How-to: Think About Model Design for Your Region

APRIL 2018

U.S. Department of Transportation
Federal Highway Administration

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16. Abstract

Over the past 15 years, advances in technology have led to the development of a variety of different travel demand model designs or frameworks. Agencies now face a complex choice when developing or updating their travel model. The alternatives include both very traditional as well as enhanced trip-based designs, activity-based designs of varying complexity and intermediate hybrid designs in between. The survey of transportation agencies by TMIP in late 2013 showed that at that time roughly a third of agencies did not know whether they would continue using a trip-based model or move to an activity-based or other more advanced design. Given that agencies typically only perform major updates to their travel models once or twice in a decade, it is important that agencies understand both the advantages and disadvantages of alternative approaches.

This report is designed to help agencies to understand the full spectrum of model designs available to them as well as their associated advantages and disadvantages. The guide includes an overview of the spectrum of travel model architectures and reviews important issues for consideration in three broad categories: theoretical issues, practical issues, and considerations for various policy and project applications, discussing at a high level the advantages and disadvantages of each design relative to each issue. The final section of the guide reviews the model design process as it was undertaken by the cities of Bellevue, Kirkland, and Redmond, WA, in anticipation of their new travel model.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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1.0 Introduction and Summary

Over the past 15 years, advances in technology have led to the development of a variety of different travel demand model designs or frameworks. Agencies now face a complex choice when developing or updating their travel model. The alternatives include both very traditional as well as enhanced trip-based designs, activity-based designs of varying complexity and intermediate hybrid designs in between. A survey of transportation agencies by TMIP in late 2013 showed that at that time roughly a third of agencies did not know whether they would continue using a trip-based model or move to an activity-based or other more advanced design. Given that agencies typically only perform major updates to their travel models once or twice in a decade, it is important that agencies understand both the advantages and disadvantages of alternative approaches.

This guidebook continues the development of TMIP's How-To series with a new How-To guide designed to help agencies understand the full spectrum of model designs available to them as well as their associated advantages and disadvantages. As TRB Special Report 288 states, "there is no single approach to travel forecasting or set of procedures that is 'correct' for all applications or all MPOs." In fact, it is worth noting that a growing number of agencies are maintaining two different models because of their distinct advantages for different types of applications. Thus, the goal of this How-To guide is not to identify a single ideal model design, but rather to provide information, a process, and examples to help agencies to thoughtfully identify the appropriate model framework for their analytical needs with careful consideration of the data available, the issues, and the risks involved.

The great twentieth century statistician, George Box famously wrote, "All models are wrong… some models are useful." It is precisely from this perspective of gauging usefulness that this How-To guide should be approached. The aim of planners, modelers, and decision-makers in choosing a model design should be to select a design or framework which will be most useful for answering their needs for the planning, design, and operation of their transportation system. Different agencies with different responsibilities – for allocating public funds, operating transit systems, designing infrastructure, operating toll systems, assessing impact fees, and all the many different functions that the various transportation agencies across the country provide – will doubtless find the various advantages and disadvantages of different methods more or less relevant depending on the particular uses for their model and their resources available for supporting and using their model.

The focus of this How-To guide is on overall demand model frameworks or architecture. Details of model design in terms of the selection of methods for specific model components, while involved and discussed where relevant in this guide, are not the focus of this guide. Interested readers may find the NCHRP 08-94 decision support tool and associated report helpful for the selection of component models and details of model design. Moreover, the focus of this guide is limited to the design of passenger travel demand models. While there have also been important advances in freight/truck and network modeling, the selection and implementation of these methods is largely (although not entirely) independent of the selection and implementation of passenger demand components which is in some ways more complicated owing largely to the wide array of options and frameworks now in use. Similarly, supply side or network modeling is not the focus, although it is addressed in so far as the integration of supply and demand models is concerned. It is also important to recognize that other travel forecasting tools and techniques can be used – sometimes with significant advantage – for particular purposes or in particular circumstances. Strategic models, growth factors models, and simple trend analysis all have their place in supporting transportation planning and analysis. However, most transportation agencies develop and maintain travel demand models (even if they also use some of these other tools), and the focus of this guide is to inform and assist them in considering the options specifically for the design of passenger travel demand models, partially in response to the indication of several agencies that this would be helpful.

This guide attempts to lay out in as objective a way as possible the issues relevant to the design of passenger travel demand models and the advantages and disadvantages of different frameworks so that those involved in choosing the design for an agency's model can evaluate and consider all the factors relevant in their context. After this introduction and summary, the following sections delve into these issues in more detail.

Source: Bernardin, V., One Size Doesn't Fit All, Activity-Based vs Trip-Based Models and Everything In Between, presented to the Tennessee Travel Model Users Group, December 1, 2015.

Figure 1. The spectrum of model designs with examples.

This guidebook attempts to recognize and address the whole spectrum of model designs from simple three-step trip-based models all the way to advanced, next generation activity-based models and everything in between. However, for simplicity and recognizing important similarities between certain model designs, this guide groups models into three broad categories of traditional trip-based, hybrid, and activity-based designs for many purposes (see Figure 1) although referring to more specific model designs when they are relevant.

Recognizing the limited ability of any single perspective to capture all the salient considerations, this guidebook approaches the comparison of model designs by identifying issues or applications from three perspectives: theoretical, practical, and applications. A brief summary of these issues is presented below while the reader should refer to the relevant sections of this guide for a more complete discussion.

1.1 Applications

Activity-based models provide important benefits for some applications, while for other applications they perform the same or even occasionally worse than trip-based models. Agencies should therefore carefully consider the uses for their model and the advantages of more advanced models relative to their costs for the applications most important for them.

Activity-based and hybrid models generally offer no advantage over traditional trip-based models for evaluating **traditional highway projects** or **air quality conformity analysis** although they do allow other **complex emissions analysis** such as to identify the relative contribution of the residents of various neighborhoods to greenhouse gas or other emissions. To some degree the similar performance of traditional and advanced models for highway forecasting may be attributable to the fact that both are still coupled with static assignment models and proponents suggest that when activity-based models are paired with regional DTA, they may provide better results. Initial tests of such systems, however, have not yet born this out.

Conducting **traffic impact analyses** can be significantly more difficult with activity-based models than hybrids or trip-based models due to simulation variation and the need to prepare more granular inputs. Hybrids may offer an advantage by reflecting some amount of internal capture without necessarily introducing simulation variation.

What model design is best for evaluating **highway pricing** scenarios is a matter of debate. Theoretically, activity-based models offer advantages in terms of being able to represent a distribution of values of time, but trip-based/hybrid models offer practical advantages such as the ability to make many model runs efficiently to understand the uncertainty associated with various assumptions and are still more commonly used for investment grade toll revenue analyses.

Studies involving **peak spreading** (or other issues or scenarios involving time) clearly benefit from more advanced model designs, with activity-based models providing the most sensitivity and realism and trip-based models the least. Traditional models generally cannot make any predictions relative to the temporal distribution of traffic.

