Multimodal Inter-Regional Origin-Destination Demand Estimation

A Review of Methodologies and Their Applicability to National-Level Passenger Travel Analysis in the U.S.

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Abstract

Since the passage of the Intermodal Surface Transportation Efficiency Act (ISTEA) in 1991 in the U.S., a significant number of state highway agencies in the U.S. have started to develop and implement state-wide travel demand models to meet policy and legislative development needs. Current and future multimodal freight flows are available from the Freight Analysis Framework (FAF), developed by the Federal Highway Administration, U.S. Department of Transportation (USDOT), to analyze national freight policy. On the passenger travel front, multimodal interregional origin destination data are still lacking. The lack of this multimodal passenger inter-regional origin destination data limits USDOT's ability to conduct quantitative analysis for infrastructure investment and operational effectiveness needs. The proposed Multimodal Transportation Analysis System (MTAS) is an attempt to develop this data and a host of other analytical functions.

Drawing from previous academic research and practical projects around the world, this paper reviews several methodologies for multimodal interregional origin destination demand estimation at the national level, including: (1). Direct demand models; (2). Trip-based and activity-based travel demand models; (3). Mathematical and statistical models based on network information such as traffic count data; (4). Compilation of various survey, ticket sales, and other datasets into a consistent OD matrix; (5). Updating an existing OD matrix based on new information. The applicability of these methodologies to the proposed MTAS in the U.S., as well as their data requirements, is discussed.

Keywords
Origin-destination matrix estimation; National travel demand model; Intercity transport; Multimodal Transportation Analysis System; National travel survey; Trip-Based, Tour-Based, Activity-Based, and Microsimulation analysis.

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1. Introduction

The U.S. has a long history of employing analytical models to guide transportation planning and decision-making. The first documented transportation planning practices with systematic modeling support in the U.S. include San Juan trip generation study in 1948 (Silver and Stowers 1964), the Detroit Metropolitan Area Traffic Study in 1953 (DMATS 1955), and the Chicago Area Transportation Studies in 1955 (CATS 1959). Planners and decision-makers in the 1950~60s quickly realized the various advantages of guiding multimodal transportation investment decision-making with transportation systems models. By 1970, 273 urbanized areas had developed systematic approaches for urban transportation planning (Weiner 2008). However, these early travel analysis tools were often criticized for their ignorance of socio-economic and environmental impacts, lack of multimodal alternative evaluation, long-range planning horizon only, and cumbersome technical procedures (Weiner 2008). With new computer technologies and the passages of the Urban Mass Transportation Assistance Act and Federal-Aid Highway Act in the early 1970s, U.S. Department of Transportation (USDOT) and the Federal Highway Administration (FHWA) developed a set of transportation planning models and tools collectively referred to as the Urban Transportation Planning System (UTPS). The development and support of UTPS by USDOT and FHWA have greatly advanced transportation planning studies, and improved highway and transit investment analysis at all levels. Most of the early travel analysis models were developed for individual metropolitan areas due to legislative requirements. Since the passage of the Intermodal Surface Transportation Efficiency Act (ISTEA) in 1991, many State highway agencies have developed and implemented statewide travel demand models to meet statewide policy and legislative development needs. Now more than 20 states have operational statewide travel demand models, with 10 additional states in the process of developing or revising their statewide models (Horowitz 2008).

The needs for analyzing transportation capital expenditure decisions at the national level in the 1970s led to two U.S. National Transportation Studies (NTS) in 1972 and 1974 respectively (Weiner 1976). These early national travel studies inventoried existing and planned U.S. transportation systems; and estimated future travel demand, system costs, performance, and broader impacts under alternative funding scenarios. The NTS process of the 1970s demonstrated the value of integrating state and metropolitan planning practices into national transportation policy analysis. They represent the first efforts in the U.S. to analyze national multimodal transportation needs, evaluate alterative investment policies, and improve the efficiency and productivity of the national transportation system. With the completion of major investments on the Interstate Highway System and the shift of transportation investment priorities from highway capacity expansion projects to operational improvements, the development of national-level passenger travel analysis tools in the U.S. has been stagnate since the 1970s, though there have been continual academic interests in improving multimodal inter-regional travel demand models (Mannering 1983, Winston 1985, Bhat 1995, Koppelman and Selhi 2005, Zhang *et al.* 2009 among others). The lack of advanced national travel analysis tools is in sharp contrast with important emerging needs for analyzing multimodal inter-regional passenger flows. Population and economic growth, along with other driving forces, will continue to cause increased medium- and long-distance passenger travel demand in the U.S. The current inter-regional transportation infrastructure already exhibits serious capacity, reliability, and congestion issues (e.g. interstate highway congestion, airport delays). Significant new investments for multimodal inter-regional travel are necessary for maintaining transportation efficiency and supporting economic development. A U.S. national multimodal transportation analysis system is in order for analyzing alternative infrastructure investments and operational improvements.

The European Union (EU) is the current leader in the development and implementation of multimodal inter-regional travel models for planning and policy analysis. National travel demand models are now available in many EU countries including Denmark, Germany, Hungary, Italy, Japan, Netherland, Norway, Sweden, Switzerland, and the U.K.. As analyzing international travel between EU countries becomes increasingly important, several operational pan-European travel demand models have also been developed, which have been successfully applied to evaluate EU-level transportation infrastructure investment scenarios and policies. Examples include the MYSTIC project, the STREAM model, the STEMM model, and the most recent TRANS-TOOLS project. In addition, aggregate inter-regional direct demand studies have been conducted to estimate multimodal travel demand patterns in several countries including Australia, Canada, Ireland, Spain, U.K., and others. In Japan, an integrated national travel analysis model has been developed and successfully applied to assess high speed rail investments. These current international practices should provide valuable information on methodological and data options, as well as institutional issues, for countries and regions that are interested in advancing their own multimodal inter-regional travel analysis capabilities. In the U.S., several prototype national travel demand models have been recently proposed or developed. Future development of a U.S. national transportation analysis system can benefit from a research roadmap and strategic vision.

This technical memo identifies and synthesizes current practices in integrating highway, rail, air, and other modes into a single multimodal modeling approach for long-distance passenger travel. This memo also summarizes and evaluates data sources in current practices with respect to data coverage, frequency, and quality. Our focus is on operational multimodal inter-regional travel analysis tools at the national or international levels. Theoretical and methodological studies will be included only if they are relevant to a particular operational model. Another important purpose of this memo is to draw recommendations from international experiences for the development of a U.S. multimodal transportation analysis tool. Since available data sources in the U.S. have certain limitations for national multimodal travel modeling, we also propose analytical methods to address these data limitations.

The following section summarizes the needs for a U.S. national multimodal transportation analysis system (MTAS) and its benefits. Section 3 synthesizes various methodological options for national travel demand modeling, including a comparison of alternative modeling approaches. Section 4 describes the data sources for current national and international travel demand models. Available data sources in the U.S. are also identified and discussed. Based on the review of modeling practices and data sources, Section 6 concludes the paper and discusses alternative roadmaps toward a national travel demand model.

2. Needs for a U.S. National Multimodal Transportation Analysis System

The development of operational travel analysis tools almost always result from the needs for understanding the full impact of transportation capacity and operational improvements, based on which strategic investment decisions can be made. Currently at the U.S. national level, existing and future multimodal freight flows are available from the Freight Analysis Framework (FAF), developed by the USDOT and FHWA to analyze national freight policies, and from several private-sector proprietary sources. However, on the passenger travel front, multimodal inter-regional origin-destination data are still lacking, which limits the USDOT's ability to conduct quantitative analysis for operational effectiveness needs and infrastructure investments. As the whole nation engages in debates on cost-effective strategies for meeting future inter-regional travel demand, it is desirable to systematically evaluate national transportation investment strategies, such as expanding the capacity of the Interstate Highway System, upgrading other facilities of the National Highway System, providing high-speed rail services along selected corridors, and building the next-generation air transportation system.

In addition to the aforementioned capacity investment options, there exist a variety of operational and management strategies, which if implemented at the national level can significantly improve transportation efficiency and productivity, support and stimulate economic growth, and produce positive social and environmental impacts. These strategies include, but are not limited to:

- Congestion pricing on the Interstate and National Highway System
- Congestion management at airports
- Advanced traffic control measures with information and commutation technology
- Separation of passenger vehicles and heavy trucks, e.g. truck-only lanes
- Fuel tax rate updates
- Innovative revenue policies, e.g. vehicle mileage fee, transit ticket surcharge
- Substituting inter-regional travel with telecommuting
- Improving ground transportation access to intermodal passenger transfer terminals

The impact of these capacity investment and operational improvement alternatives at the national and inter-regional levels can only be comprehensively studied with a U.S. multimodal transportation analysis system (MTAS), which consists of a set of core data sources and modeling tools for national-level multimodal transportation policy analysis. The MTAS can also assist in forging effective policy portfolios. In addition to enabling national-level infrastructure investment and operational analysis, the MTAS has several other important benefits:

- Analyze the impact of socio-demographic, economic, and technological changes on national travel demand and transportation needs;
- Anticipate the influence of energy (e.g. fuel price) and environmental factors (e.g. climate change, environmental regulation/standards) on national travel demand and investment needs;
- Preserve land for strategic national transportation investment;
- Improve the capability of statewide travel demand models for analyzing long-distance passenger travel;

- Reduce duplicate efforts in data collection and long-distance travel modeling at various state DOTs during the development of statewide models;
- Provide an authoritative tool for multi-state corridor analysis;
- Ensure the consistency of boundary conditions (e.g. base and future year traffic flows) as multiple agencies engage in inter-regional transportation planning/investment analysis;
- Estimate the impact of globalization and international passenger travel on the U.S. transportation system and response strategies;
- Guidance national investments in transportation reliability and security;
- Support national and inter-regional evacuation planning in preparation for natural hazards and targeted attacks;
- Model the evolution of pandemic deceases in the U.S. due to inter-regional and international passenger travel and produce transportation-related strategies for decease control.

This technical memorandum explores the feasibility of the MTAS by synthesizing current practices of national and even multi-national travel demand models in other countries and regions. The memorandum also includes a summary of available data sources and previous research in the U.S. toward a multimodal inter-regional travel analysis tool.

3. A Synthesis of Multimodal Inter-Regional Demand Analysis Methods

After reviewing about sixty studies/projects in and outside of the U.S., we categorize multimodal inter-regional travel analysis methods into four groups: (1). Direct demand and elasticity analysis; (2). Trip-based travel demand models; (3). Tour/Activity-based models and agent-based microsimulation; and (4). Origin-destination demand estimation without underlying behavioral theories. All methods are capable of estimating multimodal origin-destination demand matrices from available data sources, and have produced operational models. They differ in whether or not, and how travel behavioral responses to policy scenarios are considered (see Figure 1).

