to apply the gravity model in the trip distribution step.

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.

The ratio of regionwide productions to attractions by purpose should fall in the range of 0.90 to 1.10 prior to balancing. If this is not the case, then socioeconomic data and trip rates should be reviewed again.

To bring the regional totals in balance, either the zonal productions or 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 due to the fact that we generally have a greater degree of confidence in household data than we do in employment data. This is particularly true when a home interview survey serves as the base for developing the trip production rates. The 100% inventory of households is 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 traffic analysis zone level of geography. Although some regions have collected a complete inventory of employment, the trip attraction rates are usually calibrated from household travel survey data when no workplace survey is collected.

The exception is for non-home-based trips where trip attractions are used as the control totals and productions are scaled to match attraction totals. Special generators are another example where attractions would be the control total for the balancing process. If external trips are not treated as a separate purpose, then these may be held constant since the cordon line vehicle crossings serve as a control total. External-internal trips may need to be converted from vehicle to person trips if these are included with the productions and attractions.

4.0 Trip Distribution

Trip distribution links the trip productions in the region with the trip attractions to create matrices of interzonal and intrazonal travel, called trip tables. The critical outputs of trip distribution are trip length and travel orientation (suburb to CBD, CBD to suburb, etc.), and the resulting magnitude of traffic and passenger volumes. The results of trip distribution are assigned (after mode split has been determined) to the highway and/or public transportation systems to determine the travel demand as related to the carrying capacity of the facilities in question.

The most common form of model used for trip distribution is the gravity model. 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 theory states that the number of trip interchanges between two traffic analysis zones will be directly proportional to the number of productions and attractions in the zones, and inversely proportional to the spatial separation between the zones. The inputs for gravity model-based trip distribution models are productions and attractions for each zone and a matrix of interzonal and intrazonal travel impedances.

4.1 Determination of Travel Impedances

One of the major inputs to gravity model-based trip distribution models are the travel impedance matrices. Travel impedances reflect the spatial separation of the zones based on shortest travel time paths for each zone-to-zone interchange.

Some models use a generalized cost approach which converts highway travel time to cost and combines the time cost with other highway costs including operating expenses (i.e. gas, wear-and-tear), parking, and tolls.

In areas with minimal transit service, travel impedances for trip distribution are typically based only on highway times. For regions with extensive transit service, a "composite impedance" approach allows for the inclusion of multiple modes serving the trip interchange. One consequence of this approach is that overall predicted travel patterns will change when a transit improvement is made - this would not occur if only highway time is used. Transit travel times are separated into each component of the trip - walking or driving to a stop, waiting, in-vehicle travel, and transferring. Transit costs are the fares paid by the passenger.

The creation of highway impedances (also called *skimming the network*) involves determining the path of least resistance (impedance) between each pair of zones; summing the various components of highway impedance along that path (time, distance, toll, or a combination of these); adding the travel time for intrazonal trips and the terminal times at the trip ends; and then storing these components in travel time matrices (*skims*).

The use of feedback loops has been highlighted in a number of recent national publications and conferences as "best practice" for travel modeling. In past modeling practice, distribution used highway speeds that were estimated from static look-up tables for specified conditions (see Table 4-1). Best practice takes the congested speeds from the assignment step back to the distribution step through the use of a feedback loop.

Table 4-1
Example Look-Up Table
Average Speeds for Trip Distribution (mph)

Area Type	Facility Type					
	Freeway	Class 1 Arterial	Class 2 Arterial	Class 3 Arterial	Collector	Centroid Connector
Urban	50	35	25	20	15	10
Suburban	55	40	35	25	20	15
Rural	60	45	40	35	25	20

Regardless of the procedure used to estimate travel speeds, several types of reasonableness checks can be performed to ensure that the highway skims contain realistic values. The first is a simple determination of implied speeds for each interchange. These can be estimated by simply dividing the skimmed highway distance by the highway travel time and converting for units:

$$S_{ij} = D_{ij} / T_{ij} * 60$$

where:

S_{ij} = speed from zone i to zone j in miles per hour
D_{ij} = shortest path distance from zone i to zone j in miles
T_{ij} = shortest path time from zone i to zone j in minutes
60 = conversion of minutes to hours

Once the above calculations are made, several items can be checked. The first might be the minimum and maximum speed by interchange or from a group of zones (e.g. area type). The second might be a simple frequency distribution of speeds on all interchanges. This can be done by creating a matrix of "1's" and performing a trip length frequency distribution using the speeds as the impedance matrix and the "1's" as the trip table. In some software packages, this matrix histogram can be summarized directly as an unweighted matrix histogram (skipping the step of creating the matrix of 1's). The key items to review in this distribution are the extrema - any very slow or very fast interchange speeds.

Another aggregate network-level check is of terminal times. These represent the time spent traveling to/from a vehicle to/from the final origin or destination within the TAZ. Terminal times are generally determined using the area type of the TAZ. The terminal times may be adjusted as part of the trip distribution model calibration process in order to make the average trip lengths produced by the model more closely match the observed average trip lengths. If terminal times are used to adjust impedances, these will tend to shift the friction factor curve to the right making the distribution of trips from that zone less sensitive to impedance. Terminal times might also affect mode choice.

Two sets of terminal times are determined—one to be used at the home end of the trip and one to be used at the attraction end. An example of initial terminal times is shown in Table 4-2. These classifications of terminal times should be checked for reasonabableness by measuring actual terminal times for specific combinations of area types and trip end types.

Table 4-2
Terminal Times (minutes)

Area Type	Production End	Attraction End
Urban	2	4
Suburban	1	2
Rural	1	1

The terminal times shown in Table 4-2 are used to augment the estimated congested and uncongested travel time matrices (including intrazonal times). The production end terminal times are added at the origins and the attraction end terminal times are added at the destinations.

4.2 Gravity Model

Model Description

The gravity model trip distribution technique is an adaptation of the basic theory of gravitational force. This method is the most common technique for distributing trips. Other approaches include Intervening Opportunities and Destination Choice models. Types of aggregate validation checks remain basically the same regardless of which method is used.

As applied in transportation planning, the gravity model theory states that the number of trips between two traffic analysis zones 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.

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

The gravity model for trip distribution is defined as follows:
where:

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

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

The friction factors are inversely related to spatial separation of the zones—as the travel time increases, the friction factor decreases. A number of different functional forms have been used for friction factors. In fact, early gravity models used "hand fitted" friction factor tables. More recently, however, it has been discovered that mathematical functions such as the "gamma" function produce a realistic trip distribution and can be easily calibrated. Other friction factor calibrations are based on the power or exponential functions.

It is important to note that the trip length frequency distributions, not the observed trip tables from an origin-destination survey, form the basis for model calibration. There was typically little statistical significance to zonal interchange data collected as part of a home interview survey. In fact, even the 1%, 4%, and 10% sample surveys performed throughout the U.S. in the 1950s and 1960s were not sufficiently large to produce statistically significant trip tables at the zonal interchange level. There is, however, a reasonable degree of statistical significance to the average trip lengths and trip length frequency distribution data collected in household travel surveys.

Validation Tests

Observed and estimated trip lengths are both calculated using network-based impedance. A summary of some modeled trip lengths from different regions is shown in Table 4-3. Most packages automatically calculate average trip length for all trip interchanges. In effect, it is finding the average travel time from the skims matrix weighted by the trip matrix.

Most household travel surveys, and secondary sources such as the CTPP and NPTS, do ask respondents to report travel times to work. However, these times are not considered as reliable as the origin and destination information obtained from the survey. Reported times do serve a purpose in model validation by providing a "ballpark" estimate of trip length. Examples of Census Journey-to-Work reported trip lengths are listed in Appendix A.

The 1990 NPTS found the reported average commute travel time to be 19.7 minutes and 10.6 miles (see Table 4-4). Work trip lengths are typically in the 20 to 25 minute range, although these can be longer for large metropolitan areas and shorter for small metropolitan areas. Non-work trip lengths are typically less than those for work trips.

- *Compare average trip lengths by purpose.* The most standard validation checks of trip distribution models used as part of the calibration process are comparisons of observed and estimated trip lengths. Modeled average trip lengths should generally be within five percent of observed average trip lengths.
  If a generalized cost is used as the measure of impedance, average trip lengths and trip length frequency distributions should be checked using the individual components of generalized cost (e.g., time and distance).

- *Compare trip lengths for trips produced versus trips attracted by purpose by area type.* An example of a summary showing trip lengths produced and attracted by area type is shown in Appendix B. Average trip lengths sent and received by district could be mapped using GIS.

- *Plot trip length frequency distributions by purpose.* The trip length frequency distribution shows how well the model can replicate observed trip lengths over the range of times (see Figure 4-1). Visual comparison of distributions is an effective method for validation. A quantitative measure which can be used to evaluate distribution validation is the coincidence ratio.

Table 4-3
Comparison of Trip Lengths Among Cities

City	Year of Survey	Average Trip Length in Minutes					
		HBWork	HBShop	HBSchool	HBOther	HBNon-Work	NHB
San Juan	1991	35.4	14.2	15.5	16.1	--	16.2
Denver	1985	22.7	--	--	--	12.9	13.8
Northern N.J.	1986	23.2	14.4	--	--	15.3	17.1
Phoenix	1988	19.3	10.6	--	--	13.0	13.6
Charles-ton, WV	1993	20.7	18.7	15.9	17.3	--	15.7
Reno	1990	11.2	8.6	9.34	10.4	--	8.1
Houston	1985	20.9	9.4	8.9	11.7	10.6	12.7

Table 4-4
Commuting Patterns of Home-to-Work Trip by Mode

Mode	1969	1977	1983	1990	Percent Change (69-90)
Trip Distance (Miles)	9.9	9.2	9.9	10.6	7%
Travel Time (Minutes)	22.0	20.4	20.4	19.7	-10%

Source: NPTS

Coincidence Ratio

The coincidence ratio is used to compare two distributions. In using the coincidence ratio, the ratio in common between two distributions is measured as a percentage of the total area of those distributions. Mathematically, the sum of the lower value of the two distributions at each increment of X, is divided by the sum of the higher value of the two distributions at each increment of X. Generally, the coincidence ratio measures the percent of area that "coincides" for the two curves.

The procedure to calculate the coincidence of distributions is as follows:

Coincidence	=	sum {min ($count_{+T}/count_{+}$, $count_{.T}/count_{.}$) }
Total	=	sum {max ($count_{+T}/count_{+}$, $count_{.T}/count_{.}$) }
Calculate for T	=	1, maxT
Coincidence Ratio	=	coincidence / total

where

$count_{+T}$	=	value of estimated distribution at Time T
$count_{+}$	=	total count of estimated distribution
$count_{.T}$	=	value of observed distribution at time T
$count_{.}$	=	total count of observed distribution

The coincidence ratio lies between zero and one, where zero indicates two disjoint distributions and one indicates identical distributions. Thus, in the upper portion of Figure 4-2, the area in common is shaded. In the lower portion of the figure, the common area, also shaded is greater as the distributions are closer. Thus, the coincidence ratio will be higher for the second example.