Activity-based models are also substantially better able to evaluate many of the most common **travel demand management** strategies such as employer provided transit passes, telecommuting and alternative work schedules, parking management, etc.

Although activity-based models may be better able to represent some transit-related policies such as employer provided transit passes or land use policies or patterns that favor transit oriented design, activity-based and hybrid models have demonstrated no general advantage over traditional trip-based models in forecasting **transit ridership** or even simpler approaches such as FTA's STOPS tool.

More advanced models are better able to represent **pedestrian and bicycle trips** and both hybrids and standard activity-based models predict more non-motorized travel in more walkable neighborhoods. Sensitivity to bicycle and pedestrian infrastructure improvements such as bike lanes, etc., and assignment of non-motorized trips to the network can be added in any type of model, and have been in at least one trip-based model, but are rare in general, but more common in enhanced or advanced activity-based models. Moreover, the use of microzones in ABMs can substantially improve modeling of non-motorized trips, especially at a network level.

Traditional travel models are largely blind to **urban design** such as the density and connectivity of local street networks, the mixture of land uses at the scale of walk sheds, etc.; whereas, both hybrid and activity-based models consider and reflect the impact of these factors on travel patterns.

Activity-based models offer a clear advantage for environmental justice or **equity analysis** since they can summarize impacts for any custom defined community of concern on the fly.

Considering these various model applications, it is easy to see how various agencies may come to different conclusions regarding the best model design for their purposes. For instance, an agency focused primarily on highway forecasting with significant responsibility for assessing impact fees for new developments may understandably prefer a simpler, more traditional model design, while an agency more concerned with travel demand management strategies, peak spreading, and equity analysis might understandably prefer a more advanced design.

1.2 Practical Issues

In general, for many applications, practical considerations favor trip-based or hybrid models over activity-based models, but the reverse may be true in some circumstances or for some applications. So, again, it is important for agencies to consider the following factors in light of their particular analysis needs and resources in terms of data, staff skills, computing hardware, time, and budget.

There have been no before and after analyses comparing the **predictive validity** or **forecast accuracy** of traditional and more advanced model designs. Some point to sensitivity analyses and one study of the forecast validity of destination choice models as evidence that advanced models may produce more accurate forecasts, while others point to the fact that the only study to compare traditional and activity-based model's forecast validity found no significant difference.

Activity-based models that use microzones (which most, but not all such models do) require large amounts of detailed **spatial socioeconomic data** for both base and future year scenarios that can require significant time and effort to prepare. The **number and pricing of parking spaces** at the microzone level can also be difficult data to obtain, maintain, and forecast.

In some cases, if an agency determines they need a custom model specification, activity-based models can also require large household surveys for the **data required to estimate model parameters** as part of model development. However, in many cases, parameters can be transferred or borrowed from another area and calibrated to more modest local survey data.

New sources of passively collected "big data" such as OD flows are an important new category of available data on travel patterns that stand to potentially revolutionize the way forecasting models work. The **integration of big data** in activity-based models requires more effort than in hybrid or traditional trip-based models.

The **calibration** of more complex models is more challenging. The larger the number of parameters that may need to be checked or adjusted the greater the effort. The longer the model's runtime, the greater the time required or fewer tests/checks that can be performed, and the greater the integration of the model components the more adjustments to one component require additional adjustments to another component.

Although many factors drive the **cost** of developing and maintaining a model, more complex models do still tend to cost more than simpler traditional models; however, the cost of activity-based models has been decreasing as more are developed due to economies of scale so the cost differential between model designs is not as great as it was some years ago.

Staff skills and training are another important consideration for advanced model designs. One of the most important staff requirements of activity-based models is that they generally require skill with two (or more) different programming languages (i.e., typically one for the ABM itself and another for the network modeling software).

The **runtime** of a model is another important practical consideration, and while model runtimes tend to be more impacted by the assignment than the demand model design, more complex model designs do contribute to generally longer runtimes.

The use of random draws in activity-based models causes **simulation variation**. While it has now been demonstrated that simulation variation in activity-based models is small enough that it does not pose a problem for many common types of analysis, there are still some types of analysis, particularly involving small phenomenon or changes, such as intersection turning volumes or benefit-cost analysis, etc., that can require either multiple model runs with and/or oversampling in an activity-based model to ensure a representative result.

One advantage of hybrid models over activity-based models is that **staging** can be used to convert a traditional trip-based model into a hybrid model through a series of incremental improvements; whereas, agencies must develop a new activity-based model in addition to or in place of their existing model.

More people or a larger the **user community** working with a particular model design can both ensure a model is well tested and provide a larger pool for hiring staff or consultants.

Dynamic traffic assignment (DTA) is being increasingly used for project and subarea studies due and is important for the study of time varying tolls on express lanes and other policies and projects; however, DTA still remains computationally challenging for large regional networks at this time. DTA can be used with any travel demand model, but more advanced models can achieve much deeper **integration with DTA** than traditional models, but only with the investment of significant effort.

More advanced models generally come with some costs whether in terms of data, investments in staff time, computing hardware, and/or development time and cost. For some agencies, these costs may be well justified by the ability of advanced models to support analyses which traditional models cannot; while for other agencies, practical considerations of these costs may outweigh the benefits of a more advanced model.

1.3 Theoretical Issues

In general, theoretical considerations favor activity-based models, followed by hybrids, over traditional trip-based models.

Aggregation bias can cause errors of various sorts in traditional trip-based travel models, especially for small scale phenomenon such as pedestrian and bicycle trips.

Lack of **consistency within individual trips** in trip-based models can result in various problems, such as predicting transit trips in locations or at times of day when there is no transit service.

The lack of **spatial consistency of trips within tours** in traditional trip-based models ultimately means that these models can predict travel patterns that are physically impossible or imply that travelers appear and disappear at some locations.

The lack of **modal consistency of trips within tours** in traditional trip-based models means that these models can imply highly improbable scenarios such as a traveler who left their car at home in the morning and took the train to work, drives their car home at the end of the day after work.

The lack of **temporal consistency of trips within the day** in traditional trip-based models means that these models can imply impossible sequences or timing of trips such as a traveler leaving from the coffee shop to go to work before they arrive at the coffee shop from home.

Keeping in mind the famous quote cited earlier that, “all models are wrong… but some models are useful,” the question for an agency may be whether the theoretical problems with simpler models impact their usefulness for a particular agency’s analysis needs. In some cases, the theoretical problems in simpler models, while real, may not be important in practice for some applications; however, in at least some cases these problems can be significant and render a model useless for a particular application. Thus, again, it is important for each agency to carefully consider the import of these factors for the types of applications they are most concerned with.

1.4 Process

A robust process for selecting a model design for a region's new travel model should involve all the relevant stakeholders including the planners and decision-makers who will use the new model's results as well as the modelers who will be responsible for using and maintaining the model. Typically, some amount of education is required to familiarize these stakeholders with the various issues and considerations discussed in this guide. Ultimately, stakeholders should consider the relative importance of these various theoretical and practical issues and the particular applications their model will be used to evaluate together with their available resources including time, budget, staff, and data in order to make an informed and thoughtful decision. The final section of this guide illustrates a good example of how the cities of Bellevue, Kirkland, and Redmond, WA, engaged in such a process.