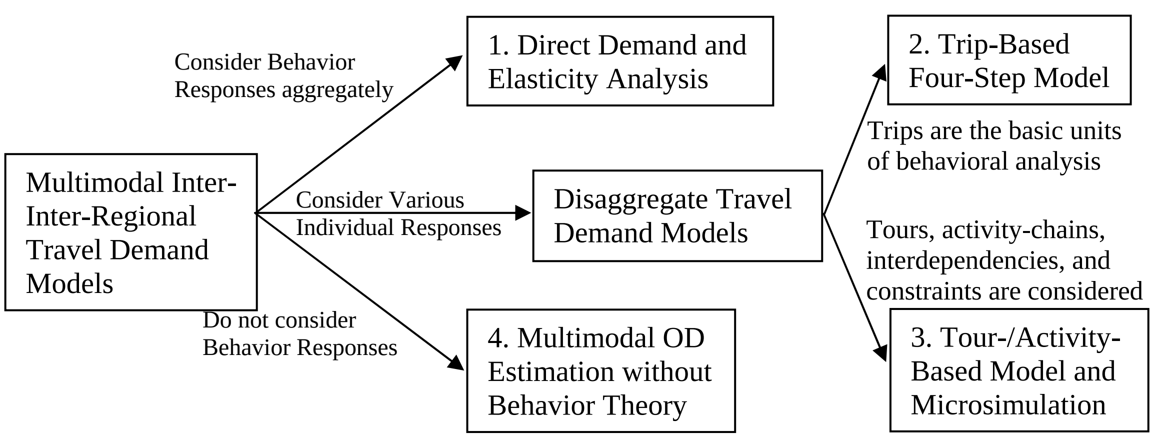

Figure 1. Categorization of Multimodal Inter-Regional Travel Demand Analysis Methods

3.1. Direct Demand and Elasticity Analysis

A number of studies have adopted direct demand models to estimate multimodal intercity passenger travel demand in Australia, Canada, Ireland, Spain, and the U.K. (Domencich Kraft 1970, Oum and Gillen 1983, Acutt and Dodgson 1996, Bel 1997, Wardman 1997, Worsley and Harric 2001, among others). In a typical direct demand model, the aggregate passenger travel demand ($\boldsymbol{D}$, e.g. number of total passenger trips, or total passenger miles traveled) between an origin-destination (OD) pair by each transportation mode is expressed as a function of economic ($\boldsymbol{E}$), land use ($\boldsymbol{L}$), and socio-demographic characteristics ($\boldsymbol{S}$) of the origin and the destination. Transportation factors influencing the aggregate OD demand by a particular mode include the attributes of that transportation mode ($\boldsymbol{A}$, e.g. travel time, cost, other level of service factors) and its competing modes ($\boldsymbol{B}$) serving the same OD pair. Equation 1 summarizes the general direct demand model structure, where lower-case symbols indicate coefficients.

$$\boldsymbol{D} = f(\boldsymbol{eE}, \boldsymbol{lL}, \boldsymbol{sS}, \boldsymbol{aA}, \boldsymbol{bB}) \tag{1}$$

If a Cobb-Douglas (i.e. log-log) functional form is specified, the coefficient estimates are direct indicators of constant own- or cross-demand elasticities. For instance, if $\boldsymbol{D}$ is the total passenger demand for an intercity high-speed rail (HSR) service between an OD pair, the coefficient vector $\boldsymbol{a}$ is the elasticity of total demand for HSR with respect to HSR ticket fare, travel time, reliability, and other HSR level-of-service factors. In other words, one percent increase in HSR fare will cause $\boldsymbol{a}$-percent decrease in total HSR demand due to completion among available transportation modes. Similarly, other coefficients in the model indicate the HSR demand elasticity with respect to attributes of automobile and air travel between the same OD pair, and with respect to socio-economic, land use, and demographic changes at the origin and the destination zones. If more flexible functional forms (e.g. translog) are specified for the direct demand model, the actual demand elasticities will no longer be constant, and can vary with other system attributes. For instance, as income increases, users usually become less sensitivity to HSR ticket fare increases. Therefore, the elasticity of HSR demand with respect to HSR ticket fare is not always the same, and should decrease as economic growth leads to increased income.

Analyses of these demand elasticities can provide direct policy implications (e.g. how will HSR investments influence inter-regional automobile and air travel demand; how will economic and population growth impact national travel demand by different modes). Direct demand models can also produce aggregate forecasts of multimodal travel demand for each OD pair by each mode, given alternative future growth and transportation system scenarios. The aggregate nature of direct demand models with its relatively low model development cost is appealing for national-level travel analysis. However, one may argue that they do not take full advantage of the information contained in available travel survey data, and that in theory more disaggregate travel analysis methods based on individual behaviors can produce more accurate forecasts and provide models with improved policy sensitivities.

The concept of direct demand analysis can also be applied to the household and even personal levels. For instance, the dependent variable, $\boldsymbol{D}$, can be total household-level travel demand indicators (e.g. vehicle ownership, total vehicle miles traveled, total travel by individual modes). Different from disaggregate demand models discussed in the next two sections, direct demand models, when applied at the household or individual level, do not consider different types of behavioral responses (e.g. trip generation, distribution, mode, time of day, and route choices). Instead, they rely on statistical/econometric models to derive the relationship between aggregate travel demand indicators and other observed variables from existing data sources. For instance, a recent study in the U.S. (Zhang et al. 2009) has developed a household-level direct demand model of vehicle miles traveled, and implemented this model to estimate the revenue, equity, and environmental impacts of several alternative national transportation taxation policies (e.g. increased fuel tax, vehicle mile fees, and increase vehicle registration fees).

A good example of direction demand and elasticity analysis applied to national travel demand forecasting is the 1997 National Road Traffic Forecast (NRTF) model in the Great Britain (Worsley and Harris 2001). Several groups of direct demand models are empirically estimated for NRTF, which use observed data to estimate vehicle ownership, passenger vehicle use, truck traffic, transportation facility level of service, and traffic flows on different types of facilities. Based on the demand elasticities from these direct demand models, a hierarchical set of demand switching rules are then defined to analyze the full impact of specific policy scenarios on the British road and transit networks. It should be noted that more recent national travel demand models in the Great Britain have incorporated disaggregate demand modeling elements, as discussed in the following section. The NRTF model has been implemented in a variety of British national transportation policy studies, including the evaluation of extensive congestion charges in British cities, estimates of road traffic's contribution to green house gas emissions, and assessment of welfare benefits from lower levels of congestion.

3.2. Trip-Based Four-Step Method

Of all the national travel demand models we reviewed, the trip-based four-step approach is the most dominant methodology. It has been employed in national models in countries including Denmark, Germany, Hungary, Italy, Japan, Netherland, Norway, Sweden, Switzerland, the U.K., and the U.S.; and in pan-European models (Leitham 1994, Gunn 1997, Gaudry 2001, Lundgvist and Mattsson 2001, Williams 2001, Davidson and Clarke 2004, Daly 2005, Yao and Morikawa 2005, Ashiabor *et al.* 2007, Nielson 2007, Cambridge Systematics 2008 among others). Compared to more mature practices outside of the U.S., modeling efforts in the U.S. are still in the beginning stage. We will focus on non-U.S. practices in this section, and Section 3.6. summarizes several pioneering studies on U.S. national travel demand modeling.

Table 1 provides an overview of selected national and European travel demand models developed (or developed initially) with the trip-based approach. Section 4 of this memo provides a more detailed discussion on the various data sources used for individual models. The most advanced trip-based models for national travel analysis usually consist of the following modules, executed in a sequential manner with feedbacks between individual modules:

- Pre-processing (e.g. socio-economic, demographic, and vehicle ownership forecasts)
- Trip generation
- Trip distribution
- Model choice
- Time-of-day switching

- Traffic assignment
- Post-processing (e.g. policy impact analysis, and emission estimation modules).

The traffic analysis zone systems in these trip-based models contain several hundred to almost 10,000 zones. Trip purposes typically are divided either into business, personal, and vacation travels or into categories based on trip ends and purposes (the later is more common for countries with smaller geographic coverage and thus have relatively richer behavioral data for intercity travel in their national surveys). Transportation modes considered include car, bus, regular rail, high speed rail, air, water, bike, and walk. A few models also include a time-of-day switching module developed from dedicated survey datasets. Traffic assignment methods range from static whole-day algorithms to multi-class multi-period stochastic equilibrium assignment. Feedbacks between the individual steps range from being nonexistent to fully integrated systems.

Table 2 summarizes the key model features of many trip-based national and pan-European models. Additional details of national and pan-European travel demand models can be found in Appendices A, B, and C at the end of this document. One may have noticed that certain models in Table 2 have departed from the traditional trip-based method, and incorporated elements from tour/activity-based and microsimulation approaches. These arguably more advanced methods for multimodal inter-regional travel analysis are discussed in the next section.

3.3. Tour/Activity-Based and Microsimulation Approaches

More recent versions of several national travel demand models in the Europe recognize tours, trip chaining, and time-of-day dynamics on the demand side, and/or time-dependent congestion evolution on the supply side, signaling a trend of moving to tour/activity-based and microsimulation approaches. For instance, the most recent Dutch model has replaced cross-classification and regression-based trip generation modules with tour-based procedures (See Table 2). In addition, it incorporates time-of-day switching propensities on the demand side. The Danish model considers three nested levels of travel representation: trips, tours, and chains (defined as a sequence of daily tours). The Italian model distinguishes three alternatives in the trip generation step for each trip purpose: not to travel, to make one tour, and to make two or more tours. Agent-based mobility simulation has been successfully conducted on the Switzerland national networks for national-level congestion analysis. A commonality among these advanced national demand models is their consideration of both short- and long-distance trips. While the analysis of short-distance daily travel can certainly benefit from these considerations of behavioral dynamics and interdependencies, the value of the activity-based approach for long-distance travel analysis in large geographies (e.g. the U.S., the European Union) is not apparent.

While more than a dozen models are discussed in detail in the Appendices, we choose to present only the Dutch Landelijk Model System (LMS; "Landelijk" is the Dutch for "national") in this section for several reasons. First, its development started in 1983, and it is one of the earliest national models. Second, it is representative of the disaggregate modeling approach, and has actually been the prototype of several other national models. Third, the Dutch model has been updated several times with the development of both advanced methods and data. Finally, LMS in its present form represents a transition from trip-based to activity-based approaches and therefore contains elements from both methodologies.