Figure 4-1
Home-Based Work - Trip Length Frequency Distribution

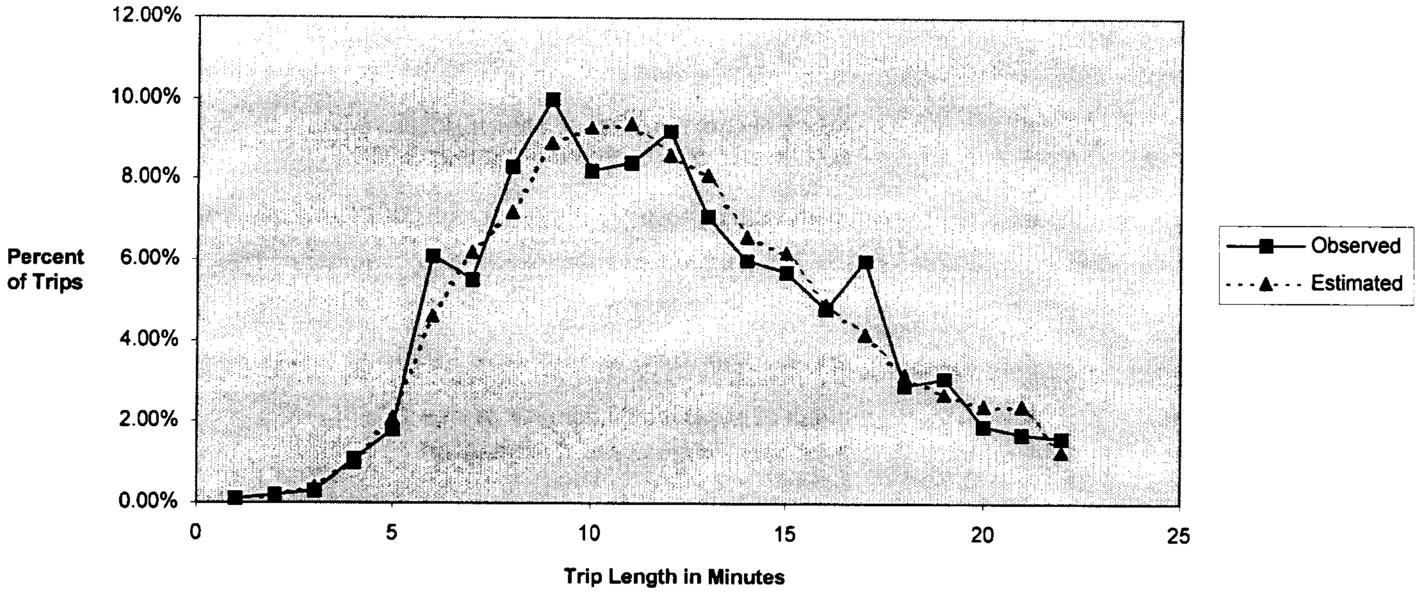
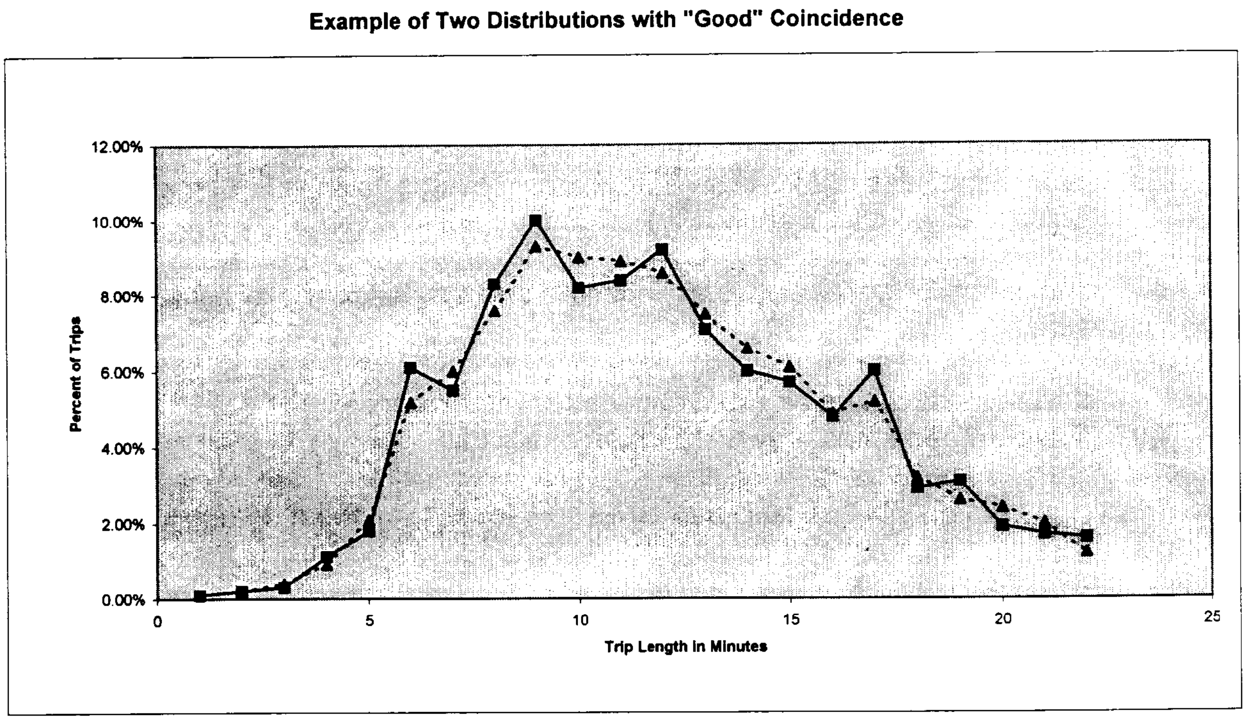
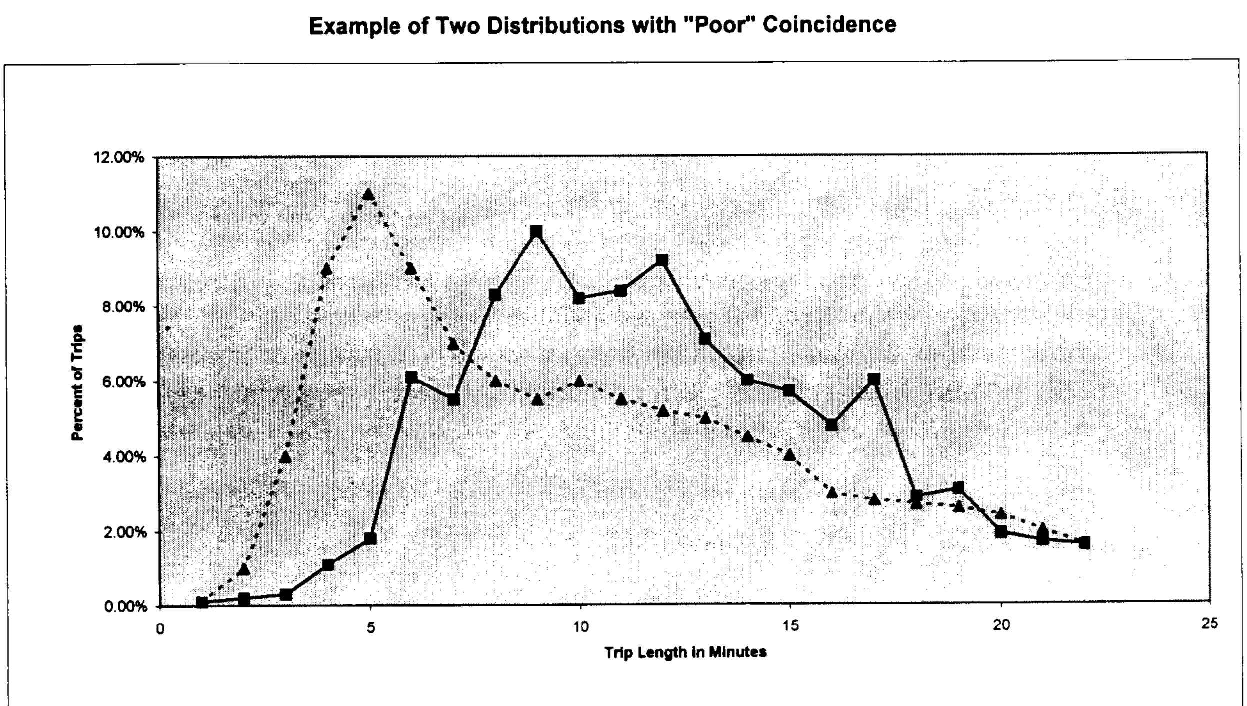


Figure 4-2
Coincidence Ratio for Trip Distribution





- *Plot normalized friction factors.* If a gravity model is used for trip distribution, it is also worthwhile to plot the calibrated friction factors (scaled to a common value at the lowest impedance value). Such a plot provides a picture of the average traveler's sensitivity to impedance by trip purpose and can be compared to friction factors from other regions. For example, travelers might be expected to be less sensitive to travel time for work trips since these trips must be made every day and can usually not be shifted to off-peak conditions or to different locations. This is shown in Figure 4-3 where the friction factors for work trips show gradual change as travel time increases.

If there are significant differences between observed and estimated trip lengths, this may be due to a number of factors:

- Inadequate closure on production/attraction balancing.
- Travel impedances may be too high or too low.

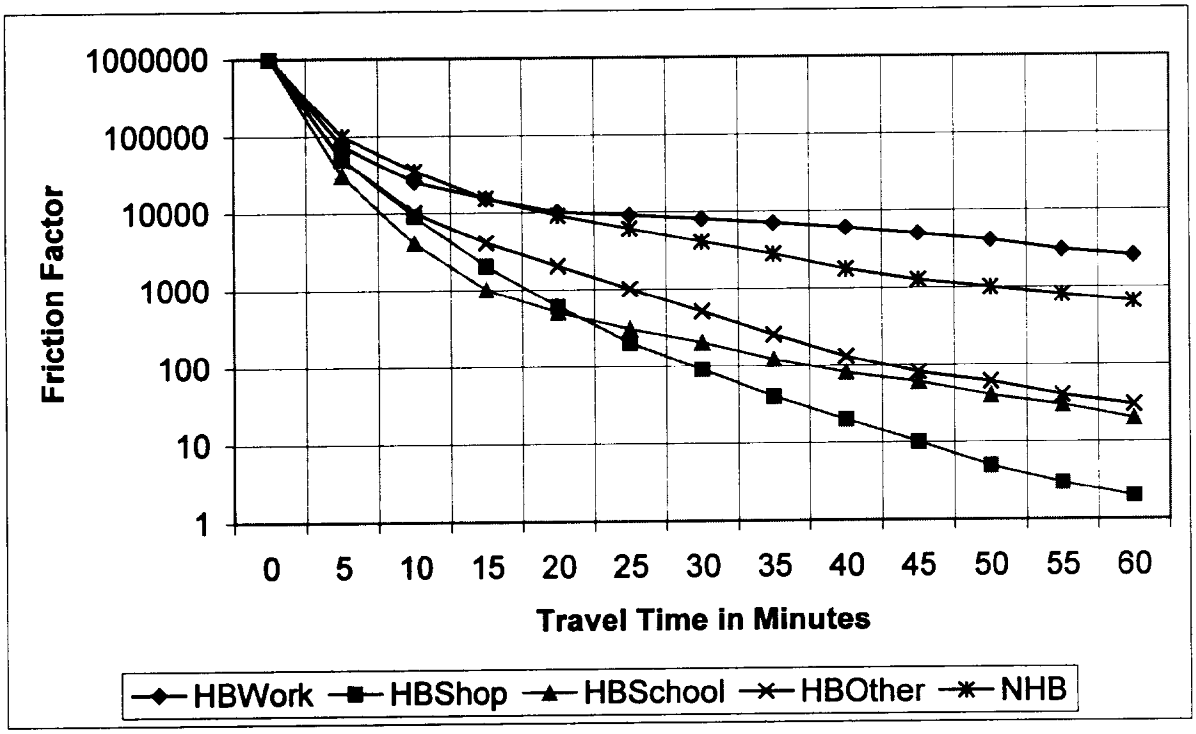
After validating the trip distribution model at a regional level, the model results should be checked for subgroups of trips and segments of the region. Appendix C shows an example of a validation summary used in New Orleans.

- *Calculate percent of intrazonal trips by purpose.* The percent of intrazonal trips by purpose should be checked for the region and by zone size (e.g., ranges in area such as 0 to 0.5 square miles, 0.5 to 1 square mile, etc.). Typically intrazonal trips account for less than 5% of total person trips. However, this percentage is highly dependent on zone size and the ideal amount will depend on whether the travel model is used for regional or local-level analysis. Systemwide link volumes can be modified by varying the number of intrazonal trips through changes to intrazonal times.

- *Compare observed and estimated district-to-district trip Interchanges and major trip movements.* Although comparing trip lengths provides a good regional check of trip distribution, the model can match trip lengths without distributing trips between the correct locations. In order to permit easier review of the person trip tables, zonal interchanges can be summarized into districts, or groups of zones. Trips to the major employment area in the region (i.e. CBD) should be reviewed. Major trip movements across rivers or other physical barriers should be summarized as well.

- *Stratify trip lengths and/or trip interchanges by income class.* Often different income classes exhibit different travel characteristics.

Figure 4-3
Normalized Friction Factors



K- Factors

K-factors are sector to sector factors which correct for major discrepancies in trip interchanges. These factors are computed as the ratio between observed and estimated trip interchanges. K-factors are typically justified as representing socioeconomic characteristics that affect trip making but are not otherwise represented in the gravity model. Physical barriers, such as a river crossing, may also result in differences between observed and modeled trip patterns. For example, trip movements between zones separated by a bridge may not be as great as would be expected using only quantifiable measures. In that case, the planner can use either k-factors or artificial times on the bridge links to match the actual interchange of travel.

A specific problem with trip distribution occurs when low income households are matched with high income jobs in the central business district, particularly for large metropolitan areas. Although there are certainly trips between low income residences and downtown business districts, trip distribution models can have a tendency to overstate these trips. This error can have an even greater impact on transit projections since low income riders tend to be more transit dependent and transit is usually more competitive with the automobile downtown.

The use of K-factors is generally discouraged and are seen as a major weakness with traditional gravity models when used to correct for socioeconomic factors. Since K-factors represent characteristics of the population which change over time, the assumption that K-factors stay constant in the future can introduce a significant amount of error in predictions of future trip distributions.

A preferred approach is to stratify trip productions and attractions by income class (or auto ownership) and perform separate distributions of trips by class. Each model can reflect the different distributions of employment types throughout the region, as well as the unique sensitivities of different classes of travelers to travel time.

5.0 Mode Choice / Auto Occupancy

5.1 Model Description

The treatment of modal choice can vary a great deal by region. For regions with limited transit facilities, it may be sufficient to apply a mode split factor to person trips to account for the percentage using transit. It may even be possible to ignore public transportation trips completely if they constitute a very small portion of regional travel. In the case of a mode split factor being used, these should be reviewed against available local transit ridership figures for reasonableness.

Appendix A contains travel to work characteristics for the 50 largest metropolitan areas in the U.S. The portion of work trips using transit varies from less than 1% in Ft.Worth Texas to nearly 50% in New York City. Thus, local characteristics are very important in determining mode split.

The remainder of this chapter will focus on mode choice models which constitute best practice for metropolitan areas with significant transit service. Mode choice models represent traveler decisions about which vehicular mode to use as a function of level-of-service (LOS) characteristics of the mode and traveler and household characteristics. The mode choice component should be adequately designed and constructed to address the data and informational requirements of regional system planning. The level of detail and precision required in the mode choice model needs to be sufficient to answer policy issues such as the impacts of rail, HOV, pricing strategies, and non-motorized travel.