1.5 Overview

Following this introduction and summary section, this guide expands on the key issues identified here. Section 1 includes an overview of the spectrum of travel model architectures and Section 2 presents how data-driven methods can be combined with different model architectures. The following sections review important issues for consideration in three broad categories: model applications or use cases in terms of projects and policy issues (Section 3), practical issues (Section 4), and theoretical issues (Section 5), discussing at a high level the advantages and disadvantages of each design relative to each issue. The final section (Section 6) of the guide discusses the process of selecting and developing a model design and presents a case study of the process as it was undertaken by the cities of Bellevue, Kirkland, and Redmond, WA, in anticipation of their new travel model.

2.0 Overview of the Spectrum of Travel Model Designs

While the discussion of travel model design sometimes is reduced to a choice between "four-step" and "activity-based" models, in reality there is a spectrum of model designs of varying complexity. Moreover, some people sometimes mean slightly different things by terms like "activity-based" or "four-step" models. For purposes of clarity in this guide the spectrum of model design will presented primarily in terms of three families or ranges of model design including "Traditional", "Hybrid", and "Activity-based". However, each of these should be understood to represent not a single model design, but a group of related and generally similar model designs. Moreover, each of these types of model designs can have purely synthetic as well as data-driven versions. This dimension of model design is discussed separately in the following section since the two dimensions of model design can be largely separated. Figure 2 presents the spectrum of passenger travel model designs currently in use together with examples of where each design is used and how designs have been grouped into families within this guide.

Source: Bernardin, V., One Size Doesn't Fit All, Activity-Based vs Trip-Based Models and Everything In Between, presented to the Tennessee Travel Model Users Group, December 1, 2015.

Figure 2. The spectrum of model designs with examples.

Figure 2 is meant to be illustrative of the spectrum of model designs rather than definitive or completely exhaustive. While all models known to the author could at least arguably be grouped into one of the model designs above, these groupings could be debated in some cases and certainly could be further sub-divided to acknowledge, for instance, the wide variety of complexity in the details of four-step model designs in terms of trip purposes, modes, feedback, and treatment of time-of-day. For instance, some might alternatively label the activity-based family as "Disaggregate" models and group all other designs as "Aggregate". However, this would group together models with very different characteristics. Others might argue that disaggregate tour-based models should be grouped with the hybrids or that advanced trip-based models should be grouped with traditional three- and four-step models. While no grouping is necessarily definitive or perfect in all regards, the families of models used in this guide were delineated to support the discussion of the general pros and cons of different approaches and the authors believed that the similarities within these families were much greater than between them.

2.1 Traditional Trip-Based Models

Trip-based models were the first travel demand models developed. The first models were developed for large cities such as Chicago and Detroit in the 1950's and early 1960's to support the development of long range transportation plans. These models leveraged the most advanced technology and research of the time, making use of the newly invented computer and methods from the emerging science of operations research which developed substantially in support of military operations in World War II and the early Cold War era. The use of these travel demand models grew and spread in response to the federal mandate for formal transportation planning processes for the allocation of federal highway funds in the 1962 Federal-Aid Highway Act and in support of the design and development of the Interstate highway system throughout the country. In the early 1960's, San Francisco was the first area to add a mode choice component to their model to support transit planning and since that time both three-step models focused fairly exclusively on personal automobile travel and four-step models incorporating transit (but generally still focused on motorized or vehicular travel) have been in use throughout the country. In the 1970's, the federal government's development of the Urban Transportation Planning Package largely standardized the design of three- and four-step trip-based models and reduced their cost, further facilitating their proliferation.

As the federal government left the development of model software to the private sector with the advent of the personal computer in the 1980s, some minor variations began to develop in trip-based models especially as growing computing power and worsening congestion facilitated and motivated the development of time-of-day components in some areas. The addition of time-of-day components and feedback loops connecting trip assignment to trip distribution were further promoted and in some cases required under the Clean Air Act Amendments of 1990 and the contemporaneous federal transportation re-authorization, ISTEA. These model enhancements were directed at providing better estimates of congested speeds to support vehicle emissions modeling and analysis mandated for non-attainment areas under the Clean Air Act. Travel models were also increasingly required in practice for alternatives analyses under the National Environmental Policy Act (NEPA).

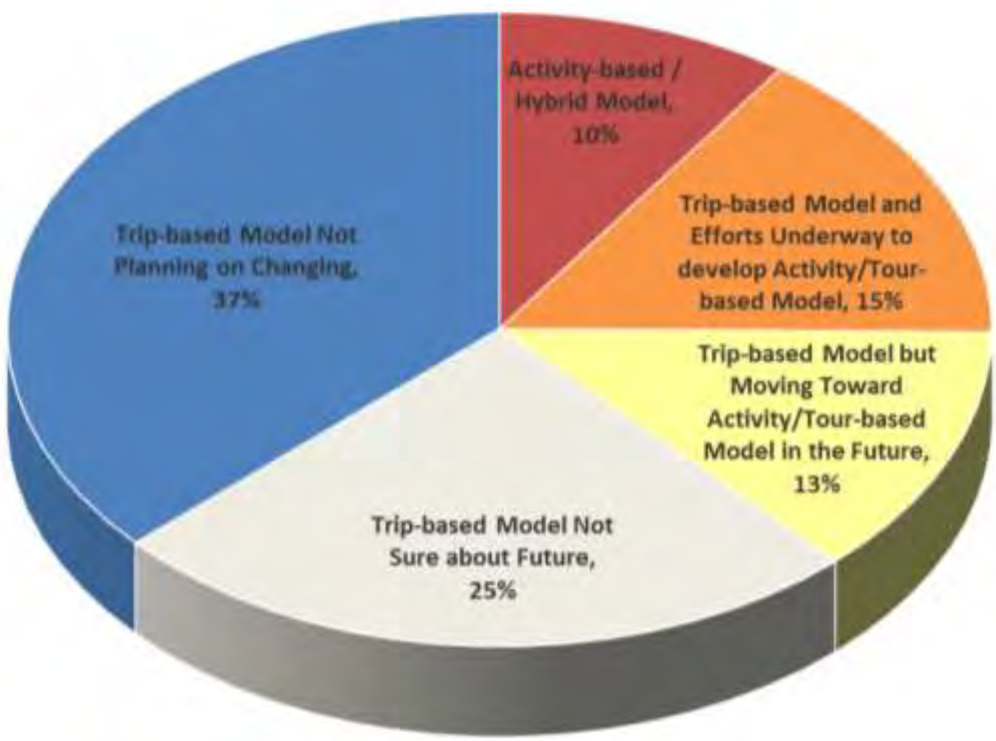
Over time in various areas of the country trip-based models also took on important functions in assessing traffic impact fees for new development. As the Federal Transit Administration's New Starts program for major capital investments in fixed-guideway projects evolved, it also required some standardization of four-step modeling methods and placed a major emphasis on the testing of models to support applications for federal transit grants. During the same timeframe and even more recently, trip-based models have been adapted to support bicycle and pedestrian planning, although these enhancements and applications are still emerging rather than established practice.