Table 1: An Overview of Selected National and European Transportation Models

Model name	**Design period**	**Data sources**	**Modes considered**	**Purposes considered**	**Zone structure**	**O-D model description**
Danish National Transport Model (PETRA)	1998	- National Travel Survey (TU), 1995	Walk, cycle, car, car passenger, bus, and train	Home, work, errand, and leisure	3,010 zones	Using activity-based nested logit model with a chain choice sub-model for trip generation
Dutch National Model System (LMS)	1983-1999	- National Travel Survey (OVG) - Panel data (The Rijkswaterstaat survey)	Car driver, car passenger, train, BTM (Bus, Tram, and Metro), and slow modes	Commuting, other work-related, education, shopping and private business, and social recreational and other	1,308 zones	Using tour frequency sub-model, using nested logit sub-model in mode and destination choice
German National Travel Demand Model (Validate)	2005	- Mobility in Germany (MiG), 2002; - Mobility in Cities (SrV), 2003	Motorized, public transit, and combined walking and cycling mode	Home, work, business, shopping, and other	7,000 zones	Using EVA algorithm, which adopted growth-factor method for trip generation, and growth-factor method with multiple balancing factors for the joint mode and destination choice sub-model
Great Britain (NTM)	2006	- National Travel Survey (NTS), 2000;	Car (driver and passenger), bus, train, and slow modes (walk and cycle)	-Home-based: work, employer's business, education, personal business recreation, holidays trips -Non home-based: employer's business, and other	17 zone types for PASS1 sub-model; 9,998 zones for PASS3 sub-model	Traditional four step method following a top-down structure
Italian Decision Support System (SISD)	1993-1996	- Household-based travel surveys; - Border-crossing interviews; - Road traffic counts.	Car, bus, air, interregional rail, intercity rail, and sleeper rail	Workplace commuting, work and professional business, university education, leisure and tourism, and other	267 internal zones, 62 external zones	Using a nested logit model, including tour frequency, distribution, and modal choice sub-models
Japanese integrated intercity travel demand model	2003	- The Inter-regional Travel Survey, 2000; - A specific SP/RP survey at six major railway stations	Air, rail (conventional rail, Shinkansen), sea, bus, and car	Business and non-business	147 zones	Using nested logit model, with route choice at the bottom.
Swedish National Model System (SAMPERS)	1998	- National Travel Survey (RiksRVU), 1994-1998;	Car, bus, normal intercity train, X2000 high-speed train, and air	Private trips, and business trips	670 zones	Using nested logit model, simplifying the trip frequency sub-model into a binomial logit choice

Model name	Design period	Data sources	Modes considered	Purposes considered	Zone structure	O-D model description
Switzerland National Travel Demand Model	2000	- Swiss National Travel Survey (Mikrozensus)	Motorized travel, public transport, and slow modes	Home, work, education, business, shopping, and leisure	2,949 internal zones, 165 external zones	Using EVA algorithm, which adopted growth-factor method for trip generation, and growth-factor method with multiple balancing factors for the joint mode and destination choice sub-model
Strategic Transport Research for European Member States (STREAMS)	1995	- National passenger travel surveys from 7 EU countries; - Tourism survey data from the World Tourism Organization (WTO)	Car, coach, slow train, high-speed train rail, air, and other	-Short distance: Commuting-business, personal business-education, visiting -Long distance: Commuting-business, personal business-education, visiting, domestic holiday, and international holiday	201 EU zones, 27 zones to represent the other European countries; 4 zones to represent the rest of world	Traditional four step method, using growth-factor method for trip generation, and a gravity model for distribution and modal split
STrategic European Multimodal Modeling (STEMM)	1996-1998	- National passenger travel surveys - Some border crossing survey data	Air, rail, and car	Business, private, and vacation	NUTS-3 (1,269 zones)	Quasi-direct demand method with combined aggregate generation-distribution model and disaggregate mode choice model
TOOLS for TRansport forecasting ANd Scenario testing (TRANS-TOOLS)	2004-2006	Pan-European Household Long-Distance Trip Survey, and ETIS-Base matrix	Air, rail, and car	Business/home-work, holiday, and other	NUTS-2 (294 zones) for economic model, NUTS-3 (1286 zones) for travel demand model	Using four-step method, which adopted growth factor method for trip generation, a logit model with disutility of generalized costs for distribution, and a multinomial logit model with non-linear utility function for mode choice.

Table 2. Structure of Selected Four-Step and Advanced Multimodal Inter-Regional Travel Demand Models

The Models	Model type	Pre-processing	Trip Generation	Trip Distribution	Modal Split	Time of day choice	Traffic Assignment
Danish National Transport Model (PETRA)	Activity-based method	Car availability model	Chain choice model	Joint with mode choice, nested logit	Joint with trip distribution, nested logit	N/A	N/A
Dutch National Model System (LMS)	Tour-based disaggregate method	License holding models, and car ownership models	Tour frequency model	Joint with mode choice, nested logit	Joint with trip distribution, nested logit	Time of day choice model based on SP sruveys	Static user equilibrium method
German National Travel Demand Model (Validate)	EVA approach	N/A	Growth factor method	Growth factor method with multiple balancing factors	Joint with trip distribution step	Specifying hourly demand matrices	Combined static and dynamic equilibrium assignment
Great Britain (NTM)	Top-down four step method	N/A	National Trip End Model	Logit and growth factor methods	National Trip End Model	Specifying AM peak, interpeak, PM peak, and offpeak matrices	AM and inter-peak traffic loads on GB road network
Italian Decision Support System (SISD)	Nested logit	License holding models, and car ownership models	Trip frequency model	Logit destination choice model	Mode/service choice model	N/A	Passengers path choice model
Japanese integrated intercity travel demand Model	Nested logit	N/A	Tour frequency	Logit destination choice model	Mode choice	N/A	Static route choice model
Swedish National Model System (SAMPERS)	Nested logit	Car ownership model	Binomial choice model for trip frequency	Logit destination choice model	Mode choice with access/egress choice sub-model	Departure time choice model	N/A
Swiss National Travel Demand Model	EVA approach	N/A	Growth factor method	Growth factor method with multiple balancing factors	Joint with trip distribution step	N/A	N/A
STREAMS	Conventional four step method	N/A	Growth factor method	Gravity model	Aggregate modal split by market sectors	N/A	Stochastic user equilibrium
STEMM	Quasi-Direct Demand method	N/A	Growth factor method	Gravity model	Logit model with non-linear utility function	N/A	N/A
TRANS-TOOLS	Four step method	Integrated spatial computable general equilibrium economic model	Growth factor method	Logit model using disutility of generalized costs	Logit model with non-linear utility function	Split into weekday (AM peak, PM peak, and rest of day), weekends, and vacation periods	Stochastic user equilibrium

The LMS adopts a disaggregate system in its four-step model, with stages of license holding, mode choice, and time-of-day decisions all linked together with models of car-ownership, trip generation and distribution, and all based on analyses of individual choices (Gunn 1997, 2001, Hofman 2001). The linkages among these choice dimensions are considered with a nested logit specification. From 1997 to 1999, the LMS model was updated, as well as the basic sources of data used for the model. Additional improvements on the LMS are currently underway with longitudinal survey data. In earlier versions of LMS, the country was divided into 345 internal zones and around 1,100 subzones. From 1997 to 1999, the zoning system was updated to a location system based on approximately 3,000 postal codes. The postal-code zones were then aggregated to 1,308 zones in the model. This update was shown to have greatly enhanced model accuracy.

Figure 2 illustrates the overall structure of the LMS. In the pre-processing mobility choice step, LMS employs a combination of license holding and car ownership models that are capable of estimating background conditions in the base year and under various policy scenarios. The tour frequency models employ two interconnected modules (i.e. the 0/1+ module and the stop-go module) to estimate the total number of tours made by each individual. Tours are also segmented by travel purposes. The tour-frequency estimation utilizes information on the household structure, license holding, car ownership, occupation, gender, age, and education. The destination and mode choice modules are nested logit models, which predict the distribution of tours over combinations of destinations and modes. This step depends on the accessibility by each mode and on the level of attractiveness of each zone by travel purpose. A time-of-day switching module has also been developed based on stated-preference data. While a static capacity-constrained algorithm is used for traffic assignment in the LMS, the possibility of combing LMS demand modules with dynamic traffic assignment has been considered in previous research (Gunn and Hofman 1998, Ben-Akiva et al. 1998). Congestion estimates are then fed back to time-of-day, and mode-destination choice models until an equilibrium is achieved. Both national economy and land use are considered exogenous in the LMS, which is also the case for almost all national and European models (The only exception is the recent TRANS-TOOLS European model wherein spatial computable general equilibrium economic models are integrated with transportation models).

In term of model calibration and validation, the LMS uses combined calibration methods to estimate base-year matrices (Gunn *et al.* 1997), and a “pivot-point” approach to forecast future OD matrices by mode based on the base-year matrix (Daly 2005) and the demand model. In other words, the pivot-point approach in the LMS forecasts changes to the most recent base-year matrix under alternative future policy scenarios and background conditions.

Despite not being a completely activity-based model, the LMS is sensitive to many socio-economic, land use, transportation systems, and policy factors. Applications of the LMS include the forecast of rail demand for railway investment analysis, impact assessment of increased fuel prices, performance impact of improved roadway signalization, evaluation of roadway investment packages, analysis of high speed trains, and estimate the transportation of socio-economic, demographic, technological, and international driving forces (Hofman 2001).