Two types of discrete choice models are prevalent today: multinomial logit models and nested logit models. A multinomial logit model assumes equally competing alternatives, which allows the "shifting" of trips to and from other modes in proportion to the initial estimate of these modes. A nested logit model recognizes the potential for something other than equal competition among modes. This structure assumes that modes and submodes are distinctly different types of alternatives that present distinct choices to travelers. Its most important departure from the multinomial structure is that the lower level choices are more elastic than they would be in the multinomial structure. For example, this model structure would assume that a person is more sensitive to the mode of access to the transit system than to the decision between auto and transit. Discrete choice models may be estimated on aggregate (zone-level) data or disaggregate (household-level) data, and the most recent modeling efforts have focused on disaggregate nested logit models.

Mode choice models require a number of inputs, many of which are produced in earlier steps in the modeling process. Variables which are typically included are transit travel time (out-of-vehicle, in-vehicle, walk time, wait time), number of transfers, highway travel time, transit fare, auto costs, household income and/or auto ownership, household size, number of workers, and land use characteristics. All of these inputs should be reviewed for reasonableness and compared with observed values. The New Orleans model validation included a comparison of the system variables, such as time and cost, by trip purpose.

As part of the model estimation process, it is useful to check the reasonableness of mode choice parameters by comparing with other regions. Tables 5-1 and 5-2 list some parameters from a number of cities for work and non-work models.

5.2 Disaggregate Validation

Disaggregate validation provides a means of exploring in detail how well a candidate mode choice model fits the observed data. It involves defining subgroups of observations, based, for example, on ranges of trip distance and household auto ownership levels. The model-predicted choices for these subgroups are then compared with the observed choices. Systematic biases revealed by these comparisons suggest the need for new variables or other changes in the utility functions for each mode. Thus, the model estimation and disaggregate validation subtasks are best carried out iteratively before final model specifications are selected.

Ideally, disaggregate validation is performed using a sample of travel observations which is independent of that used for model estimation. For the validation of the Southern California models, the data set from a large household survey and on-board survey was split into two parts, one for model estimation and one for validation. In some cases, a validation data set might be available from other sources (e.g. PUMS).

Even if a separate data set is not available, disaggregate validation can be performed using the same data set used for model estimation. Models can be applied to segments of the data set using the model estimation program to identify biases. For example, say a mode choice model is validated by auto ownership level. The validation might show that transit share is overestimated for zero car households in the suburbs. A possible solution would be to add variables where auto ownership interacts with area type (possibly replacing existing separate variables for area type and auto ownership.

Table 5-1
Review of Mode Choice Coefficients For Home Based Work Trips

Coefficients on Service Level Variables From a Sample of Home Based Work Mode Choice Model											
City	Survey Year	In-Vehicle Time	Tran Drv Acc Time	Out-of Vehicle Time	Hwy Term Time	Trn Walk Time	Tran Xfer Time	Cost	Auto Oper Cost	Tran Fare	Park Cost
New Orleans	1960	-0.015	-0.100	(M)	-0.033	-0.077	-0.032	-0.0080			
Minn/St. Paul	1970	-0.031		(M)	-0.044	-0.030	-0.044	-0.0140			
Chicago	1970	-0.028		-0.030	-0.114	-0.023	-0.114	-0.0121			
Los Angeles	1975	-0.020		-0.112				-0.0144			
Seattle	1977	-0.040	-0.286	(M)	-0.044	-0.03	-0.044	-0.0140			
Cincinnati	1978	-0.019		-0.028				-0.0045			
Washington	1980	-0.017		-0.058					-0.004	-0.004	-0.009
San Francisco	1980	-0.025		-0.058				-0.0039			
Dallas	1984	-0.030	-0.055	-0.055	-0.055	-0.055	-0.059		-0.005	-0.005	-0.012
Shirley (low)	1984	-0.022		-0.035				-0.0037			
Shirley (high)	1984	-0.034		-0.044				-0.0046			

Value of Time with the CPI Adjusted to 1979						
City	Survey Year	CPI Index	C(ivt) -------- C(cost)	C(ivt) -------- C(oper)	C(ivt) -------- C(fare)	C(ivt) -------- C(park)
New Orleans	1960	29.6	2.76			
Minn/St. Paul	1970	38.8	2.48			
Chicago	1970	38.8	2.56			
Los Angeles	1975	53.8	1.12			
Seattle	1977	59.5*	2.09			
Cincinnati	1978	65.2	2.84			
Washington	1980	82.4		2.61	2.08	0.97
San Francisco	1980	82.4	3.47			
Dallas	1984	103.9		2.68	2.68	1.07
Shirley (low)	1984	103.9	2.29			
Shirley (high)	1984	103.9	3.74			

Value of Time as Percent of Median Income						
City	Survey Year	1979 Median Income	C(ivt) -------- C(cost)	C(ivt) -------- C(oper)	C(ivt) -------- C(fare)	C(ivt) -------- C(park)
New Orleans	1960	18,933	30.31			
Minn/St. Paul	1970	24,879	20.77			
Chicago	1970	24,301	21.92			
Los Angeles	1975	22,041	10.60			
Seattle	1977	21,000*	20.31			
Cincinnati	1978	21,552	27.43			
Washington	1980	27,885		19.49	15.50	7.26
San Francisco	1980	24,599	29.36			
Dallas	1984	22,033		25.25	25.25	10.11
Shirley (low)	1984	27,885	16.75			
Shirley (high)	1984	27,885	27.36			

(m) Multiple Coefficients Depending on Car Occupancy
* Estimated CPI for 1979 was 72.6

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

Table 5-2
Review of Mode Choice Coefficients For Home Based Non-Work and Non-Home Based Trips

Coefficients on Service Level Variables From a Sample of Home Based Other Mode Choice Model											
City	Survey Year	In-Vehicle Time	Tran Drv Acc Time	Out-of Vehicle Time	Hwy Term Time	Trn Walk Time	Tran Xfer Time	Cost	Auto Oper Cost	Tran Fare	Park Cost
New Orleans	1960	-0.0066		-0.0165	-0.340				-0.012	-0.012	-0.0319
Minn/St. Paul	1970	-0.0080		-0.0200	(M)		-0.818*	-0.012			
Seattle	1977	-0.0080	-0.200	-0.0200	(M)		-0.135*	-0.035			
St. Louis	N/A	-0.238		-0.0595				-0.018			
Honolulu	N/A					-0.101	-0.041	-0.041			
San Juan	N/A	-0.0050				-0.060	-0.061	-0.061	-0.005		

* Coefficient on the number of transfers

Value of Time (Using only the original coefficients)						
City	Survey Year	C(ivt) / C(cost)	C(ivt) / C(oper)	C(ivt) / C(fare)	C(ivt) / C(park)	C(cost) Work / C(cost Non-Work
New Orleans	1960		0.33	0.33	0.12	0.67/0.25
Minn/St. Paul	1970	0.40				1.17
Seattle	1977	0.14				0.40
St. Louis	N/A	0.79				0.46
Honolulu	N/A	N/A				N/A
San Juan	N/A	0.60				0.48

Coefficients on Service Level Variables From a Sample of Non-Home Based Mode Choice Model											
City	Survey Year	In-Vehicle Time	Tran Drv Acc Time	Out-of Vehicle Time	Hwy Term Time	Trn Walk Time	Tran Xfer Time	Cost	Auto Oper Cost	Tran Fare	Park Cost
New Orleans	1960	-0.0131		-0.0328	-0.242		-0.075*		-0.005	-0.005	-0.0291
Minn/St. Paul	1970	-0.0100		-0.0250	(M)			-0.004			
Seattle	1977	-0.0200	-0.198	-0.0250	(M)			-0.031			
St. Louis	N/A	-0.0230		-0.0575				-0.011			
Honolulu	N/A	N/A				-0.126	-0.040	-0.040			
San Juan	N/A	-0.0100				-0.119	-0.026	-0.026			-0.002

* Coefficient on the number of transfers

Value of Time (Using only the original coefficients)						
City	Survey Year	C(ivt) / C(cost)	C(ivt) / C(oper)	C(ivt) / C(fare)	C(ivt) / C(park)	C(cost) Work / C(cost Non-Work
New Orleans	1960		15.72	15.72	0.27	1.60/0.275
Minn/St. Paul	1970	1.50				3.50
Seattle	1977	0.39				0.45
St. Louis	N/A	1.25				0.76
Honolulu	N/A	N/A				N/A
San Juan	N/A					2.00

Sources: Parsons, Brinckerhoff Quade & Douglas, Inc., "Review of Best Practices," Washington, DC (1992)

KPMG Peat Marwick, "Compendium of Travel Demand Forecasting Methodologies," Prepared for Federal Transit Administration, Washington, DC (February 1992)

Disaggregate validation can be performed using subsets of the observations based on ranges of the following variables:

- Household characteristics such as household size, income level, number of workers, and auto ownership;
- Traveler characteristics such as age, gender, driver license status, and employment status;
- Zonal characteristics such as geographical location, area type, population density, and parking costs; and
- Trip characteristics such as trip distance, time, and cost.

Tables 5-3 and 5-4 present an example of disaggregate validation performed for a mode choice model in the Los Angeles area. A multinomial logit mode choice model with nine alternatives was estimated for home based work trips from a combined data set from household and on-board surveys. This model was validated by applying the model to the estimation data set, and the results--the number selecting each mode chosen by survey respondents versus the number predicted by the model--were tabulated for market segments representing auto ownership and income levels. This type of validation procedure was available in the model estimation software.

The row total of each table shows that the overall performance of the model in estimating mode shares across the population is good. Although there are cells in both tables where the predicted number of users of a mode differs significantly from the number who chose each mode in the surveys, there are no systematic biases. For example, although the predicted number of users of each auto mode differs from the observed for 1-car households as shown in Table 5-1, the model slightly overpredicts auto use for the drive alone and shared ride 2 modes while it slightly underpredicts auto passengers and shred ride 3+. The predicted shares for auto for both 0-car and 2-car households, however, are very close to observed values. This indicates a lack of systematic bias. If, for example, the model showed that auto use was consistently overpredicted for multiple car households, additional auto ownership-related variables could be tested in the model structure.

It should be noted that the non-integer values for the number chosen in each cell reflect the weighting done in the expansion of the survey data set.

Table 5-3

HBW Classification by Automobiles per Household

Choice	0	1	2	3+	Total
Non-Motorized					
Number Chosen	47.4	104.5	270.2	158.5	580.6
Standard Deviation Chosen	7.5	14.1	26.5	19.0	36.3
	*A	V	A	A	A
Number Predicted	32.6	117.4	264.5	150.7	565.2
Auto Passenger					
Number Chosen	40.5	277.3	537.8	351.8	1,207.5
Standard Deviation Chosen	7.2	18.1	32.3	27.3	46.6
	V	*AAA	V	*V	A
Number Predicted	47.1	197.7	549.8	386.1	1,180.7
Drive Alone					
Number Chosen	0.0	1,265.9	4,225.5	3,233.4	8,724.8
Standard Deviation Chosen	0.0	25.4	44.8	35.7	62.7
		**V	A	A	A
Number Predicted	0.0	1,317.4	4,204.4	3,201.1	8,723.0
Shared Ride 2					
Number Chosen	0.0	49.1	186.0	142.0	377.1
Standard Deviation Chosen	0.0	12.0	20.5	16.5	28.9
		*V	V	*A	V
Number Predicted	0.0	68.0	191.5	123.2	382.7
Shared Ride 3+					
Number Chosen	0.0	36.5	84.1	35.0	155.6
Standard Deviation Chosen	0.0	7.2	13.0	11.1	18.6
		*A	A	*V	V
Number Predicted	0.0	26.1	78.1	56.1	160.3
Local Walk					
Number Chosen	28.5	24.8	10.7	3.9	67.9
Standard Deviation Chosen	7.8	7.3	8.1	4.4	14.1
	V	V	*V	V	*V
Number Predicted	35.3	28.7	21.3	5.8	91.1
Express Walk					
Number Chosen	0.2	3.5	2.7	2.5	8.9
Standard Deviation Chosen	1.6	3.5	4.2	2.1	6.0
	V	V	V	A	V
Number Predicted	0.6	5.3	5.7	1.6	13.2
Local Auto					
Number Chosen	2.6	3.3	2.7	1.4	10.0
Standard Deviation Chosen	2.4	3.0	3.4	2.2	5.6
	V	V	V	A	V
Number Predicted	2.8	4.4	4.7	1.7	13.6
Express Auto					
Number Chosen	0.1	5.6	6.6	0.3	12.5
Standard Deviation Chosen	1.6	3.6	4.2	2.6	6.3
	V	V	A	V	V
Number Predicted	0.9	5.7	6.3	2.3	15.2
Total					
Number Chosen	119.3	1,770.7	5,326.2	3,928.7	11,144.9
Number Predicted	119.3	1,770.7	5,326.2	3,928.8	11,144.9

Root-Mean-Square Error is 14.684

Table 5-4
HBW Classification by Household Income

Choice	Low	Middle	High	Total
Non-Motorized				
Number Chosen	146.8	162.8	271.0	580.6
Standard Deviation Chosen	15.9	20.4	25.5	36.3
	*A	**V	*A	A
Number Predicted	122.8	218.8	223.7	565.2
Auto Passenger				
Number Chosen	149.4	523.9	534.1	1,207.5
Standard Deviation Chosen	15.7	28.0	33.7	46.6
	*V	**A	*V	A
Number Predicted	167.4	445.0	568.2	1,180.7
Drive Alone				
Number Chosen	662.0	3,240.3	4,822.5	8,724.8
Standard Deviation Chosen	21.3	38.0	45.2	62.7
	A	A	V	A
Number Predicted	651.0	3,215.1	4,856.8	8,723.0
Shared Ride 2				
Number Chosen	44.0	124.4	208.6	377.1
Standard Deviation Chosen	8.8	17.6	21.2	28.9
	A	*V	A	V
Number Predicted	38.9	147.0	196.8	382.7
Shared Ride 3+				
Number Chosen	18.7	60.4	76.5	155.6
Standard Deviation Chosen	6.5	11.4	13.2	18.6
	V	V	A	V
Number Predicted	22.6	61.9	75.9	160.3
Local Walk				
Number Chosen	40.5	22.7	4.7	67.9
Standard Deviation Chosen	9.9	9.6	3.1	14.1
	*V	*V	A	*V
Number Predicted	54.3	34.5	2.4	91.1
Express Walk				
Number Chosen	3.5	2.0	3.4	8.9
Standard Deviation Chosen	3.1	4.8	2.0	6.0
	V	*V	A	V
Number Predicted	3.9	7.8	1.5	13.2
Local Auto				
Number Chosen	4.1	4.1	1.8	10.0
Standard Deviation Chosen	3.4	4.0	1.6	5.6
	V	V	A	V
Number Predicted	6.0	6.7	0.9	13.6
Express Auto				
Number Chosen	1.6	5.0	5.9	12.5
Standard Deviation Chosen	3.2	4.8	2.6	6.3
	V	V	*A	V
Number Predicted	3.8	8.9	2.4	15.2
Total				
Number Chosen	1070.7	4,145.7	5,928.5	11,144.9
Number Predicted	1070.7	4,145.7	5,928.5	11,144.9

Root-Mean-Square Error is 14.684

Sensitivity Tests

Typically, when mode choice models are estimated, the model coefficients, derived ratios, and model elasticities are compared to those from other regions. The comparison of model coefficients and derived variables can be considered both a validation check and a sensitivity check. If model coefficients (and constants) and derived ratios are in the range of what has been reported elsewhere, the model sensitivity should be similar to models used in other regions.