The foregoing history of traditional trip-based models is presented because it is helpful in understanding certain key aspects of traditional model design. (For a good detailed history, see Boyce and Williams, 2015.) In particular, traditional travel models evolved over time as practical planning tools to address a variety of needs including long range planning, highway design, rail transit planning, air quality analysis, impact fee assessment, and even bicycle and pedestrian planning in some cases. In this context, it is easy to understand why traditional models on the one hand tend to be practical, and on the other hand, are not necessarily well-grounded in theory. They were designed as practical tools, not on the basis of theory, per se.

Traditional models use trips (defined as just the segment of travel between one origin and the subsequent destination) as the basic unit of analysis. The original and fundamental components of these models attempt to estimate how many trips there will be (trip generation), where they will go (trip distribution), how many will be of each mode (mode choice), and how they will route over the network (assignment). These component models are typically fairly simple statistical models (regression, cross-classification, gravity/entropy) with very few explanatory variables. In many cases, only population, employment, travel times, and costs are considered. These variables are relatively dominant in many travel choices, and sufficient to understand many travel patterns, but the full richness of travel behavior and patterns are impacted by many other factors and in some cases dominated by them.

One of the key features of traditional model design that gives rise to both many of these models' practical benefits and theoretical shortcomings is that they treat all trips as independent and each dimension of an individual trip (its probability or frequency, the connection between its origin and destination, its mode, and its route) as largely independent. These simplifying assumptions make these models much easier to solve, but also result in certain limitations on their accuracy and sensitivity as subsequent sections will explain.

Another distinguishing feature of traditional models is that they represent trips in matrices, often called trip-tables. This data structure is necessary given the analytic method in which traditional models implement statistical models to produce repeatable average or expected results. Software packages to support traditional travel models have highly optimized routines for handling large matrices, but the size of matrix files (which are determined as the square of the number of zones in the model) remains a key limitation on their speed and ability to provide high resolution results whether in terms of geographic resolution or traveler characteristics.



Source: FHWA

Figure 3. TMIP survey of transportation agencies, 2013.

Traditional three- and four-step trip-based travel demand models remain the most prevalent form of travel models. A survey by TMIP of over 200 transportation agencies across the country in late 2013 showed that at that time 90% of agencies still maintained a traditional trip-based model although 25% of agencies had or were in the process of developing an advanced model and an additional 13% were planning on developing an advanced model. Given its prevalence, there is a wide range of consultants and public agency staff with familiarity and varying levels of expertise with traditional models.

Traditional trip-based models have long supported a variety of transportation analyses, continue to do so, and will continue to do so for some considerable time into the future. For some agencies and purposes, traditional models may remain a reasonable solution for their analysis needs. However, there are significant theoretical and practical planning issues that are motivating many agencies to consider alternative, more advanced designs.

2.2 Activity-Based Models

Almost as soon as they were established, traditional models began to be critiqued by academics studying travel behavior. Over time, academics put forth proposals for alternative model formulations to address various shortcomings of traditional models. Contributions were made by many researchers culminating in the work by Ben-Akiva and Bowman (1998) on day pattern choice and Shiftan and collaborators (Shiftan, 1998) on intermediate stop location choice which together provided a practical framework for what became known as activity-based models. Although anticipated by a small number of tour-based models which saw limited application, the first implementation of what is generally recognized as the activity-based model was for Portland, Oregon, in 1998, followed by the model for San Francisco in 2001, which is still in use by the San Francisco County Transportation Authority.

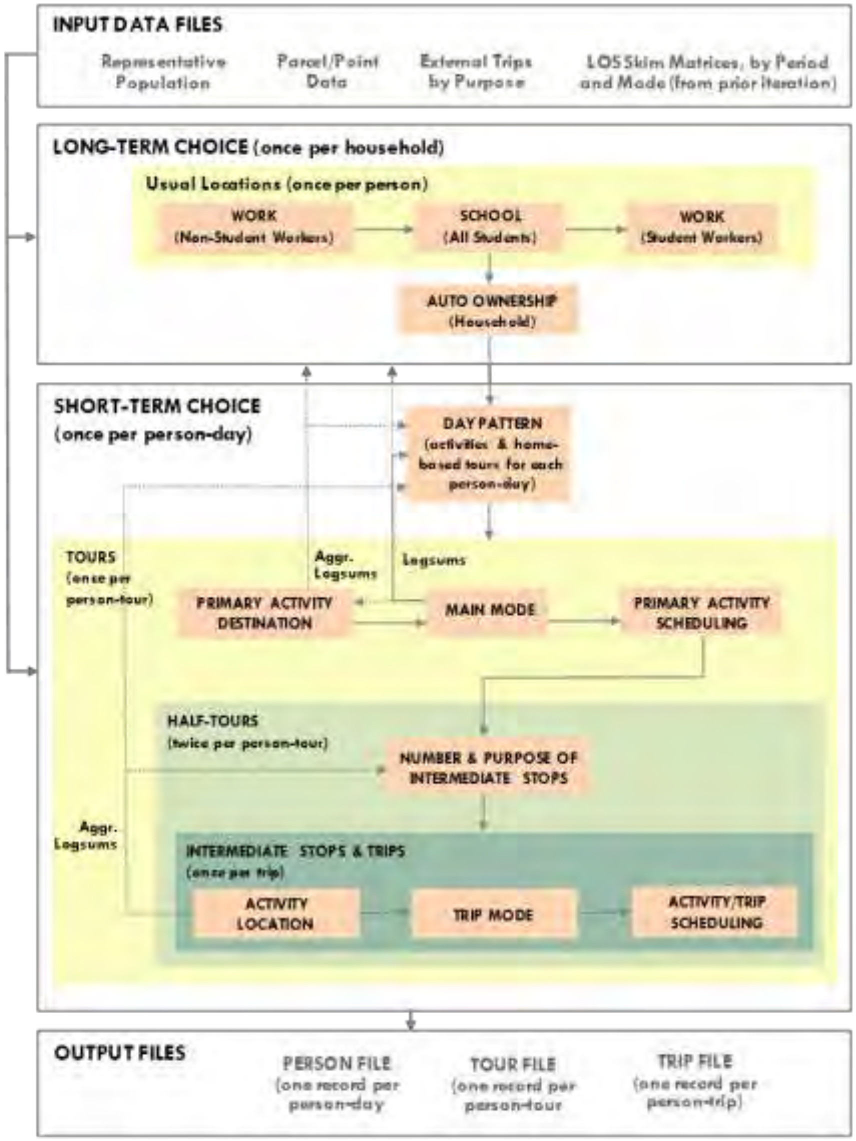
Following San Francisco, a number of agencies began developing activity-based models in hopes grounded in academic research and theory that they would prove better tools for emerging planning issues that traditional models struggled with including urban form effects, walk/bike planning, time sensitive pricing/policies, and equity analyses. Over 20 agencies across the country have now developed activity-based models including:

- Portland (1998, 2016)
- San Francisco SFCTA (2001)
- Atlanta (2001)
- Columbus (2002)
- Sacramento (2005, 2009)
- Denver (2006, 2015)
- Bay Area MTC (2007)
- Seattle (2008, 2010)
- San Diego (2010, 2014)
- Burlington (2010)
- Jacksonville (2010)
- San Joaquin Valley (2011)
- Baltimore (2011)

- Tampa (2011)
- Reno (2012)
- Philadelphia (2012)
- Houston (2012)
- Minneapolis (2012)
- Phoenix (2012)
- Chicago (2013, 2015)
- Nashville (2015)
- Chattanooga (2016)

However, some of these agencies are not using their activity-based model for routine planning and also maintain a more traditional model that they use for much of their planning and analysis.