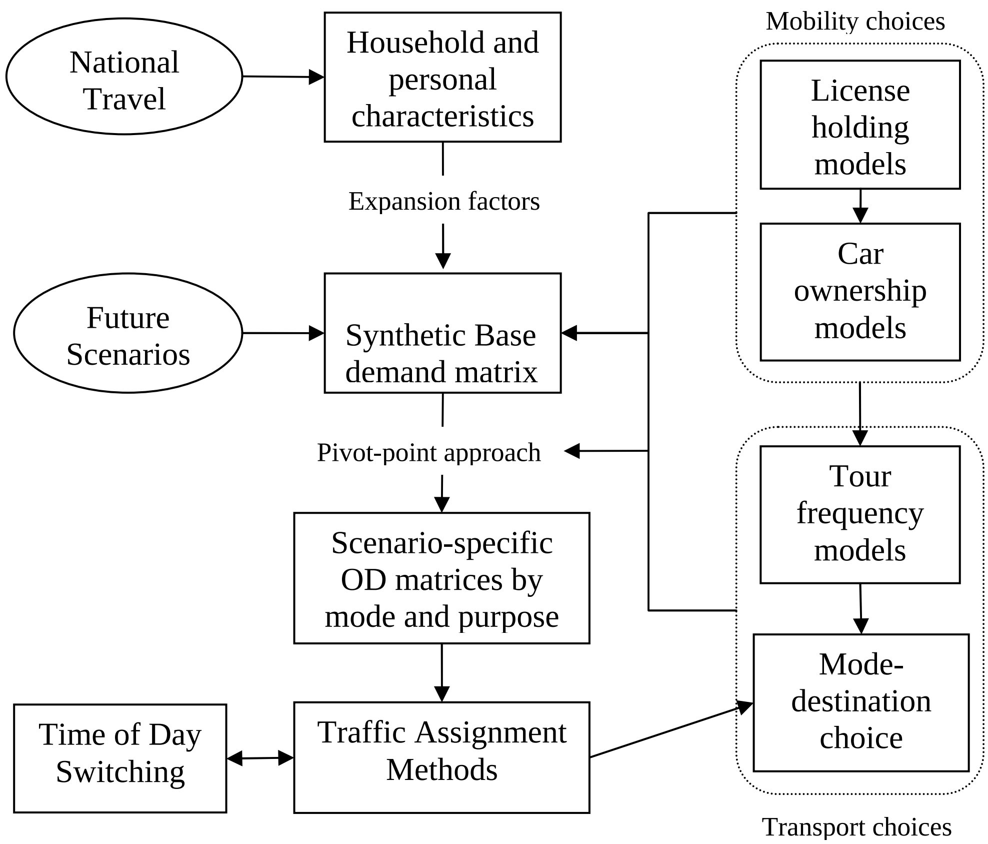

Figure 2. LMS Model Structure

3.4. Multimodal OD Estimation without Behavior Theory

The aforementioned three methods for multimodal inter-regional OD demand analysis can be referred to as top-down approaches, because they all start with zone-level socio-economic, demographic, and land use information, all require comprehensive demand models estimating behavioral responses, and all utilize data for calibration and validation of model parameters at the end of the model development process. However, OD matrices can also be estimated with a bottom-up approach directly from available data sources, including household surveys, user surveys on transportation facilities (e.g. roadside, airport, rail terminal, bus station, water port, border facilities), and link-level traffic counts.

The European Commission (EC) has funded a stream of studies that aim to estimate multimodal (car, rail, air, and other) OD matrices from available data sources without relying on behavioral theories, including the OD-ESTIM project (Hilferink 1997; Cost-efficient **O**rigin-**D**estination **ESTIM**ator), the MYSTIC project (PDC 2000; **M**ethodolog**y** and evaluation framework for modeling pa**S**sengers and freigh**T** on transport **I**nfrastructure **S**cenarios), and the DATELINE project (Davidson and Clarke 2004, Brog *et al.* 2004; **D**esign and **A**pplication of a **T**ransport survey for **L**ong-distance trips based on an **I**nternational **N**etwork of **E**xpertise). The MYSTIC project team has developed a heuristic harmonization procedure to directly merge various data sources (e.g. household, roadside, and border crossing surveys) from seven European Union (EU) countries into consistent pan-European OD matrices for multimodal passenger and freight travel. The more recent DATELINE project has refined the MYSTIC methodology, and also incorporated data from a new pan-European long-distance travel survey involving 16 countries.

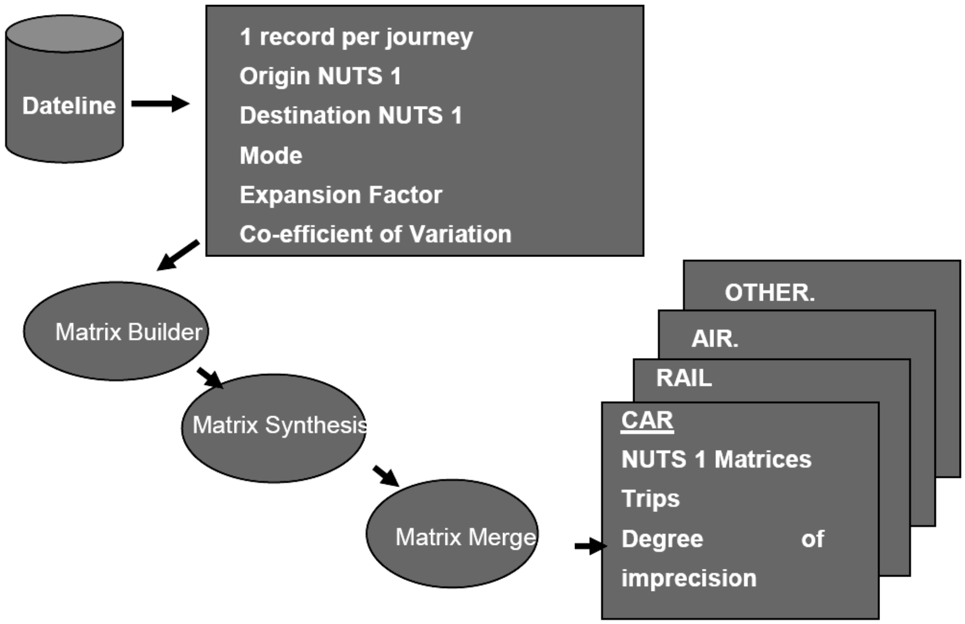

Figure 3. DATELINE OD Estimation Procedure (source: Davidson and Clarke 2004)

The DATELINE multimodal OD estimation methodology is illustrated in Figure 3. The *matrix builder* counts the accumulative numbers of journey records between zone pairs, which are then multiplied by expansion factors to get the estimated total journeys between OD pairs (the NUT1 system is used with 90 internal EU zones and 30 external zones). Variance estimates are also established for these initial OD demand estimates based on expansion factors (i.e. a smaller sample size for an OD pair indicates higher variance for the demand estimate). There are empty cells in this *observed* OD matrix, and many of them are not true-zero cells (no journeys between an OD pair in the real world). The *matrix synthesis* step first develops a gravity model based on non-empty cells in the observed matrix, and them applies the gravity model to estimate the OD demand in all cells, which produces a *synthetic* matrix. Finally, the *matrix merge* step computes the final estimates of mode-specific OD demand as the variance-weighted sum of the observed and the synthetic matrices. The variance-based weights are different for individual cells, and ensure that more reliable OD demand estimates from the observed or the synthetic matrices play a greater role in producing the final OD estimates.

Another interesting methodology for directly estimating OD matrices from survey and other available data sources has been developed for the Dutch national model system (Dunn *et al.* 1997). As described in the previous section, the Dutch model, along with several other national models, estimate the impact of policy scenarios based on the demand changes from a base-year OD matrix, which requires a procedure for updating the base-year matrix. The procedure takes the Dutch national household survey, OD data from intercepted travelers, rail ticket sales data, and an *a-priori* OD matrix (e.g. a previous, but now outdated OD matrix) as inputs. The matrix estimation procedure can be best described as a statistical method that treats each observed data item as a piece of statistical evidence to be weighed against other observations based on their relative accuracy. This method is most useful when data for OD estimation originate from different sources, when the data items in these sources have different levels of accuracy or reliability, and when the data items follow different statistical distributions.

There is also a large-body of literature on estimating or updating origin-destination demand matrices from link-level traffic count data, which can be viewed as the reverse process of traffic assignment. This method can be operationalized with proportional assignment (Bell 1991), linear programming (Sherali *et al.* 1994, Nie *et al.* 2004), or bi-level mathematical programming (i.e. Upper level: minimizing the discrepancies between observed link counts and the link counts implied by the estimated OD matrix; Lower level 2: traffic equilibrium conditions; Yang *et al.* 1992). Input data for this method include an *a-priori* matrix and at least partial traffic counts on a significant number of links in the transportation system. If traffic counts are available for multiple time periods, the *a-priori* OD matrix may not be necessary. This method of deriving OD demand matrix from traffic counts should be of value to regions and countries that have annual or daily traffic counts for a large portion of their transportation system (e.g. the Highway Performance Monitoring System in the U.S.). While this method could be computationally intensive on large-scale time-dependent networks, its applications on national networks for long-distance OD demand estimation may not require considerations for congestion evolution or time dependencies. There have been successful demonstrations of this method on large-scale networks such as the pan-European transportation network (Nielson 1998, Hansen 2008).

The advantage of the direct OD estimation methods lies in their relatively low development costs, reliance on available data only, and provision of base-year multimodal OD matrices. With growth factors, these methods can also produce future-year travel demand estimates. OD matrices developed from these direct estimation methods have also been routinely used to calibrate and validate national travel demand models developed with behavioral approaches. In terms of disadvantages, a direct OD matrix estimation model in itself is not sensitive to long-range policy alternatives due to its lack of behavioral sensitivities. They are more valuable for short-term analysis of operational improvements, and must be combined with other demand models for long-term studies.

3.5. Comparison of Alternative Analytical Methods

Table 3 offers a qualitative comparison of the four general categories of multimodal inter-regional OD demand analysis methods in current practices. The four-step and the tour/activity-based models enjoy sound behavioral foundations, and have the greatest capabilities for analyzing operational and planning policy scenarios. However, these two methods are also the most costly options, involve relatively higher development risks, and have less model transparency (important when the method needs to be explained to non-technical audiences). The direct OD estimation method is probably the cheapest to develop and can produce base-year matrices for other methods, but has serious limitations for long-range policy analysis. The direction demand model is the average-performing alternative in most categories.

Table 3. Qualitative Comparison of Multimodal Inter-Regional OD Analysis Methods

Model Properties	Direct Demand	Trip-Based Four-Step	Tour/Activity-based &microsimulation	Direct OD Estimation
Behavioral Foundation	Good	Good	Great	None
Transparency of the Model	Good	Average	Low	Good
Data Requirement	Average	Average	High	Low-Average
Development Cost	Low-Average	Average	High	Low
Development Risk	Low	Low-Average	High	Low
Maintenance/Application Cost	Low	Average	High	Low
Policy Sensitivity	Average	Good	Great	None
Short-term operational analysis?	Yes	Yes	Yes	Yes
Long-range planning analysis?	Yes	Yes	Yes	No
Produce base-year matrix	No	No	No	Yes

Note: Shaded cells represent properties that are desirable.

For a nation or a region in need of a multimodal inter-regional demand analysis tool, the choice of methodology is therefore a task that requires careful considerations based on funding resources available for model development and maintenance, types of policy analysis needs, data availability and future data collection plans, and the value of increased forecast accuracy. While surface transportation efficiency remains an important goal, other objectives such as system reliability and security can also be affected by infrastructure investment (Zhang and Levinson 2008). Not surprisingly, we have observed staged development of national travel demand models in current practices. For instance, the U.K. national travel demand analysis system has evolved from a single disaggregate auto-ownership module in the 1970s, to direct demand models in the 1980s, to hybrid (direct demand and discrete choice) national road traffic forecast system in 1997, and now towards more advanced behavioral models with even greater policy sensitivity. The pan-European travel demand model started with direct OD matrix estimation without behavioral models in the MYSTIC project in the early 1990s, and gradually advanced to the 201-zone NUTS2 (Nomenclature of Territorial Units for Statistics version 2) STREAM model with aggregate methods, then to the 1275-zone NUTS3 STEMM model with joint aggregate-disaggregate models, and finally to the most recent disaggregate TRANS-TOOLS model that integrates European transportation and economic models. In Italy, two national model systems have been developed. The SASM decision support system is designed to improve short-term operational decision-making on intercity rail services, while the Italian National Model System is dedicated to long-range strategic policy analysis.