A common sensitivity test for mode choice models is the direct or cross elasticities of the model. Elasticities can be used to estimate the percent change in demand given a percent change in supply. As with the values of the model coefficients and derived ratios, elasticities can be considered as both validation and sensitivity tests. For example, a well-known rule-of-thumb for transit fare elasticity is the Simpson-Curtin Rule. This states that transit fare elasticity is about -0.3. In other words, a 10 percent increase in transit fare will result in about a 3 percent decrease in transit ridership. While the report is somewhat dated, elasticities derived from models and from empirical studies can be found in *Patronage Impacts of Changes in Transit Fares and Services*, Ecosometrics (1980).

Sensitivity tests can be made on model elasticities for fares, in-vehicle travel time, out-of-vehicle travel time, and transfers. Additional mode choice model sensitivity tests examine changes in transit mode shares relative to changes in transit fares and travel time. Sensitivity tests are performed by applying the model with unit changes in variables, e.g. a $0.25 increase in transit fare or a 10% increase in auto travel time.

Although disaggregate validation has been discussed in the Mode Choice section of this manual, it should be done for all disaggregately estimated models. Examples of other discrete choice models where this applies include visitor or destination choice models, and auto ownership models.

5.3 Aggregate Validation

To validate the models at the aggregate level, the models should be applied to calibration year person trip tables and LOS input data. Mode shares by trip purpose should be subdivided into submode shares by purpose if, for example, the mode choice model estimates transit trips for walk access and drive access trips separately. The resulting trips by mode should be compared with secondary data sources such as:

- Available transit ridership, highway vehicle, and auto occupancy counts at screenlines by time of day;
- 1990 Census Journey-to-Work data on trips by mode and origin and destination district;
- Total patronage by transit mode; and
- Counts of transit patrons by access mode at major stations serving transfers between auto and feeder bus and express transit services.

These comparisons may lead to the specification of adjustments to the models modal constants and market segmentation procedures to ensure that aggregate versions of the models accurately replicate the observed data.

Additional aggregate validation checks which should be made of mode choice models are:

- Average auto occupancies by trip purpose (see Table 5-5)
- Percent single occupant vehicles (SOVs) by trip purpose
- Home-based work transit trips as a percent of total transit trips
- Mode shares to/from area types or major districts
- Average auto occupancies to/from area types or major districts

An example of mode share by market segment is shares of transit trips using walk access versus auto access. An example of mode shares to/from a particular area type is mode shares of work trips destined for the CBD. Conversely, the share of total transit trips destined for the CBD can be checked.

In analysis of future year alternatives, travel models are often used to evaluate the introduction of a new mode, such as a light rail system. The introduction of a new mode will clearly have an impact on the mode choice validation. One would expect the new rail mode to shift trips from existing transit modes, and (possibly to a lesser extent) shift trips from auto to transit. In evaluating the reasonableness of mode choice results, it is important to consider the underlying model structure.

5.4 Auto Occupancy

Changes in auto occupancy can result in significant changes in the number of vehicle trips assigned. If auto occupancy rates are used to convert from person trips to vehicle trips, these can easily be adjusted in validation. Increasing auto occupancy, decreases the number of vehicle trips. As shown in Table 5-5, auto occupancies have generally been decreasing. Auto occupancy factors are typically developed from household travel surveys based on the reported number of person trips divided by auto driver trips.

Table 5-5
Average Vehicle Occupancy for Selected Trip Purposes
(person miles per vehicle mile)

Trip Purpose	1977	1983	1990	Percent Change (77-90)
Home to Work	1.3	1.3	1.1	-15
Shopping	2.1	1.8	1.7	-19
Other family or personal business	2.0	1.8	1.8	-10
Social and recreation	2.4	2.1	2.1	-13
All Purposes	**1.9**	**1.7**	**1.6**	**-16**

Source: 1977, 1983, and 1990 NPTS

6.0 Time-Of-Day/Directional Split Factors

Peak period information serves many uses in transportation planning. Recent model improvement efforts have focused on improving the forecasting of peak period speeds which are used for air quality analysis and also for determining the competitiveness of transit over the automobile. Peak period volumes, both for highway and transit, are used to determine the necessary capacity of facilities and the resulting level-of-service.

The historical use of time-of-day factors (TODF) has been through post-processing of assignment results. Peak hour factors are applied to daily traffic volumes after assignment of a daily vehicle trip table. For example, peak hour volumes are often assumed to range between 8 and 12 percent of daily traffic volumes. These factors can vary by area type or facility type.

In light of recent emphasis on detailed analysis of congestion levels and peak period spreading, best-practice manuals have advocated models which use a pre-assignment approach. Three possible approaches include the following:

- Factors applied before trip distribution
- Factors applied before mode choice
- Factors applied before traffic assignment

In each of these approaches, separate peak period and off-peak period trip tables are created before assignment. Daily traffic volumes are produced by summing the results of the time-of-day assignments for each link in the network. The pre-assignment method recognizes that the traffic volume on a link is composed of trips with different purposes, each having its own peaking characteristics. For example, work trips have well-defined peaks during the morning and afternoon. Shopping trips are more pronounced in the afternoon and also on weekends.

To improve the application of the peak factors, they can be stratified by mode of travel. Distinguishing factors by mode is important since auto and transit trips exhibit very different temporal distributions. Transit trips tend to have a more concentrated morning peak with evening trips dropping off substantially compared with auto trips.

Peaking characteristics also vary by geographic location, depending on the function of the corridor (radial vs. circumferential) and the presence of special generators (such as hospitals, universities). Much of the variation is accounted for by the stratification of trip purposes in trip generation and trip distribution.

In a highway assignment, peak period trip tables representing more than one hour are normally assigned while link capacities are specified in vehicles per hour. As a result, factors specifying the percentage of trips that take place within the peak hour of the time period being assigned are used to relate the hourly capacities to multiple-hour trip tables. The peak hour percentage of daily traffic varies according to the area type and functional class of a roadway link. For example, on urban freeways the peak hour might account for only 6 to 8 percent of the daily traffic because the road is congested all day long. A suburban collector might have as much as 12 to 14 percent of the daily volume during the peak hour.

Based on the detailed trip characteristics and impedances associated with equilibrium traffic assignment, it is illogical to perform twenty-four hour traffic assignments assuming a ten percent peak-hour factor as has been done in the past. Congestion on roadways occurs at specific times-of-day. In addition, the traffic mix at the different times-of-day is different. Morning peak period traffic is composed mainly of relatively long-distance work trips, whereas the mid-day period is composed mainly of shorter home-based non-work and non-home-based trips. The afternoon peak period is composed of both the longer work trips and the shorter non-work trips. Thus, in order to be consistent with the detailed theory of equilibrium traffic assignment, trips must be assigned by time-of-day.

Based on the information included in each trip record, the direction of the trip can also be determined as being a trip from home to a non-home location (i.e. a production zone to attraction zone trip) or a trip from a non-home location to the home of the trip maker (i.e. an attraction zone to production zone trip). The trip data should be summarized by the trip purposes.

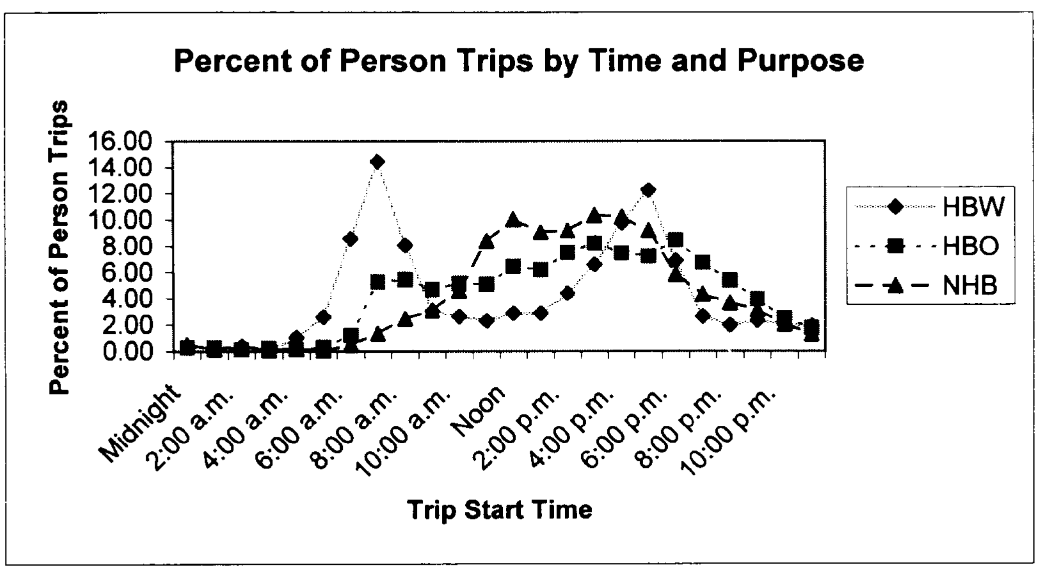
Figure 6-1 presents a diurnal distribution derived from the National Personal Transportation Survey (from NCHRP 365).

Figure 6-1
Diurnal Distribution of Trips (NPTS)

Urban Area Size = 200,000 to 499,999

Hour Beginning	HBW	HBO	NHB	All Purposes
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



Validation Tests

The following reasonableness checks for time-of-day factors should be performed:

- *Compare TOD factors used to create time-specific trip tables with secondary sources such as the NPTS and CTPP.* In particular, review the following:

    - Percent of trips by time-of-day by purpose
    - Percent of trips by time-of-day by mode (total, in autos, and in transit)
    - Percent of trips by time-of-day by direction (home to non-home, non-home to home)

- *Review and adjust peak hour factors used in assignment to relate volumes to hourly lane capacities.*

Sensitivity analysis can be used to test the affects of changes in the peak hour factor, i.e. peak spreading, on assigned traffic volumes and speeds.

Initially the peak hour factors should be based on the hour with the highest continuous volume for each of the three time periods. However, during the validation process these factors may be adjusted if it becomes apparent that these factors produce volumes which are too high for one hour. This would indicate that there is a great deal of peak period spreading, in which congested conditions are spread over a longer time period than one hour.

Peak hour factors provide an indication of the peak hour volume within the peak period. For the morning and afternoon peaks, trips may be spread evenly throughout the peak period. In this case, the capacity factor is simply the inverse of the length of the period. For example, the two hour a.m. peak period has a peak hour factor of 0.5. The three and one-half hour p.m. peak period has a peak hour factor of 0.286.

For the off-peak period, the congestion is usually not as severe and a different method is used. Since speeds should reflect the off-peak conditions in which most of the trips take place, the off-peak hour factor typically represents the middle of the day (as opposed to the middle of the night).

7.0 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 the transportation improvements in the future year(s). Depending on the level of analysis being done, the assignment can be to a regional highway and transit network for system-wide planning, or to a detailed network for a subarea or corridor study.

Historically, highway and transit assignment procedures were used primarily for systems analysis of large scale transportation improvements. A single volume-delay function for all facility type of roadways, the Bureau of Public Roads (BPR) curve, was used to estimate link travel times resulting from the assigned volumes. In recent years, a number of enhancements have been made to the process, due in part to increases in computing power. Volume-delay functions have been developed for different facility types (freeway versus arterial for example). The detail of the coding of the networks has increased dramatically, along with the associated reduction in the size of the traffic analysis zones. Better assignment algorithms (such as equilibrium assignment) and parameters have produced improved results.

The inputs for highway and transit assignments include the coded networks and the vehicle and person trip tables produced in earlier steps. The conversion of auto person trips to vehicle trips may be performed in the mode choice model or with simple auto occupancy factors. Time-of-day/direction split factors are typically used to convert the daily production-attraction trip tables into time-specific origin-destination trip tables.

In addition to assigning traffic by time-of-day, the traffic assignment process makes it possible to directly model the effects of tolls and other user costs on traffic volumes. Specifically, travel cost can be included in the calculation of travel impedance on roadways. The travel cost can be the cost to traverse a specified distance on a roadway (the vehicle operating costs), and/or it can be the cost of a toll. In both cases, unlike travel time and delay, the travel cost is relatively independent of the traffic volume.