Rather than using trips as the basic unit of analysis, activity-based models focus on individual people or travelers and their choices. Activity-based models therefore always require a population synthesizer as their first component which enumerates a list of ‘synthetic’ people and households with the same aggregate characteristics as the actual or forecast population. These synthetic travelers’ choices are modeled using discrete choice models, generally of the logit form, which take into account many more variables than traditional models. Some of the most important additional variables include various measures of accessibility or how many destinations (of a particular type) can be reached within an acceptable travel time (by a certain mode, at a certain time of day) from a particular location. Activity-based models also generally incorporate more variables designed to measure walkability and related aspects of urban form.



Source: Bradley, M., J. Bowman, B. Griesenbeck. SACSIM: An Applied Activity-based Model System with Fine-Level Spatial and Temporal Resolution. *Journal of Choice Modelling*, Vol. 3, No. 1, 2010, pp. 5-31.

Figure 4. Example of a standard activity-based model design.

One of the key design features of activity-based models is that they use Monte Carlo simulation which uses a random number generator to help determine individual travelers' choices within a framework that ensures the distribution of choices takes a certain form. This use of randomness is necessary to solve the complex network of travel choices that are represented in an activity-based model. The results of activity-based models therefore include simulation variation, like the results of other simulations such as traffic microsimulations.

Activity-based models use relational databases as their primary data structure. This allows querying of the results with standard database software and the ability to "drill down" to identify impacts on custom, on-the-fly defined market segments (e.g., low income single parent households). All activity-based models currently in use still use matrices to represent travel times, and almost all summarize trips into matrix trip tables for static assignment. However, some models now under development designed for deep DTA integration do eliminate matrices entirely, which may ultimately offer advantages for file sizes.

2.2.1 Types of Activity-based Models

Although activity-based model is often used as though there were a single model design corresponding to this term, in reality there are a spectrum of model designs that are generally labeled in this group. There are a large number of activity-based models that might be considered “standard” in that there are multiple cities sharing the same model design with little or no customization. Examples include Sacramento, Tampa, Nashville, Lake Tahoe, etc. These models typically use person level day pattern planning to generate travel. The cost of such standard activity-based models has decreased in recent years due to economies of scale, and they have the advantage of having a growing professional community of users which makes hiring staff or consultants with relevant experience easier.

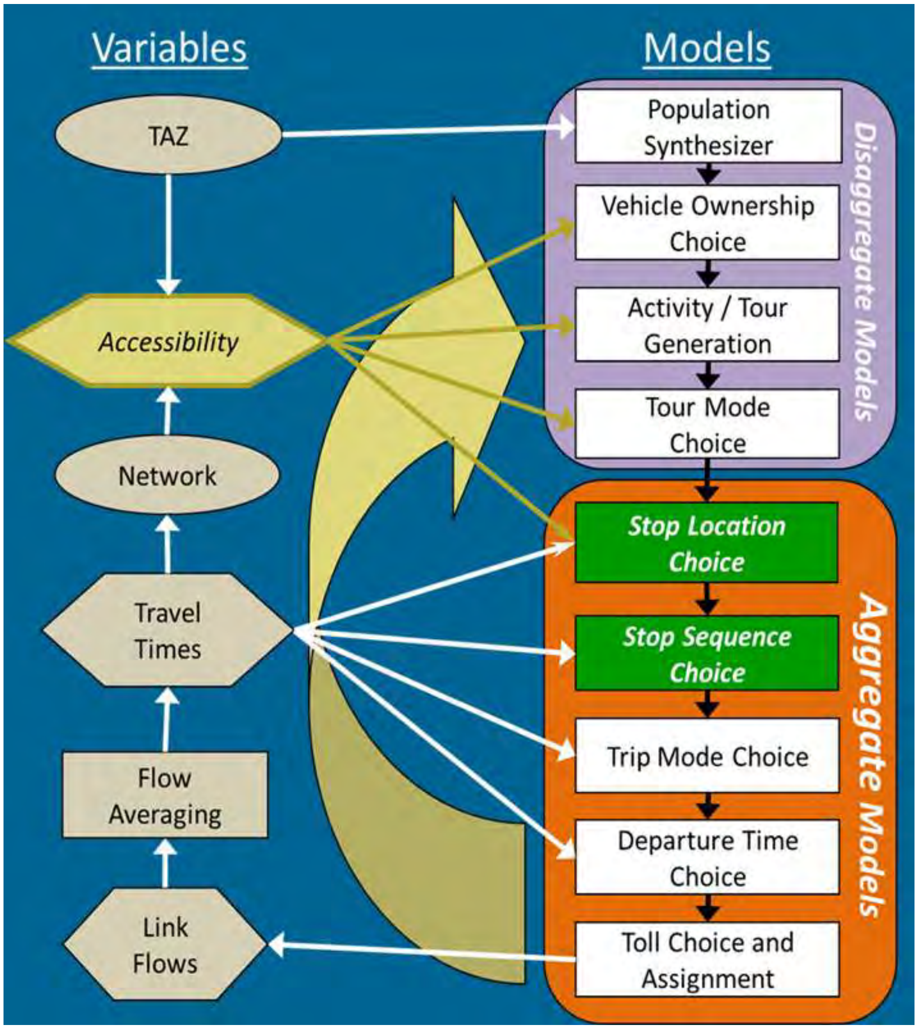
There are also some simpler models in the activity-based family that might generally be described as disaggregate tour-based models. These models share many characteristics with standard activity-based models. They use Monte Carlo simulation to apply choice models in a relational database framework. However, they offer some simplifications compared to standard activity-based models. They may use households rather than individuals as the agents or choice-makers. Typically, rather than deal with entire day patterns, they deal with travel at the level of tours, and because of this they also typically have a more simplistic treatment of time. Due to these simplifications, they may run faster than standard activity-based models. However, they lack the standard software and user community of standard models. In most other regards, they are generally similar to standard activity-based models.

There is also a spectrum of more advanced activity-based models. At the simpler end of this spectrum are models which are almost and may have begun as standard activity-based models but have one or more enhanced modules such as bicycle/pedestrian route choice, station level transit amenities, and/or complex road pricing modules. However, these models still are generally still based on the same framework as standard activity-based models.