3.6. National Travel Demand Modeling Efforts in the U.S.

Since the 1972 and 1974 USDOT national transportation studies, there have been few efforts in the U.S. toward an operational national travel demand model, though there has been a steady stream of academic studies on U.S. multimodal long-distance travel with a focus on mode choice and vehicle ownership (Mannering 1983, Winston 1985, Bhat 1995, Koppelman and Selhi 2005 among others). More recently, the emerging needs for national-level transportation planning and policy analysis have revived the interests in national travel demand modeling in the U.S. There are three notable efforts in the U.S. just in the past three years toward the development of multimodal inter-regional demand analysis tools.

Researchers at Virginia Tech (Ashiabor *et al.* 2007, Baik *et al.* 2008) have developed a four-step trip-based Transportation Systems Analysis Model (TSAM), which is based on county-level zones and considers commercial air, air taxis, and automobile modes. Rail is not considered because the model is developed to analyze the market share of the proposed light jet/air taxi system. Network assignment is composed of commercial airline and air taxi assignments only for the same reason, though there are plans to incorporate highway assignment into the TSAM. The primary travel data source is the 1995 American Travel Survey.

Cambridge Systematics (2008) has also conducted a study, in which a comprehensive framework for the preparation, development, estimation, validation, and implementation of a U.S. national travel demand model (NatMod) is proposed based on the trip-based approach. This is not yet an operational model, but the proposed framework includes a staged development process.

Epstein *et al.* (2008) have developed an agent-based microsimulation model of intercity travel for the purpose of understanding the spread of pandemic diseases (e.g. avian and swine flu). This agent-based model is capable of simulating trip frequency and destination choices of each household and each person in the U.S.. It employs a micro-level implementation of the gravity model to simulate individual-level intercity travel decisions based on a zip-code level origin-destination system. It appears there is no mode-choice or assignment steps in the simulation model because this model is not designed as a traditional travel demand analysis tool. Nevertheless, this study exemplifies the benefit of a national travel demand model beyond transportation systems applications. Agent-based modeling approaches are also demonstrated in large-scale networks in Zhang and Levinson (2005), Zhang (2007), and Zhang *et al.* (2008).

It should be noted that many statewide models in the U.S., developed by state DOTs, also consider national multimodal passenger travel either originating from or destined for their states. For instance, the models in Oregon, Michigan, and Ohio have incorporated relatively coarse U.S. national-level zones (often based on state borders), halo zones for adjacent states (often based on county borders), and sub-county traffic analysis zones within their state borders. For instance, the Oregon model analyzes long-distance passenger travel with a traditional four-step approach (Donnelly *et al.* 2009), while the Maryland model employs microsimulation (Zhang and Cirillo 2009).

4. Data Sources

4.1. Data Type, Coverage, Frequency, and Quality in Current Practices

Data sources for national travel demand analysis in current practices are listed below, with the primary demand-side data source being cross-sectional household and personal travel surveys, conducted with various methods including mail surveys, telephone interviews, and in-person interviews. Table 4 summarizes the type, coverage, frequency, collection method, and quality of various datasets used in selected national and European travel demand models.

- Household and personal travel surveys
- User interception surveys on roadsides, transit terminals, airports, and borders

- Special-purpose stated preference (SP) and SP-RP (Reveal Preference) surveys
- Tourism data
- Dedicated long-distance travel surveys
- Traffic counts, and other Supply-side network and cost data

The sample size of national surveys ranges from 5,000 in the earlier Dutch model to more than 500,000 in the more recent Japanese modeling practice. Most national surveys involve 15,000 to 70,000 households. Most of the national surveys in Europe and Japan are not designed specifically for long-distance travel analysis because of the country sizes. The recent pan-European survey, which covers about a geographic region similar to the U.S., includes about 870,000 person samples and only considers medium- and long-distance travel. Almost all survey data are cross-sectional or repeated cross-sectional, though panel data exist at the national level in the Netherland for selected years. Typically, data are collected annually, once every five years, or just one time. There are also cases (e.g. Italy) where data are collected twice in a year to account for seasonal demand variation (probably due to interests in tourism trends). One-day diary is the most popular method, with a 7-day diary adopted in the recent U.K. survey. In countries where repeated cross-sectional surveys have been conducted, the quality of data in different years is often inconsistence due to changes in the sampling framework, recruitment methods, non-response handling, and questionnaire design. Oversampling, special SP surveys, and modal-specific data collection are often employed to supplement and improve the quality of national survey datasets. The following section describes common limitations of the various data sources for multimodal inter-regional passenger travel demand analysis, and presents tested strategies that can address various data quality and completeness issues.

4.2. Data Limitations and Improvement Strategies

Limitation: Not enough observations of long-distance trips or longer long-distance trips
Strategy: Dedicated long-distance surveys; Oversampling of longer long-distance trips; Synthetic methods; and/or larger analysis zones

While standard national surveys in general provide sufficient long-distance trip observations for the development of national demand models in many European counties, they do not provide enough long-distance trip samples for pan-European modeling practices. The European Commission (EC) therefore decided to conduct a European long-distance survey for strategic transportation analysis in Europe (Nielson 2007). With random sampling, even dedicated long-distance surveys can have issues with not enough observations of longer long-distance trips. In the EC long-distance survey project, oversampling techniques are employed to ensure a sufficiently large sample of longer long-distance trips is observed for modeling purposes. If empty cells in OD matrices still exist despite oversampling or other frond-end efforts, synthetic estimation (e.g. based on gravity or choice models) can be used to fill the empty cells, though this method does not distinguish true empty cells from empty cells caused by sampling limitation. If policy analysis needs do not dictate a very detailed zone structure, reducing the number of zones can significantly decrease the number of OD pairs, which can better accommodate smaller samples.

Table 4. Summary of Data sources in Current National and Pan-European Travel Demand Models

The Models	Primary Data Sources	Survey Period	Data Type	Data Coverage Range	Collecting Method	Comments
Dutch National Model System (LMS)	Netherlands National Travel Survey (OVG), Special SP surveys	1985-present	Repeated cross-sectional used. Panel available	10,000-68,000 households Supplemented by several hundred SP surveys	Computer Assisted Telephone Interview (CATI), and a one-day travel diary	
Great Britain (NTM)	National Travel Survey (NTS)	1988-present	Repeated cross-sectional	5,000-15,000 households	Home interview, and a 7-day travel diary	
Italian Decision Support System (SISD)	1. Household-based survey 2. Border-crossing interviews 3. Manual traffic counts	1. 7/94 and 4/95 2. 7/94 and 3/95 3. 7/94 and 3/95	1. Twice in 1 year 2. Twice in 1 year 3. Twice in 1 year	1. 8,500 households in summer, 10,000 in winter 2. 16,000 interviews in summer, 12,000 in winter 3. 138 traffic counts	1. Household telephone interview, 2. Border face-to-face interview, 3. Bidirectional traffic counts	Surveys were held in summer and winter separately to capture seasonal variation
Swedish National Model System (SAMPERS)	National Swedish Travel Survey (RiksRVU)	1994-1998	Repeated cross-sectional	30,000 personal interviews	CATI, and a one-day travel diary	
Danish National Transport Model (PETRA)	National Travel Survey (TU)	1995	One year cross-sectional	13,793 personal interviews	CATI, and a one-day travel diary	One year cross-sectional data was insufficient to produce variation over time
German National Travel Demand Model (Validate)	1. Mobility in Germany (MiG) 2. Mobility in Cities (SrV)	1. 2002 2. 2003	1. One year cross-sectional 2. One year cross-sectional	1. 49,000 households 2. 34,000 persons	1. CATI, and a one-day travel diary 2. N/A	
Swiss National Travel Demand Model	Swiss National Travel Survey (Mikrozensus)	2000	cross-sectional, collected every five years	27,918 households	CATI	
STREAMS	National travel surveys, Border crossing, roadside, tourism	Mostly 1994	Cross-sectional	7 EU countries: Denmark, Finland, France, Germany, Netherlands, Sweden, and UK		
Japanese integrated intercity travel demand Model	1. The Inter-regional Travel Survey 2. SP data	1. 2000 2. 2000	1. cross-sectional, collected every five years 2. 1 year	1. Approximately 500,000 passengers 2. 2,000 interviews in total	1. Separate one weekday sample interview taken for 5 inter-regional mode systems 2. interview at six main rail stations on the HSR line	The latest survey in 2005 includes weekend days.
DATELINE	Pan-European Household Long-Distance Trip Survey	2000~2002	Cross-sectional	86,969 persons in 16 European counties; Over-sampling on very long-distance trips.	Combined postal, telephone, and in-person interviews with a two-phase design	Special journey-tour-trip design for long-distance survey

Limitation: Available data sources not suitable for standard modeling procedures
Strategy: Modified/Hybrid modeling procedures

In some cases, available data may not provide all necessary inputs for the development of completely disaggregate models. A hybrid modeling approach may be more appropriate, which combines aggregate and disaggregate models. Both the U.K. national model and the STEMM European model have adopted hybrid modeling methods. For instance, trip generation and distribution in the STEMM model are jointly considered in an aggregate direct demand model, while mode choice is based on a disaggregate logit model (Williams 2001). In some other cases, existing modeling methods may need to be modified in response to data limitations. For instance, due to the lack of information about access and egress trips for air and rail modes, the Swedish model incorporates mode-specific dummy variables based on specific origins and destinations in the access-egress choice model (Beser and Algers 2001, Sveder 2001). In the Japanese model (Yao and Morikawa 2003), a weight factor is introduced to the likelihood function of the joint mode-route choice model, which effectively removes biases due to the integration of multiple data sources. In the Danish model (Fosgerau 2001), the one-year cross-sectional data do not provide sufficient variations in fuel or auto prices for the auto ownership model. This drawback is addressed with a modified method that links the influence of auto prices on household auto availability with household income, and links the effects of fuel prices on car travel to destination accessibility and attractiveness.

Limitation: Data from different sources with different levels of accuracy
Strategy: Statistical methods weighing data items from multiple sources based on accuracy

The development of national travel analysis tools often requires the merging of data items from various sources, because in many cases necessary information for model development cannot be provided by any single source. Due to the different sample sizes and collection procedures, data items from different sources tend to have different levels of accuracy and reliability. This issue is present in many current practices, and especially significant in the development of pan-European models that use data from many different countries. Several statistical procedures have been developed to address this issue. In general, these methods weigh data items from different sources based on their relative actuary, which can be measured by the variances of the data items (Nielson 1998, PDC 2000, Davidson and Clarke 2004). For instance, data items based on a smaller sample exhibit larger variances and less accuracy than those based on a larger sample. Similar weighing procedures can also be found in the estimation of the Dutch base-year matrix (Gunn *et al.* 1997).