An alternative to evaluating the impacts of tolls on highway demand using the assignment model is to incorporate a toll "path" in the mode choice model. The use of the toll path is a choice similar to the choice made to use transit or take competing transit paths.

The validation of the highway assignment is the final validation of the complete travel model set. Most assignment validation efforts have focused on obtaining accurate link volumes, because that has traditionally been viewed as the primary output of the assignment process. However, with the strengthening connection between travel models and air quality models, there has been a renewed interest in the congested speeds produced by the final iteration of the assignment procedure.

7.1 HIGHWAY ASSIGNMENT

7.1.1 Impedance Calculations

Traffic assignments are dependent on the calculation of travel impedances. At the simplest level, the impedance is the travel time. As noted above, a more refined procedure is to incorporate both time and cost into the impedance calculation. Many trip distribution and traffic assignment models are based on this combined impedance measure. A common impedance unit is generalized costs. On non-toll links, the following equation is often used:

$$Cost_{Total} = Cost_{Distance} + Cost_{LinkTime}$$

where:

$Cost_{Total}$	=	total link impedance
$Cost_{Distance}$	=	travel cost due to link distance
$Cost_{Link\ Time}$	=	travel cost due to the time required to traverse the link

The cost of travel distance for traffic assignments has been calculated in other studies as roughly $0.10 per mile, accounting for gas and maintenance. However, this value can vary depending on geographical location and may need to be adjusted.

In order to implement the generalized cost function, the value of time from the mode choice model can be used as a basis to convert travel time to travel cost. Unlike mode choice, all trip purposes are combined in traffic assignment. As a result, weighted average values of time that considered the varying mixes of trip purposes by time-of-day are used in the time-of-day traffic assignments.

For toll facilities, the travel impedance for the toll link can be calculated as follows:

$$Cost_{Total} = Cost_{Toll} + Cost_{ServiceTime}$$

where:

$Cost_{Total}$	=	total link impedance
$Cost_{Toll}$	=	travel cost due to the toll
$Cost_{Servicetime}$	=	travel cost due to the delay at the toll booth

The cost of tolls for traffic assignments will be calculated as the actual toll paid in dollars. The travel cost associated with the time spent paying the toll (deceleration, queuing, and acceleration) is computed by applying the same value of time described above to the "toll" time.

A primary method for calibrating and the subsequent validation of the highway assignment model is the adjustment of these generalized cost impedance calculations.

7.1.2 Volume-Delay Relationships

The traffic assignment process is driven by volume-delay relationships. As traffic volumes increase, travel speeds decrease due to increased congestion.

The state-of-the-practice in traffic assignment uses link-based volume-delay functions. The variables that control the final assigned travel speeds, the beginning or free-flow speed, and the link capacity are link based. Typically, free-flow speeds and link capacities are determined via a look-up table that relates these variables to the facility type or functional class of the link and the area type surrounding the link. As an example a look-up table of free-flow speeds and per lane link capacities is shown in Table 7-1. Such a look-up table approach was used in the Urban Transportation Planning Software (UTPS) distributed by the Urban Mass Transportation Administration in the 1970s and 1980s and, as a result, has become a commonly used approach to estimating link-specific, free-flow speeds and capacities.

Table 7-1
Look-up Table of Free-Flow Speeds and Link Capacities

Area Type		Functional Class				
		Freeway	Class 1 Arterial	Class 2 Arterial	Class 3 Arterial	Collector
Urban	Capacity	2000	1000	870	670	470
	FF Speed	50	35	25	20	15
Suburban	Capacity	2000	1000	870	670	470
	FF Speed	55	40	35	25	20
Rural	Capacity	2000	1000	870	870	470
	FF Speed	60	45	40	35	25

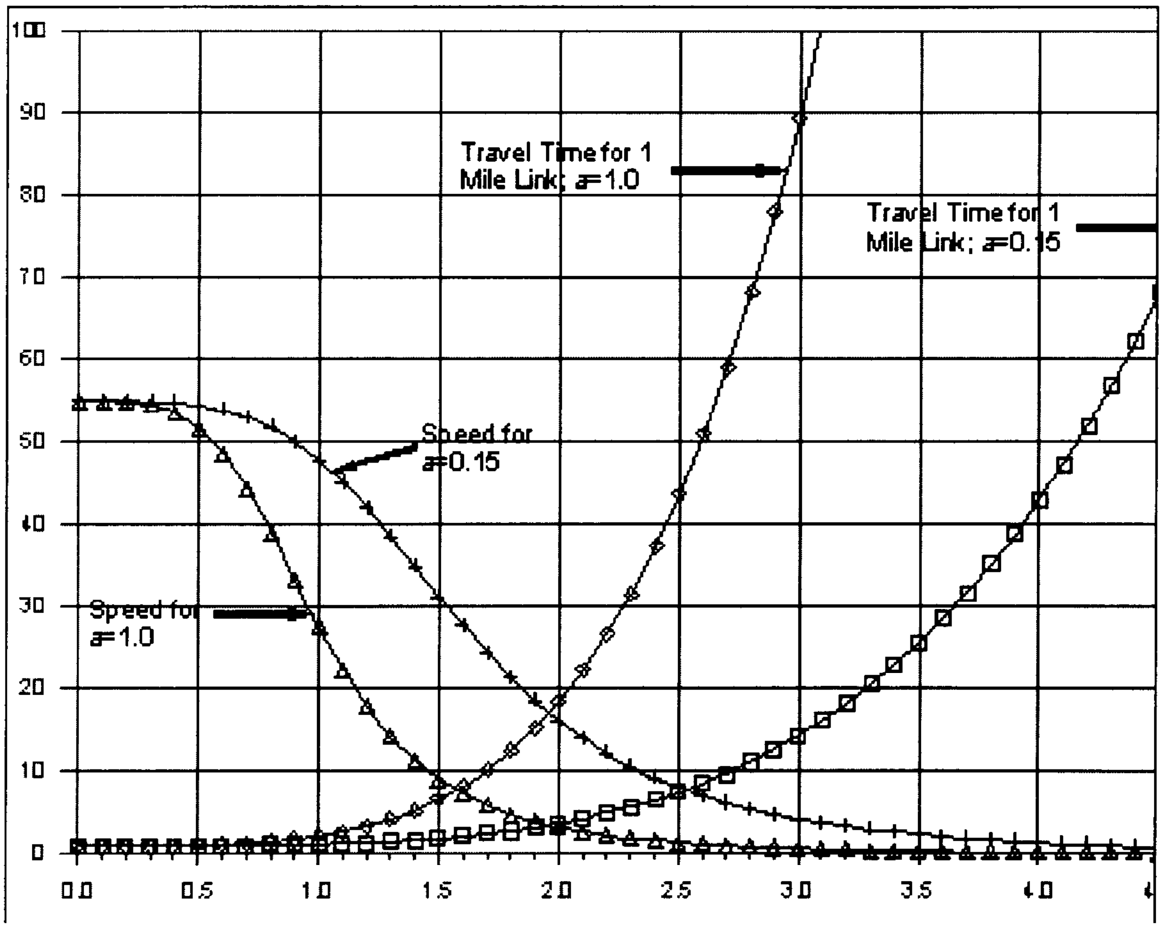
In addition to the use of look-up tables to estimate link-specific, free-flow speeds and capacities, the Bureau of Public Roads (BPR) function is the most commonly-used function for relating changes in travel speed to increases in travel volume. The BPR function is specified as follows:

$$T_f = T_o * \left(1 + \alpha * \left[\frac{V}{C} \right]^{\beta} \right)$$

where:

T_f	=	final link travel time
T_o	=	original (free-flow) link travel time
α	=	coefficient (often set at 0.15)
V	=	assigned traffic volume
C	=	the link capacity
β	=	exponent (often set at 4.0)

Figure 7-1 shows the effect of the BPR function on travel time and travel speed with the "a" coefficient set at values of 0.15 and 1.0, and the "b" exponent set at 4.0. A one-mile long freeway link was used for the example. As can be seen, if the "a" coefficient is set at 1.0, the congested speed at a volume / capacity ratio of 1.0 is one-half of the free-flow speed. In addition, as can be seen in the figure, the travel times increase very slowly at volume / capacity ratios less than 1.0 and very rapidly (actually, exponentially) at volume / capacity ratios greater than 1.0.



The BPR function is not "well behaved" in equilibrium traffic assignments. At low volume/capacity ratios (i.e., less than 1.0), additional traffic assigned to a link has very little affect on the travel speed. However, at volume/capacity ratios greater than 1.0, additional traffic has an exponential effect on travel times. Thus, the BPR function can cause an equilibrium assignment to iterate to closure more slowly due to oscillation of travel times on highly congested links.

The parameters used with the BPR formulation of volume-delay should be updated to correct some of the weaknesses. Alan Horowitz's 1991 report for FHWA, "Delay-Volume Relations for Travel Forecasting Based on the 1985 Highway Capacity Manual", contains parameters which were fit to the speed/volume relationships contained in the Highway Capacity Software, Version 1.5. 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 (LOS E). The second parameter β was found by nonlinear regression. The updated BPR parameters are shown in Table 7-2.

Table 7-2
Updated BPR Parameters Using HCM Procedures

Coefficient	Freeways			Multilane		
	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	9.80	5.50	3.60	5.40	2.70	2.10

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. Note that the BPR curve has a much higher speed at a v/c equal to 1.0 than does the HCM curves.

The ultimate capacity used for these curves was 1800 vehicles per hour per lane for a one mile section. This value is the ultimate capacity for typical prevailing conditions, not those under ideal conditions which would have a capacity of 2000 vehicles per hour per lane (and even higher based on recent changes to the Highway Capacity Manual). The curves extend beyond the point where the v/c ratio is 1.0, or where the flow has reached capacity. In capacity analysis, this portion of the curve is considered unstable. However, for travel demand modeling, the curve must extend beyond 1.0 to account for the theoretical assignment of the traffic.

The calibration and validation of the assignment model includes both the systematic adjustment of any lookup speed and capacity tables as well as the adjustment of the coefficients of the volume-delay function, by facility type.

7.1.3 Validation Tests

The validation tests for highway assignment are presented at three levels; systemwide, corridor, and link specific. This increasing detail of validation tests is correlated to the step(s) in the model chain that could be the cause of the possible error(s).

There are several systemwide or aggregate validation checks of the auto assignment process. The checks are generally made on daily volumes, but it is prudent to make the checks on volumes by time-of-day as well. Systemwide checks include Vehicle Miles of Travel (VMT), Vehicle Hours of Travel (VHT), cordon volume summaries and screenline summaries. In addition to checking summations of VMT, VHT, and volumes, the average VMT and VHT per household and person should be checked.

Vehicle Miles of Travel (VMT)

Validation of the model using VMT addresses all major steps in the travel demand models including trip generation (the number of trips), trip distribution (the trip lengths), and assignment (the paths taken).

VMT validation is particularly important in urban areas that are designated by the Environmental Protection Agency (EPA) as non-attainment for moderate and serious carbon monoxide (CO). The EPA has published guidance for the forecasting and tracking of VMT as required by Section 187(a) of the Clean Air Act Amendments of 1990 (CAAA). This guidance should be read and understood by those developing travel demand models for these urban areas. The document can be found on the Internet at http://www.bts.gov/smart/cat/vmt.html. The Bureau of Transportation Statistics has an Internet home page at www.bts.gov and this is an excellent resource for all information relating to transportation statistics.

The first check is observed versus modeled Vehicle Miles of Travel (VMT). VMT is simply the product of the link volume and the link distance, summed over the desired geographic area and facility types. The observed VMT is a product of a comprehensive traffic count program. Since not every link in the network will be counted for the validation year, estimates of observed VMT must be developed.

The primary source of observed VMT is the Highway Performance Monitoring System (HPMS) data. The VMT tracking and forecasting guidance issued by the EPA requires that the HPMS be used for tracking VMT in urban areas that are in violation of the air quality standards. The HPMS estimate for VMT is calculated from samples of observed traffic counts in a region and updated regularly. It is part of the reporting requirements to the Federal Highway Administration. The FHWA publishes a report, *Highway Performance Monitor System (HPMS) Field Manual* that should be referred to when comparing HPMS VMT with modeled VMT.

When using the HPMS estimate of VMT, is it important to account for the basic differences in the highway system covered by HPMS and that included in the typical highway network for the travel demand model. The HPMS data includes VMT estimates for all functional classifications of roadways within the Federal Aid Urbanized Area (FAUA), including local streets. Most regional model networks do not include local streets. The lowest level of roadway in most models is the collectors. The local streets are typically represented by the centroid connectors. Recognizing this difference, the direct estimates of VMT from the model should be lower than the HPMS estimate of VMT.

In addition to the differences in the functional classification of the highway system, the different geographic areas covered by each estimate of VMT must be recognized. The HPMS is designed primarily for the area within the FHWA's designated Federal Aid Urbanized Area (FAUA). On the other hand, when the EPA designates an area as being in non-attainment, the area usually includes all counties within the nonconforming area. This non-attainment area is typically larger than the

FAUA. The EPA's guidance for VMT forecasting and tracking allows for non-HPMS methods to be used in the non-attainment areas that are outside of the FAUA. Therefore, it is important to reconcile the various geographic areas of the modeled area, the HPMS area, and the non-attainment area.