As of the writing of this guide, there were a number of advanced activity-based models under development but nearing deployment that belong to a somewhat different category and represent a new generation of activity-based models. Some have termed these agent-based models in reference to greater incorporation of bounded rationality and limited information in these models, but the term agent-based is still somewhat controversial and may not be applicable to all ‘next generation’ activity-based models. In addition to aspects of bounded rationality and limited information, next generation models generally attempt to deal with dynamic within-day re-scheduling of activities and are designed to operate with DTA rather than static assignment models.

2.3 Hybrid Models

Hybrid travel models are the most recent family of model designs to evolve and generally developed as an attempt to compromise between practical and theoretical concerns or trip-based and activity-based designs. More recently, some hybrid models have also been developed as an incremental step on the way to the development of an activity-based model. (Vyas, 2017) The hybrid designation is a somewhat loose one in that it describes a wide range of model designs that offer some blend of trip-based and activity-based features. They can be distinguished from activity-based models in that they have at least some aggregate components and often (but not always) do not employ Monte Carlo simulation. They can be distinguished from trip-based models in that they make some connections between trips, offer improved consistency with tours, and generally have at least some disaggregate components.



Source: Michiana Area Council of Governments. MACOG Travel Model Development and Validation Report, 2014.

Figure 5. Example of a hybrid model design.

Most but not all hybrid models have at least some disaggregate component models at the front end of the model stream which use individual travelers or more commonly households as agents in choice models in a database or table-based framework similar to activity-based models. These component models may in some cases be mathematically identical to corresponding component models in activity-based models. In many, but not all, hybrid models, they are implemented differently, however, and applied to estimate expected values rather than realizations of probabilities using Monte Carlo simulation. However, this approach cannot be extended beyond the spatial or destination choices because the size of the data would explode due to the need to keep track of the probabilities for every candidate destination (and mode, etc.). Therefore, all hybrid models ultimately use aggregate trip matrices like traditional trip-based models at the end of their model stream.

Although all hybrid models improve consistency with tours over traditional trip-based models and make some connections between trips, different types of hybrid models do this in different ways. Aggregate tour-based models actually model entire tours explicitly, sometimes with some simplifications like limitations on the number of stops. Hybrid trip-/tour-based models generate and in some cases do mode choice for tours on the front end, but ultimately assign locations and sequence to the stops on those tours to create trip tables such that the information about individual tours is lost mid-way through the model, although the resulting trips were produced from and are guaranteed to be consistent with tours. Some advanced trip-based models can also be considered to belong to the hybrid family if their non-home-based trips are linked together with their home-based trips in terms of location and mode choices.

In terms of implementation, because they retain matrix data structures for at least a significant portion of their components and are more similar to traditional trip-based models in this way, hybrid models tend to be implemented entirely in standard travel modeling software packages using their scripting languages, similar to trip-based models and unlike activity-based models which require custom software in addition to standard travel modeling software which is still used for skimming and assignment. However, some more recent hybrid models have instead been implemented primarily using activity-based model software libraries.

Although it is not in any way an essential aspect of hybrid model design, many hybrid models buck the general trend in the U.S. and model destination choice after and conditional on mode choice rather than the other way around. There are multiple reasons for this, including research (Abrahamsson and Lundqvist, 1999; Debrezion et al., 2009; Newman and Bernardin, 2010) which indicates that this hierarchy is more appropriate for most travel market segments. The traditional hierarchy with mode choice dependent or conditional on destination choice implies that travelers are more likely to change modes than destinations. While this is true for small but important choice rider markets in large, transit-rich metropolitan areas, it is likely not true for the population in general even in most large U.S. metro areas. Rather, for most travelers in most situations in the U.S., mode is a foregone conclusion either because the traveler has a car and does not even consider another mode or because they do not have access to a car and rely on transit, choosing their destinations, possibly even workplace, based on where transit can get them. It is possible that the assertion of this hierarchy is one cause of the well-documented optimism bias in transit forecasts (see, for example, Flyvberg et al., 2005). In any event, the reverse hierarchy is even more attractive in hybrid frameworks because it has the added benefit of allowing the mode choice model to reduce aggregation bias and take advantage of disaggregate demographic data prior to aggregation in destination choice.

Although it can be hard to generalize about hybrid models to some extent due to their diversity, they all, to varying degrees do offer some compromise between traditional trip-based and full activity-based models. All offer some improved consistency with tours and consistency between travelers' choices and most offer at least some reduced aggregation bias, but none as much as fully disaggregate models. Because, like activity-based models more of their components tent to be discrete choice (logit) models, most offer at least some improved sensitivity to additional factors such as urban form, walkability, etc., and some hybrid models may be just as sensitive as activity-based models to these factors. Because of the lack of fully disaggregate data, none of the hybrids can conduct the type of equity analyses that full activity-based models make possible, and most hybrid models treat time more simplistically than activity-based models, although in some cases still more robustly than traditional trip-based models.

2.3.1 Types of Hybrid Models

As has been noted, there are a wide variety of model designs that incorporate elements of both traditional trip-based and activity-based models which can be considered in this sense, hybrids. Some of these model designs, particularly some of the models outside the U.S., are quite unique to the city for which they were developed. However, hybrid models can generally be grouped into three sub-categories based on how/whether they represent tours. There are at least several examples of models in each of these sub-categories, and in some cases some standardization among them.

Aggregate tour-based models are generally the most complex type of hybrid models. These models are not as common in the U.S. but have gained some traction in other parts of the world. They are not very standardized, but rather tend to be custom designed for each city, making different compromises on what complexity to include and what to simplify based on the particular behavior and planning issues relevant for the city (or country) in question. Rather than have a disaggregate front end like hybrid trip-/tour-based models, they tend to reduce aggregation bias through the use of market segmentation, sometimes with fairly elaborate and detailed segments. These models actually model entire tours explicitly, sometimes with some simplifications like limitations on the number of stops. Due to their complexity and aggregate nature they can require large amounts of memory and disk space and to some extent longer run times. In this regard, they may be considered more comparable to activity-based models. However, they are importantly different from activity-based models, including even disaggregate tour-based models, in that they do not employ Monte Carlo simulation or random draws and retain matrix data structures more similar to trip-based models rather than the relational databases of disaggregate activity-based models.

Hybrid trip-/tour-based models were the first models to be labeled as hybrids and are hybrid both in that they use both trips and tours in different parts of the model and in that they use both aggregate and disaggregate model components (Bernardin and Conger, 2010). They use simple population synthesizers and a synthetic population of households to support disaggregate tour and stop generation models and sometimes tour mode choice models. Most then use aggregate stop location and stop sequence choice models to create trip-tables for each tour type. The trip tables are guaranteed to be consistent with the individual tours generated earlier in the model but do not retain the details of the location and sequence of stops on each tour. Models which avoid simulation offer run time savings and less intense computing requirements than full activity-based models. Most if not all of the component models are discrete choice (logit) models as in activity-based models and they typically include all the same general factors in travelers' choices as in activity-based models; the main difference is the inability to directly represent space-time constraints on travel. While the spatial dimension of these constraints is still captured well by these models, the temporal aspect is less so, and the sensitivity of the timing of travel is probably the most significant limitation of these hybrids relative to full activity-based models.