Limitation: Lack of longitudinal observations of behavioral dynamics in standard surveys
Strategy: SP or joint SP-RP surveys on a smaller sample

A well-known limitation of cross-sectional survey datasets is their lack of information on how individuals change their behaviors over time in response to policy scenarios, especially new system alternatives. Stated preference (SP) or joint SP-RP (Revealed preference) surveys specially design to examine a particular dimension of behavioral dynamics can address this issue effectively. For instance, during the development of the Dutch national model (Gunn 2001, Hofman 2001), SP surveys were conducted among several hundreds of drivers to examine their time-of-day switching tendencies, which supported the development of a time-of-day choice module. Likewise, the Japanese model (Yao and Morikawa 2003) relied on a joint SP-RP survey to capture user preferences toward a new high speed rail route.

Limitation: Lack of network and other supply-side data
Strategy: Synthetic methods for estimating costs/impedances between OD pairs

In order to estimate OD demand by mode with a behavioral demand model, it is necessary to know the costs/impedances of travel between OD pairs (i.e. the OD cost matrix or skim matrix by mode). This information for air and rail travel may be collected from respective service providers. However, for automobile travel, especially long-distance driving trips, this OD cost information is not readily available because very long trips usually have costs associated with lodging and meals. In this case, the OD cost matrix cannot be reliably obtained from a traffic assignment algorithm based on free-flow travel conditions. Synthetic methods have been developed for OD cost estimation, which make reasonable assumptions about additional travel costs associated with long-distance travel (Baik *et al.* 2008). There are also other issues with supply-side data availability. While most countries or regions that have developed inter-regional demand models have existing network and other supply-side information, such information often needs to be processed and improved for the purpose of inter-regional analysis. For instance (Nielson 2007), in order to ensure the consistency of the multimodal transportation network for the European TRANS-TOOLS model, the project team has undertaken extensive work in coding and modifying the European road network. Sometimes, manual checking is required, which can be time consuming

4.3. U.S. Data Sources

The primary sources of long-distance travel information in the U.S. include the 1995 American Travel Survey (over 550,000 trips longer than 100 miles), the long-distance portion of the 2001 National Household Travel Survey (45,165 trips longer than 50 miles), and the continuous airline origin-destination ticket sale sample. It is not clear if Amtrak (rail) and intercity bus passenger ticket sales information is proprietary. In addition to these travel-related datasets, there are also a number of other demand-side (see Table 5) and supply-side (Table 6) data sources, which may support the development of a U.S. multimodal inter-regional demand analysis tool. Many of these data source are previously summarized by Cambridge Systematics (2008). We have expanded the list by adding information on several national surveys, and including more details on several supply-side data sources.

The U.S. has over time developed and maintained a variety of network and traffic data sources for the nation’s transportation system, which should provide a solid foundation for the supply-side development of a national travel demand model. However, there are several limitations with the U.S. demand-side data sources. First, the last national survey with a sufficiently large sample of long-distance trips for national travel analysis is the 1995 American Travel Survey, which may be considered a bit outdated. Second, the lack of multiple surveys at different points of time implies no information on longitudinal behavioral changes. Third, demand information on intercity passenger rail and bus is not readily available for modeling purposes. These data limitations can be addressed with various methods described in Sections 3.4 and 4.2.

Table 5. U.S. Demand-Side Data Sources for Multimodal Inter-Regional Passenger Demand Analysis

Source(s)	Description of Data	Data Coverage	Period of Data Collection
Airline Origin Destination Survey from Bureau of Transportation Statistics (http://www.transtats.bts.gov/)	A 10% sampling of all airline ticket sales for the entire United States. Includes information on the orgin, destination, and travel distance of each flight for each individual passenger.	10% sampling of participating commercial airlines	Updated every quarter of every year since 1993
American Community Survey (http://www.census.gov/acs/www/)	Includes information on individuals, demographics, economics, society, and housing units. Offers data for local, state, and federal governments for implementing and evaluating government programs. It replaces the Census Bureau long form	One-in-five people and households	2006 (recorded monthly; rolling 12 month summations reported each year for geographic areas with population sizes of 65,000+)
American Travel Survey, 1995	The American Travel Survey was prepared for the Bureau of Transportation Statistics. It contains long-distance data (one way trips of over 100 miles) for over 550,000 person trips including the origins and destinations of those trips.	550,000+ person trips	1995 (no longer updated, as it was replaced by the NHTS and CTPP)
Automatic Data Processing National Employment Report (http://www.adpemploymentreport.com/ index.aspx)	Used to compare with BLS employment statistics; generates monthly nonfarm private payroll statistics	Represents approximately 400,000 businesses and 23 million employees	2008 (updated monthly)
Census Bureau -- 2000 Census Public Use Microdata Sample (http://www.census.gov/Press-Release/www/2003/PUMS.html)	Information on housing units	One percent sample of households	2003 (every 10 years)
Census Bureau – 2000 Census Summary File 1 (http://www.census.gov/Press-Release/www/2001/sumfile1.html)	Information on households, individual, and workers in TAZs and census tracts	All 50 states and the District of Columbia	2001 (every 10 years)
Census Bureau – 2000 Census Summary File 3 (http://www.census.gov/Press-Release/www/2002/sumfile3.html)	Income, education, employment status, and place of birth of household members	About 19 million households (1 in 6 of all households)	2002 (every 10 years)
Census Bureau (http://www.census.gov/support/ PLData.htm)	Total American population 18 years or older	All households	2001 (every 10 years)
Census Transportation Planning Package 2000 Part 1 (http://www.trbcensus.com)	Provides information on individuals and residencies	Not specified; based on decennial Census long form	2003 (every 10 years)
Census Transportation Planning Package 2000 Part 2 (http://www.trbcensus.com)	Provides information regarding employment and place of work	Not specified; based on decennial Census long form	2003 (every 10 years)

Census Transportation Planning Package 2000 Part 3 (http://www.trbcensus.com; http://www.census.gov/mp/ www/spectab/specialtab.html)	Provides information on traffic flow between location of work and home	Not specified; based on decennial Census long form	2004 (every 10 years)
Dun and Bradstreet business data (http://www.dnb.com/us/)	Potential use in determining freight data	Not specified	2007 (updated quarterly)
InfoUSA (http://www.infousa.com/)	Information on sales	Not specified	2007 (updated quarterly)
Longitudinal Employer –Household Dynamics Program (http://www.fhwa.dot.gov/ planning/Census/lehd.htm; http://lehd.did.census.gov/led/ index.html)	Quarterly records of income and employment situation of nearly all individuals; useful for data on places of work and flow	Not specified; combines data sources ranging from state and federal administrative data, to Census surveys, to private firms data	2006 (updated quarterly)
National Household Travel Survey, 2001 (http://nhts.ornl.gov/index.shtml)	Gives insight into travel behaviors based on trip purposes, trip distances, origins and destinations, and modes of transportation; includes long-distance trip information (> 50 miles)	70,000 households; 45,165 person trips for long-distance, multimodal transportation	2001 (updated as needed at no particular frequency)
National Household Travel Survey, 2008-09 (http://nhts.ornl.gov/index.shtml)	New NHTS surveys	155,000 households from April 2008 to May 2009	2008 (updated as needed at no particular frequency)
State Employment Security Departments (http://www.subnet.nga.org/ workforcecouncilchairs/ StateEmpTrainAg.htm)	Provides information on the employment or unemployment status at a state level	Not specified; varies by each state	2007 (monthly updates)
U.S. Census Bureau Employment Opportunity (EEO) (http://www.census.gov/eeo2000/ index.html)	Residential data, residence to work location flow data, and worksite data; used for affirmative action	471 census occupations, 268 Office of Personnel Management occupations, and 8 state and local government occupational categories	2004 (updated every 10 years)
U.S. Department of Labor Bureau of Labor Statistics (NAICS) (http://www.bls.gov/data/home.htm)	Publishes monthly data on employee earnings, hours worked, and the number of employees	152 metropolitan areas; surveyed 200,000 business in May and Nov. since 2002	2006 (updated quarterly)
U.S. Department of Labor Bureau of Labor Statistics (SIC) (http://www.bls.gov/data/home.htm)	Published monthly data on employee earnings, hours worked, and the number of employees	Surveyed 400,000 establishments a year	Stopped in 2003 (previously updated quarterly)
Woods and Poole Metropolitan and County historical and forecast data (http://www.woodsandpoole.com/)	Projects up to year 2040 information on employee earnings per industry; includes 900 variables on economics and demographics data	Not specified	2007 (updated annually)

Table 6. U.S. Supply-Side Data Sources for Multimodal Inter-Regional Passenger Demand Analysis

Source(s)	Description of Data	Period of Data Collection
CTA Railroad Network (http://cta.ornl.gov/transnet/ RailRoads.html)	Includes information on every railroad in the United States, Canada, and Mexico in operation since at least 1993, and was intended to generate accurate intercity route combinations	2005
Federal Railroad Administrations (FRA) (http://www.bts.gov/publications/ national_transportation_atlas_database/ 2007/zip/railway_lin.zip)	Provides data on the railroad systems inside the 50 states and the District of Columbia	N/A
Highway Performance Monitoring System (HPMS) (http://www.bts.gov/publications/ national_transportation_atlas_database/ 2007/html/hpms.html)	Offers insight on the performance, usage, accessibility, and operation of highways. AADT for universal and sample highway segment; average AADT estimates for groups of lower-level roads. Go back to the 1980s. ATR records go back to the 1950s.	Annually
National Highway Planning Network (NHPN) (http://www.fhwa.dot.gov/ planning/nhpn/; http://www.bts.gov/publications/ national_transportation_atlas_database/ 2007/html/nhpn_lin.html)	Defines over 450,000 miles of current and proposed highways, ranging from minor rural roads to interstates. It considers the geospatial aspects of highways.	2005
NAVTEQ (http://www.navteq.com)	Describes attributes of roads related to their accessibility (turn restrictions, one way streets, barriers, and other restrictions	Varies by year
Oak Ridge National Highway Network (ONHN) (http://www.cta.ornl.gov/transnet/ Highways.html)	Attributes of roadways and their locations are outlined; it is mainly used for understanding vehicle routes and scheduling issues	2004
ORNL (http://cta.ornl.gov/transnet/ Intermodal_Network.html)	Provides details on the nation's highways, railroads, an waterways, and connection points between those modes of transportation	2002 (with occasional updates at nonspecific times)
U.S. Census Bureau TIGER Database (http://www.census.gov/geo/www/ tiger/tiger2005fe/tgr2005fe.html)	Uses USGS data to provide information on the cartographical and geographical details of the Census tracts, including the defined area boundaries of those zones	2005

5. Conclusions: Alternative Roadmaps toward a National Travel Demand Model

Based on our synthesis of methodological and data options for multimodal inter-regional demand modeling, we develop the following flowchart, which presents alternative roadmaps toward a national travel demand model (see Figure 4). If we consider “Available Data Sources” as our origin, and “National Travel Demand Model” as our destination or goal, there are alternative “routes” in this flowchart for us to reach the destination. Each route represents a unique roadmap toward the national model. Each node (i.e. textbox) represents an intermediate product, and node IDs (i.e. A through G) do not necessarily imply sequencing. For instance, a model development roadmap could be ACFDG. In this case, a base matrix is first estimated from the available data sources, which are both used for the developing disaggregate travel models (e.g. trip frequency, destination, model, and route choices). These disaggregate models are then linked together to form a trip-based four-step model. After extensive new data sources become available, the trip-based model may be improved to a tour/activity-based microsimulation model.