While the EPA requires the HPMS method be used for *tracking* VMT, the network based travel demand model is the preferred method for *forecasting* VMT in non-attainment areas. In order to simplify the forecasting of VMT for air quality purposes, many urban areas have elected to include the entire non-attainment area in the travel demand model. This has the added advantage of not only covering the entire FAUA as required by the FHWA, but also allows for forecasting travel demand in areas that are likely to become urbanized in the future, as required by the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991.

- *Check VMT values for the region, per household, and per person.* There are many useful statistics that can be calculated for the systemwide-level validation of VMT. These include both the absolute and relative (percent) difference. Compare current estimates of regionwide VMT with the historical trend and rate of growth from HPMS.

The absolute difference is the simple difference between observed and modeled VMT. The difference is typically large for high-volume links and low for low-volume links, so the size of the numerical difference does not reliably reflect the true significance of error.

Percent difference is often preferred to absolute difference since its magnitude indicates the relative significance of error. Modeled regional VMT should generally be within five percent of observed regional VMT. This five percent difference is particularly important in light of the accepted error that EPA allows for VMT tracking using the HPMS data. The EPA has allowed margins of error in VMT estimates as high as five percent in 1994 to a new margin of three percent in 1996 and afterwards.

Table 7-3 is an example of a VMT validation summary.

Table 7-3
Example VMT Validation Summary

	VMT		Error		VMT Distribution	
Facility Type	Estimated[1]	Observed[2]	Difference	Percent	Estimated	Observed
Freeways						
Principal Arterials						
Minor Arterials						
Collectors						
Total					1	1

Notes: 1 - Estimated is the VMT produced by the model
2 - Observed is based on either traffic counts or the HPMS estimates of VMT

Typical distributions of VMT by facility type are presented in Table 7-4.

Table 7-4
Urban Area VMT by Facility Type

Facility Type	Urban Area Population		
	Small (50-200K)	Medium (200K-1M)	Large (>1M)
Freeways/Expressways	18-23%	33-38%	40%
Principal Arterials	37-43%	27-33%	27%
Minor Arterials	25-28%	18-22%	18-22%
Collectors	12-15%	8-12%	8-12%

Source: Christopher Fleet and Patrick De Corla-Souza, *Increasing the Capacity of Urban Highways - The Role of Freeways*, presented at the 69th Annual Meeting of the TRB, January 1990

As noted, VMT per household and VMT per person are useful measures to determine if the modelled estimates of VMT are within reasonable limits. These unit measures of VMT are also useful in determining the source of modelling error. A model that underestimates regional VMT, yet has reasonable VMT per household may have errors in the household data (underestimation of the number of households). All of these pieces of data assist the analyst in determining the cause of the modelling error and the associated adjustment or correction.

Reasonable ranges of VMT per household are 40-60 miles per day for large urban areas and 30-40 miles per day for small urban areas. The 1990 NPTS reported an average of 41.37 vehicle miles traveled per household daily. Reasonable ranges of VMT per person are 17-24 miles per day for large urban areas and 10-16 miles per day for small urban areas.

When models are originally calibrated from survey data (or transferred from other regions), the modeled regional VMT will frequently be substantially lower than the observed regional VMT. An initial response to this occurrence is often to increase trip generation rates, especially for home-based non-work and non-home-based trips, under the justification that these trips are the most commonly under-reported trips in a household travel survey. Frequently, increases in modeled trip rates of 10 to 20 percent produce modeled results that reasonably match the observed regional VMT. However, some regions have increased trip rates by as much as 60 to 70 percent.

Traffic Volumes

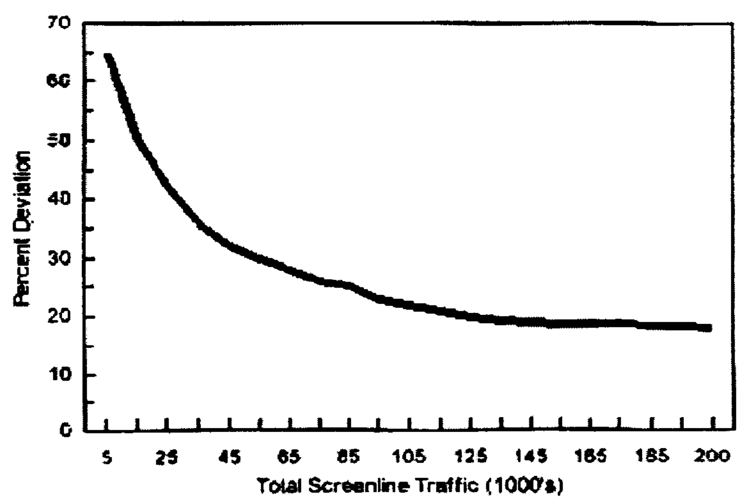
After validation of the VMT, the next level of validation of the highway assignment is the comparison of observed versus estimated traffic volume on the highway network. The observed count data are derived from the ongoing traffic counting and monitoring program in the urban area as described in section 2.3. This data may be developed primarily for the HPMS requirements and supplemented as required. Traffic volumes are validated at the systemwide level by comparing summations of volumes at both cordons and screenlines. While the comparison of volumes on cutlines can be used as a systemwide measure, it will be treated as a localized measure in this document.

- *Compare observed versus estimated volumes by screenline.* The Michigan Department of Transportation (MDOT) has targets of 5% and 10% for screenlines and cutlines, respectively, for percent differences in observed and estimated volumes by screenline. Figure 7-2 shows maximum desirable deviation in total screenline volumes according to the observed screenline volume.

- *Compare observed versus estimated volumes for all links with counts.* With the use of the on-screen network editors and plots of network attributes, the checking of link level counts visually is relatively simple. In addition to visually checking the correlation of the counts to volumes, it is also useful to compute aggregate statistics on the validity of the traffic assignment. Two measures can be computed; the correlation coefficient and the Percent Root Mean Square of the Error. Each is discussed below.

- *Calculate R^2 (Coefficient of Determination) comparing regionwide observed traffic counts versus estimated volumes.* R^2 regionwide should be greater than 0.88. Another useful validation tool is to plot a scattergram of the counts versus the assigned volumes. Any data points (links) that lie outside of a reasonable boundary of the 45° line should be reviewed.

Figure 7-2
Maximum Desirable Deviation in Total Screenline Volumes



Source: NCHRP 255 p.41 (cited in FHWA, Calibration and Adjustment of System Planning Models, Dec. 1990)

- *Calculate percent RMSE as follows:*

$$\%RMSE = \frac{(\Sigma_j (Model_j - Count_j)^2 / (Number\ of\ Counts - 1))^{0.5} * 100}{(\Sigma_j Count_j\ /\ Number\ of\ Counts)}$$

The Montana Department of Transportation (MDT) suggests that an appropriate aggregate %RMSE is less than 30%. The %RMSE can be calculated for all links with counts or by facility type and area type as shown in Tables 7-5 and 7-6.

Table 7-5
Percent Root Mean Square Error Comparisons

	Reno		Phoe nix	Concord	
Facility	*PM*	*ADT*	*ADT*	*PM*	*AM*
Freeway	*18.3*	*18.6*	*25.4*	*NA*	*NA*
Arterial	*39.2*	*36.8*	*38.5*	*NA*	*NA*
Collector	*76.1*	*77.5*	*62.7*	*NA*	*NA*
Total	*39.9*	*36.8*	*40.6*	*31.1*	*36.8*

Table 7-6
Percent Root Mean Square Error - 24-Hour Assignment (Reno)

	Area Type					
Facility Type	*1*	*2*	*3*	*4*	*5*	*All*
Freeway	*11.649*	*18.092*	*21.891*	*0.000*	*11.271*	*18.334*
Major Art	*22.547*	*37.778*	*42.209*	*43.162*	*43.283*	*36.768*
Collector	*0.000*	*52.953*	*88.920*	*115.326*	*70.148*	*77.482*
Minor Art	*25.874*	*44.072*	*52.353*	*28.367*	*60.121*	*43.895*
Ramp	*24.237*	*63.524*	*47.574*	*80.649*	*131.009*	*74.846*
Total	*21.303*	*37.210*	*37.793*	*43.742*	*38.694*	*36.767*

Assigned Speeds

If actual observed speed data are available, this should be summarized in highway segments consisting of a number of links and intersections so that intersection-based delay is averaged into highway travel time. Speed observations should be classified by facility type and area type to compare with modeled speeds for the same categories. Checks of highway skims include the following:

- Summarize link speeds by facility type and area type, showing the minimum, maximum, and average speed for each category. Compare assigned speeds with speeds used for distribution and mode choice.
- Compare observed and estimated speeds by highway segments, if available.

Model Parameters

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 5mph for example) that only worked 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.

There are a number of parameters in highway assignment that are potential sources of error. While the actual parameters and calculation options involved depend on the modeling software and assignment methodology being used, possibilities include:

- Assignment procedures including number of iterations, expansion of incremental loads, and damping factors,
- Volume-delay parameters such as the BPR coefficient α and exponent β.
- Peak-hour conversion factors used to adjust hourly capacity and/or daily volumes in volume-delay function.
- Scaling or conversion factors to change units of time, distance, or speed (mi/hr or km/hr).
- Maximum/minimum speed constraints.
- Preload purposes (HOV, through trips, trucks, long/short trips).
- Toll queuing parameters (diversion, shift constant, etc.)

Other validation tests include:

- Path trees based on assigned travel times.
- Select Link Analysis
- Assign through trip table separately to check routing of external-external trips. Should use higher-level facilities.

7.2 Transit Assignment

The primary validation check of the transit assignment process is of observed versus modeled boardings. These should be checked for the region, by mode and possibly sub-mode, and by trip length. In addition, a check of observed versus modeled boardings per trip (transfer rates) is a more detailed check that tests reasonability of the number of transfers made per trip.

Model Calibration

The first step of the validation of a transit assignment occurs during the mode-choice model calibration. In the calibration step, the mode-specific constants for a region are derived so that the mode-choice model produces the appropriate share of transit trips for the region. The structure of the mode-choice model will affect the order in which the bias constants are derived. In a multinomial logit model, the bias constants for all transit modes can be derived simultaneously. If a nested logit model is employed, the bias constants for the lower levels of the nest should be derived first, then the next higher level, until the top level of the nest is reached. Several iterations of this process are normally required before an acceptable set of bias constants are derived. Note: care should be used to avoid bias constants that have an absolute value greater than 2.0 or 3.0 at the top level of the nest. If the constants are too large, the model will lose its sensitivity to level of service changes.

Validation

The amount of time and effort required to validate a transit assignment is directly correlated with the level of precision demanded. For highway planning purposes, it is generally sufficient to validate to the regional number of boardings, so that the appropriate number of person trips are removed from the highway network. For transit planning purposes, however, it may be necessary to validate to the mode, corridor, route, segment, or even station level of detail. Such precision is very difficult to attain with a fully synthetic model. (One option available when a finer level of detail is required is to utilize a pivot-point model.)

A few of the common problems that occur when validating a transit assignment are discussed in the following paragraphs, along with suggested solutions.

Number of Transfers - It is very common for a transit assignment to produce more transfers than are occurring in the actual transit systems. This problem can sometimes be solved by adjusting the transfer penalty.

However, the problem of assigning too many transfers may also result from having a shortage of walk access links to serve the transit system. The walk access links should be checked to make sure that each transit route has walk access to each TAZ within the accepted walking distance, especially when an automated access coding routine is employed. This can be difficult in CBD areas, where numerous transit routes often serve even more numerous TAZs. In order to avoid the problem of having to code too many walk access links, a CBD walk network should be employed.

Trip Length Frequency Distribution - If the average trip length for the assigned transit trips is not right, check the trip length frequency distribution for the person trip table used to create it. If the person trip distribution reflects the same pattern as the transit trip, the problem may be attributed to the trip distribution model.

Otherwise, the district-to-district transit trip summaries should be examined. The problem of an erroneous trip length frequency distribution may result from trips associated with a specific zone or district in the region. If the comparison of an observed transit trip table vs. an estimated trip table shows a large imbalance for a specific area, the route and access coding for that area should be checked first. If that network coding is reasonable and consistent with the rest of the model, you may wish to derive and apply a bias constant specific to that district.

Express or Limited Service - During the transit validation process it is often helpful to examine the relative assignments of different types of transit service. For example, it may be helpful to compare the assignments of local bus service and express bus service to determine whether or not a pattern can be found.

If the express service is being under-assigned the cause could be insufficient drive access, since express bus riders are more likely than local bus riders to drive to either a formal or an informal park-and-ride lot along the route. Alternately, the under-assignment could be due to an excess of wait time, since express bus riders who know the schedule of their service would not need to wait as long as the infrequent level of service would tend to indicate.

On the other hand, if express bus ridership is overestimated in comparison to local service, you may wish to check the transit route coding to make sure that the route is not allowed to collect passengers on the limited- or non-stop portions of the journeys.

Corridor Analysis - Most transit systems have corridors, of varying lengths, that are served by more than one transit route. These corridors have the benefit of improving the perceived, or composite, frequency of service for some of the potential transit riders in that corridor. However, with most transportation planning software, care must be taken when coding the transit lines in these corridors to ensure that the stop sequence is identical, or else a composite headway will not be calculated for that trip.

Another aspect of corridors served by multiple routes is the assignment of trips to competing transit routes. The most common practice is to have the software distribute the trips to the competing routes based on the relative frequency of service. However, this practice is only valid if certain assumptions are true: 1) the potential riders must be aware of all routes that serve their particular trip; and 2) the transit service must be spaced evenly between the competing routes. Since these assumptions are usually *not* true in real life, it is unlikely that the assignment of transit trips to competing routes in a corridor will be consistent with reality. Therefore, it is appropriate in the validation phase to analyze competing routes as a group, and to ignore the assignments to the individual routes.