Not all advanced trip-based models belong in the category of hybrids. Enhancements such as basic time-of-day modeling or more refined trip purposes or modes do not fundamentally alter the model in most regards. However, some advanced trip-based models do include fundamental structural changes to the model that result in different model properties and behavior both in theory and practice. These models represent at least some connections or connectedness between trips within the same tour with the result that the locations and modes of these trips are related. This group of models could be further sub-divided into two groups. The first models developed in this category were models that represented trip-chains, at least on work tours. These models were related to aggregate tour-based models, but less complex. A number of these models were developed in the U.S. around or shortly after the turn of the millennium. However, in recent years, these models seem to have seen less use. In contrast, more recently a new type of hybrid advanced trip-based models has begun to proliferate (Bernardin and Chen, 2016). These models do not represent trip-chains explicitly, but borrowing more from hybrid trip-/tour-based models, produce trip-tables that are more consistent with tours through the use of a two-stage distribution (at least of non-home-based trips). However, they accomplish this in a simpler way than hybrid trip-/tour-based models, by simply moving the component models for non-home-based trips so that they run after and conditional on the home-based trip models rather than in parallel and independently of them. Depending on the details of other model components, these advanced trip-based may remain more like traditional trip-based models with limited sensitivities to additional factors affecting travel or may incorporate such factors offering sensitivities more similar to more advanced hybrids or activity-based models.

3.0 Data-Driven Modeling Frameworks

Despite many years of efforts over time to improve travel models, many forecasting models, regardless of architecture or design, still struggle to accurately represent current year travel patterns. The most critical deficiency occurs with the representation of trip origin-destination patterns. This critical difficulty in replicating the spatial distribution of trips is widely acknowledged in both practice (TFResource.org) and research (Zhao and Kockelman, 2002) as the largest source of error in travel forecasting. Although recent destination choice models offer some important improvements over traditional gravity models, destination choice models still struggle to reproduce observed OD patterns.

Traditional, hybrid, and activity-based models can all be used by themselves in a "pure" synthetic form or together with and incorporating observed data on actual travel patterns in a more data-driven approach to address the difficulty in reproducing OD patterns. Given the even greater difficulty in representing intercity OD patterns with gravity and destination choice models than representing local patterns in urban models, data-driven approaches have become a common practice in statewide modeling (e.g., Michigan, Indiana, Tennessee, Florida). These models pivot off base-year OD matrices that have been developed through the combination of large, passive OD data and count information (see for instance, Bernardin *et al*., 2017). Data-driven modeling is also widespread for metropolitan modeling outside of the United States; in fact, this practice is required in the United Kingdom. (UK Department of Transport) Awareness of this in the United States has increased recently due to greater global interaction and communication, and through TMIP webinars by RAND Europe showcasing their work in both Europe and Australia. Data-driven forecasting methods are also now being applied in metropolitan modeling in the United States (e.g., Chattanooga, Ann Arbor, Charleston). Metropolitan planning organizations (MPOs) and state departments of transportation have begun to capitalize on the commercial availability of large-scale, aggregated, anonymous, passively collected OD data, also commonly referred to as "Big Data." The performance of new models of this type using these data is promising and is the focus of another TMIP How-to guide (How-To: Develop Big Data Driven Demand for Traffic Forecasting).

Unlike traditional travel demand models, which rely almost exclusively on survey data, or earlier data-driven forecasting methods, which often relied primarily or exclusively on traffic counts, contemporary data-driven traffic forecasting incorporates passive OD data, together with traffic counts which are important for properly expanding it. Passive OD data is large in scale (generally including millions of trips), typically aggregated (to protect privacy concerns and for data manageability), anonymous (not including any traveler characteristics), and passively collected. Cost is one of the main advantages of these passive datasets, which can provide OD data more cost effectively than surveys. However, the completeness or adequacy of the sample in the spatial dimension provides another powerful motivation for the use of these datasets. While traditional travel surveys typically provide observations on 2% or fewer of the OD pairs in a region, new sources of Big Data can provide observations covering more than one-quarter to one-third of all OD pairs. This order of magnitude difference in the completeness of the data provides a more complete picture of spatial travel patterns in a region that traditional data cannot.

It is generally well understood how travel models can be used to produce forecasts of future OD travel patterns in the absence of Big Data, but in the current context of the availability of large scale, passive OD datasets, it is important to consider how travel models can produce forecasts together with Big Data.

There are generally two methods for using travel demand models together with passive OD data or incorporating passive OD data in travel demand models. The first approach uses travel demand models (usually of more traditional, aggregate designs) to pivot off OD matrices developed from

Big Data and traffic counts. The second approach instead uses these OD matrices to develop fixed factors (or constants) that are incorporated into the travel model; this approach is more attractive for activity-based demand simulation models, although it can also be applied with aggregate trip-based travel models. The following sections describe and discuss these two similar and related, but alternative and potentially different, approaches.

3.1 Pivot-Point Methods

The most common approach to using travel demand models together with an independently data-derived trip matrix is to apply the change in OD travel patterns predicted by a model to the data-driven OD matrix. (Daly et al., 2005; Fox et al., 2012)

This approach often uses rules or a weighting scheme to combine additive pivoting and multiplicative pivoting, but pure additive pivoting is also sometimes used. Pure multiplicative pivoting is to be avoided because it can result in unreasonable results in cells where the synthetic model and actual data differ significantly in the base case. However, multiplicative pivoting is sometimes preferred for normal, moderate growth or changes, but because it can produce poor forecasts in some cases, particularly when there are very few or no trips for an OD pair in one or more of the matrices, this motivates a mixture of the methods. Rules or weighting are therefore commonly used to select or combine the two basic pivoting methods, additive and multiplicative. For more details on these methods see the TMIP guide, *How-To: Develop Big Data Driven Demand for Traffic Forecasting*.

Pivot-point methods have the clear advantage of requiring relatively little modification to an existing travel demand model. Pivot-point methods also are attractive because they are straightforward and easy to understand in concept and explain. Many professionals are already familiar with pivot-point methods from their use to pivot off individual traffic counts to produce facility-specific forecasts (a la NCHRP 255 and 765).

Pivot-point modeling can substantially improve forecasts by removing the error in a travel demand model's base-case OD matrix. This error is known to be the largest source of error in traffic modeling (Zhao and Kockelman, 2002) thus, pivot-point methods promise substantially improved accuracy in forecasting. However, pivot-point methods have no effect on the sensitivity of the travel model or resulting forecast to changes in travel time, tolls, land use, or other factors. This can be viewed in either a positive or negative light. On the one hand, the independence of the model's sensitivity to the approach can alleviate any concerns related to overfitting or over-specification. On the other hand, this same independence of the model's sensitivity to the approach also means that the information in the passive OD data does not necessarily improve the sensitivity of the travel model or resulting forecast to changes in travel time, tolls, land use, or other factors. The large amount of error in base-case models suggests the strong possibility of under-specification errors in existing or traditional models which may translate into over-sensitivity of models to travel times, tolls, land-use variables, and other factors, and pivot-point methods do not help to address this issue.