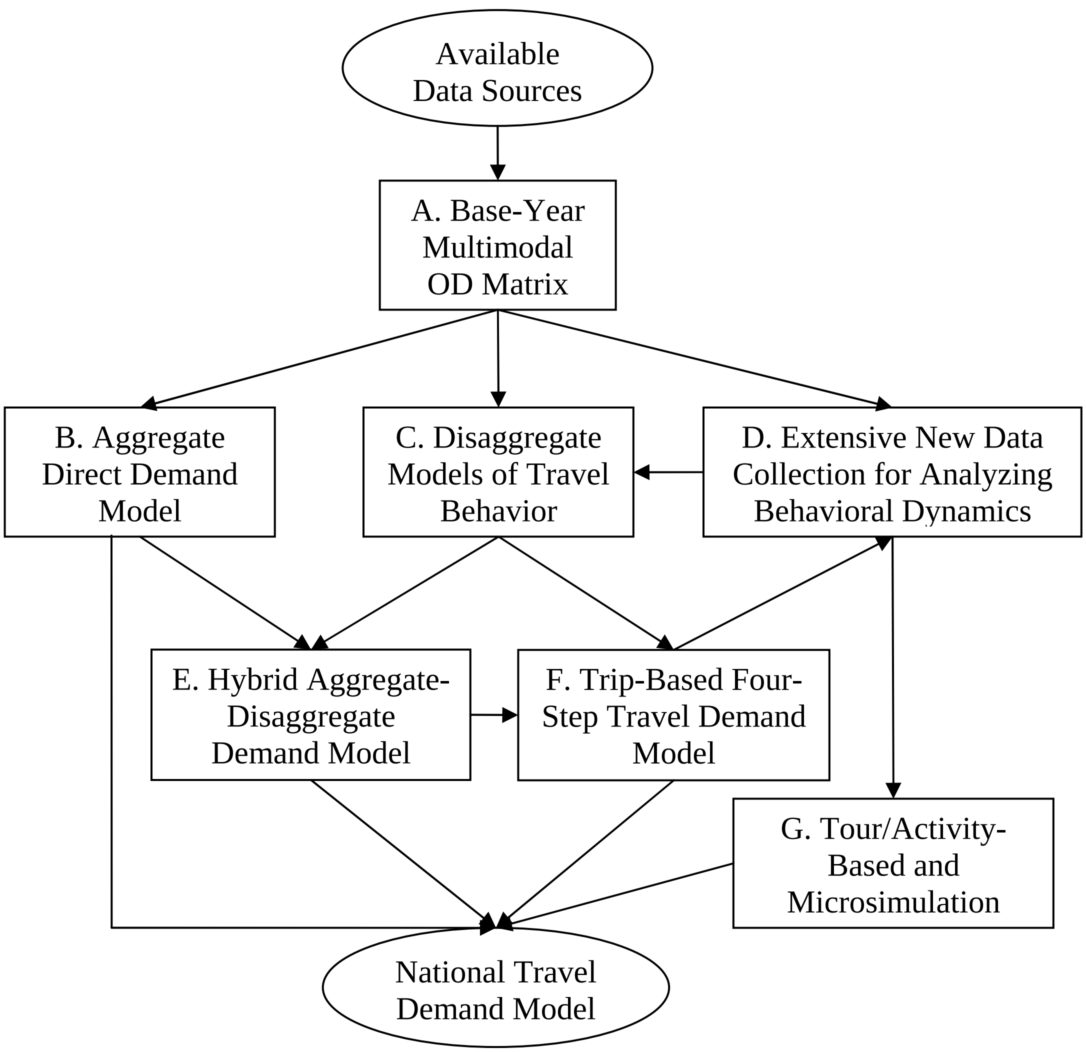

Figure 4. Alternative Roadmaps toward a National Travel Demand Model

The roadmap selection for a particular country should depend on available data sources, resources for new data collection, resources for model development, policy analysis needs, and possibly other factors. In order to provide additional examples, we recommend several roadmaps under loosely-defined resource availability (for data collection and model development) and policy analysis needs scenarios respectively (see Table 7). The roadmap selection may also be based on model development risks. The most aggressive and highest-risk roadmap would be ADG. The lowest-risk incremental approach would be ABEFDG. We believe the development of a base-year multimodal OD matrix is almost always a good initial investment for several reasons: (1). It provides immediately useful results for system evaluation and monitoring; (2). It provides the basis for the development of various types of aggregate or disaggregate models; (3). The matrix can be used to calibrate more advanced models; (4). The matrix can be the starting point of policy scenario analysis in a pivot-point implementation; (5). Its development does not have to rely on new data sources in many countries and regions; (6). Its development cost should be relatively low; (7) Once developed, the base matrix, unlike behavioral models, does not require any maintenance.

Table 7. Selection of a Roadmap for Multimodal Inter-Regional Demand Analysis

	Low Needs	Medium Needs	High Needs
Low Resource	AB	ABE	Need more resource
Medium Resource	ACE	ACF	ACFDG
High Resource	Unlikely	ADCF	ADG

Textbox 1: Roadmap for the STREAM European Model (Williams 2001)

Demand Modeling

- Develop a model specification to incorporate the main mechanisms which influence passenger travel demand in terms of car availability, and behavioral and demographic change.
- An in depth analysis of national passenger travel survey data was undertaken for seven European countries to develop the trip generation model.
- Collection and analysis of detailed zonal socio-economic and demographic data for implementing the trip generation and distribution models.

Supply Modeling

- Development of a comprehensive multimodal transportation network.
- Development of cost and or tariff functions for all passenger modes.
- Design and implementation of an innovative approach to modeling short- and long-distance intra-zonal trips.
- Development of a new all-day road capacity restrain function based on disaggregate data.

Model Calibration and Validation

- Assemble observed passenger data across countries and models for calibration and validation.
- Model runs for base and forecast years, and also for 1975~1985 as part of a backcasting exercise to test the structural stability of the model.

Textbox 2: Roadmap for the TRANS-TOOLS European Model (Martino 2006)

1. Understand needs of the European Commission (EC) regarding policy assessment and related indicators;
2. Develop a European model with frequent communication with the EC;
3. Include auditing, updating and validating by non-project experts;
4. Understand and reconcile differences with national models to facilitate discussions with national member state representatives;
5. Produce available, accessible, well documented and understandable documents;
6. Establish maintenance procedures including a funding framework for the maintenance of the model.

In addition to technical and cost considerations, a roadmap for multimodal inter-regional travel demand model development may also include model calibration-validation plans, model maintenance procedures, and institutional considerations. The above two textboxes provide examples of roadmaps in current practices that incorporate some of these considerations.

6. References

Acutt, M., and Dodgson, J. (1996). Policy instruments and greenhouse gas emissions from transport in the UK. Fiscal Studies 17(2): 65-82.

Algers, S. (1993). An integrated structure of long distance travel behavior models in Sweden, Transportation Research Record 1413, Washington D.C.

Ashiabor, S., Baik, H., and Trani, A., (2007). Logit models to forecast nationwide intercity travel demand in the United States. Journal of the Transportation Research Record 2007: 1-12.

Baik, H., Trani, A., Hinze N., Swingle, H., Ashiabor, S., and Seshadri, A. (2008). Forecasting model for air taxi, commercial airline, and automobile demand in the United States. Journal of the Transportation Research Record 2052: 9-20.

Bel, G. (1997). Changes in travel time across modes and its impact on the demand for inter-urban rail travel. Transportation Research 33E: 43-52.

Bell, M. (1991). The estimation of origin–destination matrices by constrained generalized least squares. Transportation Research B 25, 13–22.

Ben-Akiva, M., Gunn, H.F., van Vuren, T., and Hofman, F. (1998). The AIUTO project, implementation of a time dependent assignment at the Randstad test site. Presented at the 8th World Conference on Transport Research, Antwerpen.

Bergess, A., Chen, T.M., Snelder, M., Schneekloth, N., Korzhenevych, A., Szimba, E., Kraft, M., Krail, M., Nielsen, O., Hansen, C., Martino, A., Fiorello, D. and Christidis, P. (2008). Final report TRANS-TOOLS (TOOLS for TRansport forecasting And Scenario testing) deliverable 6. Funded by 6th Framework RTD Programme. TNO Inro, Delft, Netherlands.

Beser, M. and Algers S. (2001). SAMPERS – The new Swedish national travel demand forecasting tool. in Lundqvist, L. and Mattsson, L.-G. (eds), National Transport Models: Recent Developments and Prospects, The Swedish Transport and Communications Research Board, Stockholm.

Bhat, C.R. (1995). A heteroscedastic extreme value model of intercity travel mode choice. Transportation Research Part B: Methodological, Volume 29, Issue 6, Pages 471-483.

Brog W., Erl, E. .and Schulze, B. (2004). DATELINE: Concept and methodology. Paper presented at the 2004 European Transport Conference.

Bundesamt für Raumentwicklung (ARE) and Bundesamt für Statistik (BFS) (2001), Mobilität in der Schweiz, Ergebnisse des Mikrozensus 2000 zum Verkehrsverhalten, Bern and Neuenburg.

Cambridge Systematics, 2008. National Travel Demand Forecasting Model Phase I Final Scope.

Cascetta, E., Nuzzolo, A., Biggiero, L. and Russo, F. (1995) Passenger and freight demand models for the Italian transportation system, Proceedings of 7th WCTR '95, Sydney.

Cascetta, E. (1995) The Italian Decision Support System for transportation policies and investments: general architecture and development status, Proceedings of 7th WCTR '95, Sydney.

Chalasani, V.S., Engebrestsen, O., Denstadli, J.M., and Axhausen, K.W. (2005). Precision of geocoded locations and network distance estimates. Journal of Transportation and Statistics, 8(2):1-15.

Chicago Area Transportation Study (1959). Study Findings, (Volume I), December, 1959.

Harrison Lithographing, Chicago, IL.Costinett, P., Mayank, J., Rolf, M., Wardell, E., Weidner, T. (2009). Maryland Statewide Tranposrtation Model: MSTM model user's guide draft report.