Summary

In summary, the transit validation can include analysis of the following comparisons:

- Observed vs. estimated boardings for region, by mode, by time of day, and by trip length;
- Observed vs. estimated transfers per trip;
- Observed vs. estimated screenline volumes;
- Observed vs. estimated boardings by route or group of routes;
- Observed vs. estimated district-to-district transit trips.

Most modeling software platforms can generate a number of reports useful in the validation process, both at the regional and local levels. Typical reports provide information relating to:

- Passenger loadings by line, company, and mode;
- Access modes;
- Station-to-station/transfer nodes;
- Specified/calculated headways;
- Passenger- and vehicle-hours or miles of service;
- Peak loads.

Data Sources

The primary data source for transit ridership data is from the transit operator(s) within the region. Transit ridership data that can be obtained from transit operators include:

- System-wide linked trips, unlinked trips, and transfer rates;
- Route-specific boardings and fare collection data;
- Boardings and alightings at transit stations;

- Passenger-hours and passenger miles of service.

Additional ridership data can be obtained with the use of field surveys. The most common forms of transit survey include on-board surveys, ride-check surveys, and load-check surveys. These transit surveys can be conducted separately or in concert with each other.

Ride-check surveys are conducted by placing an observer on a transit vehicle to collect on/off count data at each stop. The observer is trained to record the stop location, time, the number of passengers boarding and alighting at each stop, and the passenger load following the stop. The observer can also be trained to collect other information about the passengers, such as gender, age, or the method of fare payment. The ride-check data can be used to calculate the peak load-point along a route.

On-board transit surveys involve the use of questionnaires which ask transit riders to provide information such as the origin and destination of their trip, modes of access and egress, trip purpose, and personal information such as gender, age, income level, and automobile availability. When conducted in conjunction with a ride-check survey, information from an on-board survey can be geo-coded and expanded to build trip tables describing the zone-to-zone trips made by the riders on a specific route.

Load-check transit surveys are used to count the number of passengers boarding and alighting at a transit stop, and the number of passengers on the transit vehicles travelling through that stop. Load-check surveys are used for two main purposes, to count the transit traffic at a major terminal or transfer location, and to count the number of passengers passing through a peak load point.

7.3 Validation Targets

Although absolute criteria for assessing the validity of all model systems cannot be precisely defined, a number of target values have been developed. These commonly-used values provide excellent guidance for evaluating the relative performance of particular models.

As noted earlier, observed versus estimated volumes should be checked by facility type and geographic area. The Federal Highway Administration (FHWA) and Michigan Department of Transportation (MDOT) define targets for daily volumes by facility type as shown in Table 7-7.

Table 7-7
Percent Difference Targets for Daily Traffic Volumes by Facility Type

Facility Type	FHWA Targets	MDOT Targets
Freeway	+/- 7%	+/- 6%
Major Arterial	10%	7%
Minor Arterial	15%	10%
Collector	25%	20%

Sources: FHWA, *Calibration and Adjustment of System Planning Models*, 1990; Michigan Department of Transportation (MDOT), *Urban Model Calibration Targets*, June 10, 1993

The Contra Costa Transit Authority (CCTA) in the San Francisco Bay Area has developed the following targets for peak-hour model validation:

- 75% of all freeway links must be within 20% of traffic counts.
- 50% of all freeway links must be within 10% of traffic counts.
- 75% of all major arterial links must be within 30% of traffic counts.
- 50% of all major arterial links must be within 15% of traffic counts.
- 50% of all intersection major turning movements must be within 20% of traffic counts.
- 30% of all intersection secondary turning movements must be within 20% of traffic counts.

For the CCTA, a major arterial is defined as one that carries over 10,000 vehicles per day, a major turning movement is defined as over 1,000 vehicles per hour, and a secondary turning movement is defined as 500-1,000 vehicles per hour.

R^2 and %RMSE values for VMT can be calculated for subsets of links, such as by facility type, volume range, or district.

Standards also exist for comparing observed versus modeled volumes for individual links. Table 7-8 shows percent difference targets for individual links as defined by FHWA and MDOT.

Table 7-8
Percent Difference Targets for Daily Volumes for Individual Links

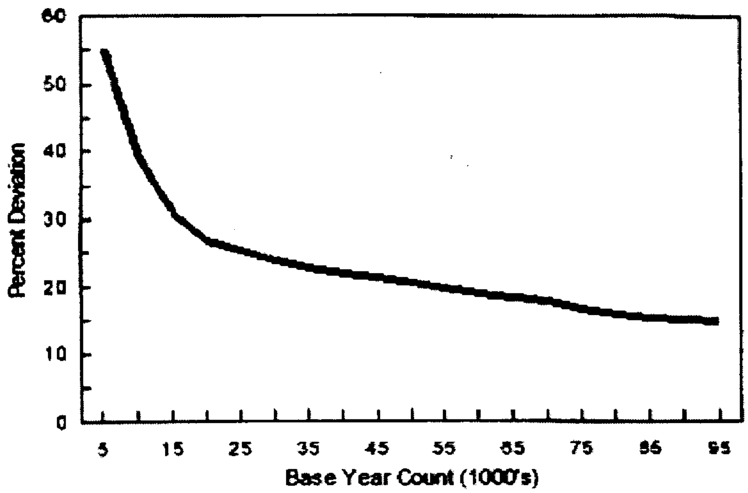
Average Annual Daily Traffic	Desirable Percent Deviation	
	MDOT	FHWA
<1,000	200	60
1,000-2,500	100	47
2,500-5,000	50	36
5,000-10,000	25	29
10,000-25,000	20	25
25,000-50,000	15	22
>50,000	10	21

Source: MDOT, *Urban Model Calibration Targets*, June 10, 1993

The FHWA targets are displayed graphically in Figure 7-3.

Additional checks should be made of observed versus modeled VHT and observed versus average speeds by facility type, area type, and district.

Figure 7-3
Maximum Desirable Error for Link Volumes



7.4 Troubleshooting Strategies

The recommended approach to model validation discussed in this manual is to carefully check each component of the travel modeling process before the complete chain of models is applied. However, even the best structured model will contain errors and show a difference between the observed data and the model results. The assignment validation measures discussed in Section 7.1, such as screenline volumes and VMT, are typically the "bottom-line" check of how well the model performs on a systemwide basis. Section 7.3 presents typical accuracy targets for these overall measures, although many regions may have their own targets. The next step in the validation process is to evaluate the extent to which the model achieves accuracy targets, determine whether the problems are regional or local, and identify the likely causes of error.

The strategies are grouped according to the level of comparison and the likely source of error including:

Systemwide - *Number of total trips and average trip length?*

Corridor level - *Trip interchanges between activities?*

Local level - *Auto trips assigned to the correct highway routes?*

Transit - *Transit trips assigned to the correct routes?*

These levels of comparison are described in detail below. They are listed roughly in the order in which validation should be performed, i.e. from regional to local. In many areas, transit modes account for a very small portion of regional travel and transit validation is typically a low priority. However, for areas with more significant transit facilities or where transit investments are expected in the future, the transit checks can become more important than the local highway checks.

Systemwide

Systemwide problems are identified using the aggregate highway measures such as screenline volumes and total VMT. If volumes are consistently high or low across all screenlines, then adjustments are probably needed in the following areas:

Trip generation rates: Check the total number of person trips by purpose. If trip generation rates were calibrated from a household survey, then they probably do not need to be modified. Instead, consider trip purposes which may have been omitted, such as truck and commercial vehicles, visitor or tourist trips, external trips, as well as trip chaining.

Mode choice / Auto occupancy: Check the number of auto person trips and vehicle trips.

Socioeconomic inputs: Check the totals number of households and employment for the region.

Employment is typically more uncertain, especially if households were obtained from the Census.

Trip Distribution: Check average trip length by purpose and percentage of regional trips which are intrazonal.

Corridor

Corridor-level problems are identified by cutline volumes or link volumes on major facilities. A comparison of capacity-restrained assignment with all-or-nothing results can reveal the difference between the desired interchanges and the modeled interchanges. Check typical paths in corridor for reasonableness. Areas to investigate include:

Highway Assignment: Parameters and inputs which affect all facilities should be reviewed, such as:

- speeds and capacities
- coding convention for freeway interchanges
- tolls and cost of distance
- volume delay functions
- treatment of peak spreading
- intersection delay

Trip Distribution: Consider K factors particularly if only some of the screenlines show discrepancies. Trip interchanges may vary by income class.

Socioeconomic Inputs: Even if totals for the region are correct, major activity centers may not have correct household and employment allocations.

Local

Local highway problems are identified by looking at specific links for critical roadways. In areas with parallel facilities, traffic assignment may shift trips to the wrong facilities under congested conditions. The following should be reviewed:

Link attributes: Check any values which are specific to a particular link or class of links, such as posted speeds and capacities.

- Centroid connectors and driveway access.
- Special generators may not be fully accounted for. Zonal data may be miscoded.
- Turn penalties may be omitted or not coded correctly.

Transit

Transit validation typically focuses on the path-building characteristics and assignment of transit trips to specific routes. The total number of transit person trips should be verified first.

If regional transit trips by mode are high or low, check the following:

Socioeconomic inputs or parking costs.
- Transit path-building parameters such as wait time, calculation of transit speeds.
- Auto times and costs.

Transit trips are not always assigned to the correct route, particularly if the assignment algorithm does not account for competing transit service in the same corridor. When transit trips are not being assigned to the correct routes, check the following:

Route itineraries
- Access connectors
- Headways
- Station dwell times
- Link-specific speed problems, possibly due to underlying highway assignment problems.

Future Year Application

If the step-by-step process outlined in this manual has been followed, and the validation targets have been achieved as best as possible, then the application of the model set to future year forecasts should produce reasonable results. The problem with evaluating the reasonableness of future-year forecasts is that no observed data are available for comparison. Therefore, the analyst must compare projected changes in travel demand with historical trends, forecasts for similar urban areas, and assumptions about changes in model inputs, such as socioeconomic conditions and transportation network improvements. In addition, the model may be used to evaluate transportation policy changes, such as the introduction of pricing mechanisms, which were not present in the validation year.

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Appendices

A. 1990 Journey to Work Summary by State

Travel to Work Characteristics for the 50 Largest Metropolitan Areas by Population in the United States: 1990 Census

MSA/PMSA of Residence	Total workers 16 years and over	Means of transportation (%): Drove alone	Car-pool	Public transit	Other means 1/	Average travel time to work (min.)
U.S. TOTAL METROPOLITAN	91,515,002	73.0	12.9	6.5	7.6	23.2
Los Angeles-Long Beach, CA PMSA....................	4,115,248	70.1	15.5	6.5	7.9	26.5
New York, NY PMSA.........	3,798,814	30.7	8.9	47.3	13.1	35.3
Chicago, IL PMSA..........	2,888,784	63.8	12.0	17.1	7.1	29.1
Philadelphia, PA-NJ PMSA..	2,280,559	67.8	11.9	11.6	8.7	24.8
Detroit, MI PMSA..........	1,931,153	83.4	10.1	2.4	4.1	23.7
Washington, DC-MD-VA MSA..	2,214,350	62.9	15.8	13.7	7.6	29.5
Houston, TX PMSA..........	1,576,078	75.7	14.6	4.1	5.5	26.4
Boston, MA PMSA...........	1,488,501	65.8	9.8	14.2	10.2	24.5
Atlanta, GA MSA...........	1,481,781	78.0	12.7	4.7	4.6	26.0
Nassau-Suffolk, NY PMSA...	1,303,936	73.0	10.0	11.4	5.7	30.0
Riverside-San Bernardino, CA PMSA.................	1,079,948	74.6	17.2	0.8	7.4	27.7
Dallas, TX PMSA...........	1,312,173	77.6	14.0	3.2	5.3	24.6
San Diego, CA MSA.........	1,230,446	70.9	13.8	3.3	12.1	22.2
Minneapolis-St. Paul, MN-WI MSA...............	1,307,624	76.0	11.2	5.3	7.5	21.1
St. Louis, MO-IL MSA......	1,144,336	79.7	12.0	3.0	5.2	23.1
Anaheim-Santa Ana, CA PMSA	1,278,661	76.8	13.7	2.5	7.0	25.5
Baltimore, MD MSA.........	1,191,813	70.9	14.2	7.7	7.2	26.0
Phoenix, AZ MSA...........	996,495	75.0	14.4	2.1	8.5	23.0
Oakland, CA PMSA..........	1,034,364	68.6	13.2	9.1	9.1	27.2
Tampa-St. Petersburg-Clearwater, FL MSA......	914,711	78.8	13.3	1.5	6.4	21.8
Pittsburgh, PA PMSA.......	881,624	70.7	12.9	8.5	7.9	22.6
Seattle, WA PMSA..........	1,037,749	72.8	11.6	7.4	8.2	24.4
Miami-Hialeah, FL PMSA....	887,996	72.4	15.6	5.9	6.2	24.8
Cleveland, OH PMSA........	823,684	77.7	10.5	6.2	5.5	22.6
Newark, NJ PMSA...........	901,453	70.9	12.4	10.0	6.7	26.2
Denver, CO PMSA...........	843,070	75.6	12.6	4.4	7.5	22.7
San Francisco, CA PMSA....	853,948	56.3	12.2	19.5	11.8	25.9
Kansas City, MO-KS MSA....	771,309	79.9	12.5	2.1	5.5	21.4
San Jose, CA PMSA.........	796,605	77.7	12.3	3.0	7.0	23.3
Sacramento, CA MSA........	685,945	75.2	13.7	2.4	8.7	21.8
Cincinnati, OH-KY-IN PMSA.	678,121	78.6	11.6	4.3	5.5	22.4
Milwaukee, WI PMSA........	690,002	76.7	11.0	5.2	7.1	20.1
Norfolk-Virginia Beach-Newport News, VA MSA....	698,999	72.7	14.1	2.2	10.9	21.6
Columbus, OH MSA..........	677,859	79.5	11.4	2.7	6.4	21.2
Fort Worth-Arlington, TX						

PMSA	664,433	80.9	13.5	0.6	4.9	23.0
San Antonio, TX MSA	569,149	74.6	14.8	3.7	7.0	21.9
Bergen-Passaic, NJ PMSA	649,697	71.7	11.9	9.3	7.0	24.7
Fort Lauderdale-Hollywood-Pompano Beach, FL PMSA	588,089	79.7	12.8	2.1	5.4	23.0
Indianapolis, IN MSA	624,971	79.7	12.9	2.1	5.3	21.9
Portland, OR PMSA	615,587	72.6	12.5	6.0	8.9	21.8
New Orleans, LA MSA	514,726	70.9	15.3	7.3	6.5	24.4
Charlotte-Gastonia-Rock Hill, NC-SC MSA	604,856	78.8	14.5	1.8	4.8	21.6
Orlando, FL MSA	557,448	78.1	13.3	1.5	7.1	22.9
Salt Lake City-Ogden, UT MSA	479,338	76.3	14.0	3.0	6.7	19.8
Middlesex-Somerset-Hunterdon, NJ PMSA	545,739	77.5	10.5	6.4	5.6	26.3
Rochester, NY MSA	481,467	77.7	11.6	3.2	7.5	19.7
Monmouth-Ocean, NJ PMSA	453,204	76.5	12.1	5.3	6.1	27.1
Nashville, TN MSA	495,717	79.1	13.8	1.7	5.3	22.7
Memphis, TN-AR-MS MSA	448,237	78.2	13.6	2.8	5.4	21.6
Buffalo, NY PMSA	432,883	76.3	11.4	5.4	7.0	19.7

1/ This category includes motorcycle, bicycle, walked only, worked at home, and all other means.

Source: 1990 Census of Population, STF3C.
Contact: Journey-to-Work and Migration Statistics Branch, Population Division, U.S. Bureau of the Census, (301) 457-2454.

Median Household Income and Percent of Households in Income Intervals, Thirty-Nine Metropolitan Areas, 1990

Metropolitan Area	Median HH Income	< $15	$15-29.9	$30-49.9	$50-74.9	$75+
NYC	$37,869	20.3%	19.4%	23.4%	18.8%	18.1%
LOS	$36,711	18.5%	21.7%	25.2%	18.7%	15.9%
CHI	35,916	19.1%	21.9%	27.1%	18.9%	13.1%
SFC	41,459	15.1%	19.3%	25.5%	21.2%	18.9%
PHI	35,735	19.5%	21.9%	26.8%	18.8%	13.0%
DET	34,729	22.0%	21.2%	25.8%	18.7%	12.3%
BOS	40,647	17.5%	18.4%	24.9%	21.3%	17.8%
WAS	46,856	10.4%	17.2%	25.9%	23.7%	22.7%
DAL	32,825	19.3%	25.6%	26.8%	16.9%	11.3%
HOU	31,488	22.3%	25.0%	25.2%	16.3%	11.2%
MIA	28,503	26.0%	26.1%	24.0%	14.1%	9.8%
ATL	36,051	17.2%	23.1%	27.8%	19.0%	12.9%
CLE	30,332	24.0%	25.4%	26.8%	15.3%	8.5%
SEA	35,047	17.4%	24.2%	29.1%	18.4%	10.9%
SDG	35,022	17.9%	24.3%	26.7%	18.2%	12.9%
MIN	36,564	16.6%	22.8%	29.5%	19.7%	11.4%
STL	31,706	21.9%	24.7%	27.7%	16.7%	9.0%
BAL	36,550	18.2%	21.8%	27.3%	19.5%	13.1%
PIT	26,501	28.2%	27.4%	24.7%	12.6%	7.0%
PHX	30,797	21.1%	27.3%	27.0%	15.3%	9.2%
TAM	26,036	26.3%	30.8%	24.9%	11.5%	6.5%
DEN	33,126	19.5%	25[illegible]	27.4%	17.4%	10.7%
CIN	30,979	23.1%	2[illegible]	27.[illegible]%	15.9%	8.8%
MIL	32,359	21.3%	2[illegible]	28[illegible]%	[illegible]1%	8.4%
KSC	31,948	20.9%	2[illegible]	28[illegible]	[illegible]4%	8.7%
SAC	32,734	20.2%	24[illegible]	27.0%	17.7%	10.2%
POR	31,070	20.8%	27.[illegible]%	28.5%	15.4%	8.2%
NFK	30,841	20.1%	28.2%	28.8%	15.7%	7.2%
COL	30,668	22.0%	26.[illegible]%	27.9%	15.3%	8.1%
SAT	26,092	27.8%	28.8%	24.5%	12.3%	6.6%
IND	31,655	20.4%	26.5%	27.9%	16.5%	8.7%
NRL	24,442	32.7%	26.1%	22.7%	11.8%	6.7%
BUF	28,084	26.8%	28.1%	26.4%	14.0%	6.7%
CHA	31,126	21.2%	26.6%	27.9%	15.9%	8.4%
PRO	31,857	23.5%	23.3%	27.4%	16.7%	9.2%
HAR	41,440	15.0%	1[illegible]%	26.7%	22.8%	16.3%
ORL	31,230	19.2%	2[illegible]%	28.4%	15.6%	8.5%
SLC	30,882	19.7%	2[illegible]	29.8%	15.1%	6.9%
ROC	34,234	19.8%	2[illegible]	27.9%	18.5%	10.4%
ROC	34,234	19.8%	2[illegible]	27.9%		

Workers per Household*, 1980 and 1990, for Large Metropolitan Areas.

Metropolitan Area	1980	1990	Metropolitan Area	1980	1990
Washington, DC	1.41	1.52	Columbus	1.22	1.29
Norfolk	1.38	1.42	New York City	1.18	1.29
Atlanta	1.3	1.4	Rochester	1.25	1.29
Minneapolis	1.37	1.4	Milwaukee	1.29	1.28
Los Angeles	1.26	1.39	Kansas City	1.25	1.28
Orlando	1.29	1.39	San Antonio	1.3	1.26
San Diego	1.27	1.39	Portland	1.19	1.26
Salt Lake City	1.33	1.38	Cincinnati	1.18	1.24
San Francisco	1.26	1.37	St. Louis	1.2	1.24
Charlotte	1.38	1.37	Phoenix	1.21	1.23
Dallas		1.36	Sacramento	1.13	1.23
Baltimore	1.28	1.35	Miami	1.12	1.21
Houston	1.36	1.32	Detroit	1.15	1.21
Chicago	1.26	1.32	Cleveland	1.18	1.17
Denver	1.33	1.31	Buffalo	1.12	1.15
Seattle	1.23	1.31	New Orleans	1.16	1.13
Indianapolis	1.25	1.3	Pittsburgh	1.09	1.07
Philadelphia	1.21	1.3	Tampa	0.95	1.05

*Total workers divided by total households. Total workers includes workers who live in group quarters.

(Sorted by 1990 number and based on 1983 geography. New England areas excluded)

Demographic Ratios and Urban/Rural Population
Percentages, 1990

Metropolitan Area	Persons Per HH	Vehicles Per HH	Workers Per HH	% Urban Population	%Rural Population
NYC	2.67	1.2	1.29	95.7%	4.3%
LOS	2.91	1.74	1.39	97.4%	2.6%
CHI	2.72	1.49	1.32	96.0%	4.0%
SFC	2.61	1.73	1.37	96.1%	3.9%
PHI	2.66	1.49	1.3	89.0%	11.0%
DET	2.67	1.66	1.21	88.4%	11.6%
BOS	2.61	1.54	1.39	87.1%	12.9%
WAS	2.62	1.67	1.52	91.5%	8.5%
DAL	2.64	1.74	1.36	92.6%	7.4%
HOU	2.75	1.65	1.32	89.7%	10.3%
MIA	2.58	1.49	1.21	98.9%	1.1%
ATL	2.64	1.8	1.4	80.9%	19.1%
CLE	2.56	1.62	1.17	90.1%	9.9%
SEA	2.49	1.81	1.3	89.9%	10.1%
SDG	2.69	1.75	1.39	95.2%	4.8%
MIN	2.58	1.74	1.4	89.9%	10.1%
STL	2.59	1.66	1.24	87.9%	12.1%
BAL	2.64	1.57	1.35	87.2%	12.8%
PIT	2.46	1.45	1.07	80.9%	19.1%
PHX	2.59	1.65	1.23	96.4%	3.6%
TAM	2.32	1.52	1.05	89.2%	10.8%
DEN	2.46	1.77	1.31	94.2%	5.8%
CIN	2.61	1.69	1.25	85.1%	14.9%
MIL	2.61	1.59	1.28	89.6%	10.4%
KSC	2.55	1.72	1.28	89.2%	10.8%
SAC	2.6	1.78	1.23	87.9%	12.1%
POR	2.52	1.75	1.26	84.7%	15.3%
NFK	2.69	1.68	1.41	94.8%	5.2%
COL	2.54	1.71	1.29	80.9%	19.1%
SAT	2.82	1.63	1.26	91.2%	8.8%
IND	2.56	1.71	1.3	82.7%	17.3%
NRL	2.67	1.41	1.13	93.2%	6.8%
BUF	2.51	1.47	1.15	85.4%	14.6%
CHA	2.58	1.8	1.37	68.7%	31.3%
PRO	2.57	1.3	1.27	87.1%	12.9%
HAR	2.56	1.72	1.37	80.3%	19.7%
ORL	2.6	1.71	1.38	90.3%	9.7%
SLC	3.04	1.88	1.38	98.4%	1.5%
ROC	2.58	1.64	1.28	70.6%	29.4%

*Total workers divided by total households. Total workers includes workers who live in group quarters.

Appendix B
Observed and Estimated Average Trip Lengths in San Juan

Area Type	Observed Average Trip Length (Minutes) Sent	Observed Average Trip Length (Minutes) Received	Estimated Average Trip Length (Minutes) Sent	Estimated Average Trip Length (Minutes) Received
Home-Based Work				
CBD	35.5	44.4	34.5	46.3
Fringe	33.0	43.4	32.3	44.0
Urban	34.5	34.0	33.9	34.1
Suburban	35.9	28.5	35.2	29.0
Rural	37.3	33.3	42.3	31.5
Total Region	35.4		35.7	
Home-Based Shop				
CBD	14.8	16.0	17.7	21.5
Fringe	15.1	16.9	16.6	19.8
Urban	13.1	15.6	12.7	14.9
Suburban	13.6	11.0	13.7	11.6
Rural	17.0	9.3	17.3	10.4
Total Region	14.2		14.4	
Home-Based Shop				
CBD	19.6	27.8	19.0	25.3
Fringe	16.6	20.6	17.6	23.0
Urban	14.3	17.7	14.0	17.3
Suburban	15.8	11.9	15.5	12.5
Rural	15.3	10.8	18.1	13.4
Total Region	15.5		16.0	
Home-Based Shop				
CBD	18.6	23.6	18.7	24.7
Fringe	16.7	21.9	17.4	22.0
Urban	14.9	16.1	14.7	16.1
Suburban	16.5	13.0	15.9	13.2
Rural	16.4	15.0	17.3	13.1
Total Region	16.1		16.1	
Home-Based Shop				
CBD	18.8	20.8	19.5	20.5
Fringe	18.2	18.9	18.0	18.7
Urban	15.1	15.5	15.1	15.1
Suburban	15.8	14.4	15.8	14.9
Rural	17.1	17.0	16.0	16.8
Total Region	16.2		16.2	
Internal-External				
Total Region	26.2		26.0	

Appendix C
Trip Distribution Validation Summary (New Orleans)

AVERAGE TRAVEL TIME COMPARISONS

	Highway running Time			Highway Distance			Composite Impedance		
Income Group	Observed	Estimated	Percent Error	Observed	Estimated	Percent Error	Observed	Estimated	Percent Error
1	10.17	10.56	+3.83	4.29	4.49	+4.66	62.19	62.18	-0.02
2	10.18	10.31	+1.28	4.29	4.35	+1.40	56.34	56.14	-0.35
3	10.87	10.77	-0.92	4.72	4.68	-0.85	47.17	46.85	-0.68
4	11.16	11.04	-1.08	4.91	4.84	-1.43	38.06	37.85	-0.55
TOTAL	10.68	10.70	+0.19	4.61	4.62	+0.22	48.94	48.73	-0.43

NUMBER OF INTRAZONAL TRIPS

					Intrazonal Trips as a Percentage of Total Trips	
Income Group	Observed	Estimated	Percent Error	Total Trips	Observed	Estimated
1	936	884	-5.56	61,994	1.51	1.43
2	2,202	2,438	+10.72	105,327	2.09	2.31
3	2,895	3,477	+20.10	120,191	2.41	2.89
4	3,113	2,906	-6.65	127,533	2.44	2.28
TOTAL	9,146	9,705	+6.11	415,045	2.20	2.34

MAJOR MOVEMENT COMPARISONS

Movement	Income Group	Observed Trips	Estimated Trips	Percent Error
Across Mississippi River	1	3,253	3,584	+10.18
	2	5,088	5,572	+9.51
	3	8,594	8,874	+3.26
	4	8,334	8,610	+3.31
	TOTAL	25,269	26,639	+5.42

NOTICE

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