COWI (1997a), PETRA working paper No. 7 – The travel demand module, COWI, Lyngby.

COWI (1997b), PETRA working paper No. 8 – Data, COWI, Lyngby.

COWI (1997c), PETRA synthesis report – The forecast model, COWI, Lyngby.

Davidson, P., and Clarke, P. (2004). Preparation of OD matrices for DATELINE. Paper presented at the 2004 European Transport Conference.

Daly, A., Fox, J. and Tuinenga, J.G. (2005) Pivot-point procedures in practical travel demand forecasting, Paper presented at European Regional Science Association meeting 2005, Amsterdam.

Department for Transport (2006) Equilibrium modelling – Phase 2B implementation report for NTM v3, DfT, UK.

Detroit Metropolitan Area Traffic Study, 1955, Part I: Data Summary and Interpretation; Part 2: Future Traffic and a Long Range Expressway Plan, Speaker-Hines and Thomas, State. Printers, Lansing, MI, July and March.

Donnelly, R., Costinett, P., and Upton, W.J. (2009). The Oregon statewide and substate travel forecasting models. Transportation Research Circular E-C011: 155-165.

Domencich, T.A., and Kraft, G. (1970). Free transit. Lexington, Mass: Heath Lexington Books.

Eijkelenbergh, P.L.C. (2007). European transport models and scenarios: fitness-for-purpose. TRANSFORUM, the Netherlands.

Engelhardt, K., Follmer, R., Gilberg, R., Kloas, J., Kuhfeld, H., Kunert, U. and M. Smid (2003) Methodological advances in National Travel Surveys: Mobility in Germany 2002, paper presented at the 10th International Conference on Travel Behavior Research, Lucerne, August 2003.

Epstein J.M., Parker J., Cummings D., Hammond R.A. (2008) Coupled Contagion Dynamics of Fear and Disease: Mathematical and Computational Explorations. PLoS ONE 3(12): e3955. doi:10.1371/journal.pone.0003955

Fosgerau, M. (2001). PETRA – An activity-based approach to travel demand analysis. in Lundqvist, L. and Mattsson, L.-G. (eds), National Transport Models: Recent Developments and Prospects, The Swedish Transport and Communications Research Board, Stockholm.

Fox, J., Daly, A. and Gunn, H. (2003), Review of RAND Europe's Transport Demand Model Systems, RAND, The Netherlands.

Gaudry, M. (2001). Test of nonlinearity, modal captivity and spatial competition within the STEMM multicountry applications for passengers. in Lundqvist, L. and Mattsson, L.-G. (eds), National Transport Models: Recent Developments and Prospects, The Swedish Transport and Communications Research Board, Stockholm.

Gunn, H.F., Mijjer, P.H., Lindveldt, K. and Hofman, F. (1997), Estimating base matrices: The combined calibration method, in Proceedings of the PTRC Summer Annual Meeting.

Gunn, H.F. (2001). An overview of European National Models. In Lundqvist, L. and Mattsson, L.G. editors, National Transport Models: Recent Developments and Prospects, Springer, New York.

Gunn, H.F. and Hofman, F. (1998). TDM simulations in Randstad NL. Presented at the 8th World Conference on Transport Research, Antwerpen.

Hansen, S., Nielsen, O.A., and Frederiksen, R.D. (2008). Adjustment of trips-matrices in large-scale networks. Paper presented at the 2008 European Transport Conference.

Hilferink, P. (1997). Cost-efficient Origin-Destination Estimator: OD-ESTIM. Final Summary Report.

Hofman, F. (2001). Application areas for the Dutch national model. in Lundqvist, L. and Mattsson, L.-G. (eds), National Transport Models: Recent Developments and Prospects, The Swedish Transport and Communications Research Board, Stockholm.

Horowitz, A.J. (2008). White paper: Statewide travel demand forecasting. Requested by AASHTO and presented at the Conference on Meeting Federal Surface Transportation Requirements in Statewide and Metropolitan Transportation Planning.

Hunt, JD., Donnelly, R. Abraham, JE., Batten, C., Freedman, J., Hicks, J., Constinett, PJ., Upton, WJ, (2001). Design of a statewide land use transport interaction model for Oregon. WTCR 2001.

Yang, H., Sasaki, T., Iida, Y., Asakura, Y. (1992). Estimation of origin–destination matrices from link traffic counts on congested networks. Transportation Research B 26, 417–434.

Justen, A., Beuck, U. and Nagel, K. (2007), Application of the VISEVA demand generation software to Berlin using publicly available behavioral data. Paper presented to the Transportation Research Board Annual Meeting, 2007.

Kershaw, A., Barton, J., Noble, B., Williams, D. and Hird, D. (2001) National Travel Survey Technical Report 2000, Office for National Statistics, London.

Koppelman, F.S., and Sethi, V. (2005). Incorporating variance and covariance heterogeneity in the Generalized Nested Logit model: an application to modeling long distance travel choice behavior. Transportation Research Part B: Methodological, Volume 39, Issue 9, Pages 825-853.

Mannering, F.L. (1983). An econometric analysis of vihicle use in multivehicle households. Transportation Research Part A: General, Volume 17, Issue 3, Pages 183-189.

Martino A. (2006). Roadmap of the TRANS-TOOLS model. Paper presented at the TRANSFORUM Fourth Forum Meeting, Amsterdam.

Leitham, S., Downing, J., Martino, A. and Fiorello, D. (1999), European transport forecasts for 2020: The STREAMS model results, in Proceedings of the ETC ’99, Cambridge UK.

Lundqvist, L. and Mattsson, L.G., editors. (2001), National Transport Models: Recent Developments and Prospects, Springer, New York.

McElhaney, D.R., Jarema, F.E., Pisarski, A., Fulton, P., Tweedie, R. and Purvis, C. (1994) FHWA study tour for National Travel Surveys, FHWA, Washington D.C.

Ministry of Land, Infrastructure and Transport (MLIT) (2005), 2005 Inter-Regional Travel Survey, MLIT, Government of Japan.

Nie, Y., Zhang, H.M., Recker, W.W. (2005). Inferring origin-destination trip matrices with a decoupled GLS path flow estimator. Transportation Research 39B: 497-518.

Nielsen, O.A. (1998). Two new methods for estimating Trip Matrices from Traffic Counts. Chapter in Travel Behaviour Research: Updating the state of play. Edited by Ortúzar, H. D., Hensher, D & Jara-Díaz, D. Elsevier Science Ltd. Oxford, UK. 1998. pp. 221-250.

Nielson, O.A. (2007), European TRANS-TOOLS transport model course, Technical University of Denmark. Retrived on November 16, 2009 from ftp://ftp.jrc.es/users/transtools/public /Documentation/

Oum, T.H., and Gillen, D.W. (1983). The structure of intercity travel demands in Canada: Theory tests and empirical results, Transportation Research Part B: Methodological, Volume 17, Issue 3, Pages 175-191.

Peter Davidson Consultancy (2000), MYSTIC towards origin-destination matrices for Europe. The PD Consultancy, London.

Russo, F. and Vitetta, A. (1995), Network and assignment models for the Italian National Transportation Systems, Proceedings of 7th WCTR ’95, Sydney.

Sherali, H.D., Sivanandan, R., Hobeika, A.G. (1994). A linear programming approach for synthesizing origin-destination trip tables from link traffic volumes. Transportation Research B 28, 213–233.

Silver, Jacob and Joseph R. Stowers, 1964, Population, Economic, and Land Use Studies in Urban Transportation Planning, U.S. Department of Commerce, Bureau of Public Roads, Washington, DC, July.

Sveder, G.J. (2001). The new Swedish national model – SAMPERS: System and validation. in Lundqvist, L. and Mattsson, L.-G. (eds), National Transport Models: Recent Developments and Prospects, The Swedish Transport and Communications Research Board, Stockholm.

Vortish, P. and Waßmuth, V. (2007), VALIDATE – A Nationwide Dynamic Travel Demand Model for Germany, Presented at the 2007 Transportation Research Board Planning Applications Conference in Daytona, Florida.

Vrtic, M., Lohse, D., Fröhlich, P., Schiller, C., Schüssler, N., Teichert, H., and Axhausen, K. W. (2005), A simultaneous two-dimensionally constraint disaggregate trip generation, distribution and mode choice model: Theory and application for a Swiss national model, Arbeitsbericht Verkehrs- und Raumplanung, 2xx, IVT, ETH Zürich, Zürich.

Wardman , M. (1997). Inter-urban rail demand, elasticities, and competition in Great Britain: Evidence from direct demand models. Transportation Research 33E: 15-28.

Weiner, E. (1976). Assessing National Urban Transportation Policy Alternatives. Transportation Research, Volume 10, Pergamon, London, England, pp.159 – 178.

Weiner, E. (2008). Urban Transportation Planning in the United States: History, Policy, and Practice. Springer Science Business Media, LLC.

Winston, C. (1985). Research on intercity freight and passenger transportation; An economist's perspective. Transportation Research Part A: General, Volume 19, Issues 5-6, Pages 491-494.

Williams, I. (2001). Designing the STREAMS model of Europe. in Lundqvist, L. and Mattsson, L.-G. (eds), National Transport Models: Recent Developments and Prospects, The Swedish Transport and Communications Research Board, Stockholm.

Worsley, T.E. and Harris, R.C.E. (2001), ‘GB traffic forecasts - status and development’, in Lundqvist, L. and Mattsson, L.-G. (eds), National Transport Models: Recent Developments and Prospects, The Swedish Transport and Communications Research Board, Stockholm.

Yao, E., and Morikawa, T. (2003), A study on integrated intercity travel demand model, paper presented at the 10th International Conference on Travel Behavior Research, Lucerne, August 2003.

Zhang, L., (2007). Developing a positive approach to travel demand forecasting: Theory and model. Transportation and Traffic Theory 17.

Zhang, L., and Levinson, D. (2005). An agent-based approach to travel demand forecasting: An exploratory analysis. Journal of the Transportation Research Board 1898: 28-36.

Zhang, L. and Levinson, D. (2008). Investing for reliability and security in transportation networks. Journal of the Transportation Research Board 2041: 1-10.

Zhang, L., McMullen, B.S., Nakahara, K., Valluri, D. (2009). The short- and long-run impact of a vehicle mileage fee on income and spatial equity. Journal of the Transportation Research Board (In Press).

Zhang, L. and Cirillo, C. (2009). Feasibility and benefit of advanced four-step and activity-based models for Maryland. Maryland State Highway Administration, Research in Progress.

Zhang, L., Zhu, S., and Levinson, D. (2008). Agent-based modeling of price competition, capacity choice, and product differentiation in congested networks. Journal of Transport Economics and Policy 42(3): 435-461.