While the inability of pivot-point methods to address under-specification errors affecting model sensitivities is an important theoretical concern, one of the main drawbacks of pivot-point approaches in practice is the inability of applying the approach at the level of disaggregate demand in demand simulation models such as activity-based models. The fixed-factor approach presented in the following section offers an alternative method that can be applied to disaggregate demand simulation models as well as traditional aggregate models.

In summary, pivot-point approaches may not be theoretically ideal or practical for use with activity-based models, but they are easy to apply with most traditional and hybrid travel models and can substantially reduce error.

3.2 Fixed-Factor/Constant Rich Methods

Fixed-factor or constant rich approaches involve a deeper integration of passive OD data into a travel model. As such, they generally require more effort, but they can also potentially yield greater benefits than pivot-point methods and are applicable to activity-based models as well as more traditional aggregate trip-based models and hybrids.

The fixed-factor approach works by incorporating a set of constants into the spatial (gravity, destination, or activity location choice) model components of a travel demand modeling system. These factors are estimated in a statistically rigorous way to allow the model to reproduce expanded passive OD data with minimal error.

Fixed factors or constants can be specific to individual or groups of origins or destinations or OD pairings. In the context of destination choice models, these are alternative specific bias constants.

Fixed-factor methods can be developed in two importantly different ways. First, a sequential estimation approach in which the factors are estimated after and independently of other model parameters is like pivot-point methods in that it does not affect model sensitivities for good or ill, and it is easier to apply. This method usually involves estimating the constants as shadow prices and has been successfully applied in practice with very encouraging results (Lee et al., 2016). Second, simultaneous estimation of fixed factors together with other model parameters requires more effort, but it also offers the potential for better results by addressing likely under-specification errors and potential model over-sensitivities. Over-specification errors are still possible, though this is less of an issue with Big Data. This approach, while theoretically appealing, remains untested in practice. Again, for more details on these methods see the TMIP guide, *How-To: Develop Big Data Driven Demand for Traffic Forecasting*.

It is worth noting that the constant rich methods presented above are importantly different than traditional k factors sometimes used in gravity models. The constants discussed here are theoretically motivated, incorporated in a behavioral framework, and can be systematically statistically estimated from a sound support of passive OD data. In contrast, k factors were developed in an ad hoc fashion, with little or no theory, based on survey or traffic count data that often could not actually support them.

Constant rich approaches allow spatial choice models to incorporate passive OD data, better replicate observed OD patterns in the base case (Lee et al., 2016), and presumably better forecast future or alternative OD patterns. Moreover, constant rich methods can produce both agreement of aggregate OD patterns with observed data and consistency between the disaggregate and aggregate results of a simulation modeling system. In the context of simultaneous estimation of constants with other utility parameters, this approach should theoretically lead to less biased, more realistic model sensitivities, as well.

The main drawback to constant rich methods is the level of effort required, which is generally somewhat greater than the effort required for pivoting. However, the shadow-pricing method of sequential estimation of constants is only modestly more difficult than pivoting. Simultaneous estimation, despite its theoretical attractiveness, remains challenging in practice.

4.0 Projects and Policy Issues as related to Model Design

While the evaluation of transportation projects and policies are inextricably also involved in both the theoretical and practical considerations discussed in the next two sections, this guide begins with a high-level overview of the advantages and disadvantages of model designs for some of the most common types of projects and policies that agencies are called on to evaluate. This is motivated by the belief that model design should be driven first and foremost by the intended model applications to ensure that the model is useful for the things it will actually be used to do. The following discussion does not necessarily cover every possible model application, or every special circumstance that might occur in the topics that are covered, but is offered to help agencies consider the likely general advantages and disadvantages of different model designs for the different types of applications of most importance to many of them.

4.1 Traditional Highway Projects

Traditional trip-based models were developed to forecast highway volumes in response to projects such as new roadways or lane additions and can generally be expected to be able to estimate the number of lanes required to achieve a given service threshold. Activity-based and hybrid models therefore offer no substantial advantage in evaluating these type of projects. Most activity-based and hybrid models produce similar highway assignment errors as trip-based models. There is some limited evidence from a few regions that activity-based or hybrid models may be able to provide slightly better forecasts for lower volume roads, but it is unclear at this point in time whether that result is generalizable, and even if it is, low volume roads are not generally candidates for capacity improvements. See also Section 5.1 for a discussion of forecast accuracy as it relates to highway projects.

It is worth noting that highway forecasts are importantly a function of the network assignment model used as much as the travel demand model. The fact that advanced demand models are still generally paired with the same type of static network assignment model as traditional models may, therefore, account at least in part for their similar performance. However, the SHRP2 C10 studies of ABM-DTA systems have not thus far provided strong evidence that this type of more advanced and wholly disaggregate simulation system necessarily leads to superior results.

4.2 Air Quality Conformity Analysis

Another common and important application for travel models in many regions is emissions analysis to demonstrate conformity to the Clean Air Act (by way of the state implementation plan's motor vehicle emissions budgets). The design of a travel demand model offers no advantage or disadvantage for this purpose. Traditional trip-based, hybrid, and activity-based models can all equally well predict regional VMT and the relevant distributions required as inputs for EPA's MOVES model. So, conformity analysis is not a consideration in selection of a model design.

4.3 Complex Emissions Analysis

However, in response to local concerns or statutes, some agencies have conducted other types of emissions analysis such as analysis of how many greenhouse gases are produced by different residents of the region. Because non-home-based trips are disconnected from the travelers who make them in traditional trip-based models, it is difficult to conduct this type of analysis with that model design. Activity-based models, and to a lesser extent hybrid models, offer an advantage for this type of analysis since they can more properly track the total emissions produced by residents of various subareas of the model (e.g., emissions produced by residents of the central city versus residents of its suburbs).

4.4 Traffic Impacts

Traditional trip-based models are also widely used to predict traffic impacts of new developments. Hybrid models may offer some advantage over traditional models because they account for some degree of internal capture when complementary uses in the same new development satisfy a trip within the development so it never loads onto the network. While it has been demonstrated that hybrid models do reflect some amount of internal capture, further study comparing the amount of internal capture predicted by hybrid models to driveway counts or other empirical studies of internal capture would be helpful in understanding the significance of this advantage.

In contrast, as noted in Section 5.7, activity-based models offer a distinct disadvantage for conducting traffic impact studies due to simulation variation and the need for multiple runs. Although they may reflect internal capture like hybrid models, the practical issue of simulation variation can often require multiple model runs in order to establish impacts at the level of intersection turning movements and other performance measures of interest in traffic impact studies. The result can be that a traffic impact study may require a few hours of runtime with a traditional trip-based model may require a few days or more with an activity-based model.

4.5 Highway Pricing

There may be some disagreement about the relative advantages of different model designs for evaluating highway pricing scenarios. On the one hand, there are strong theoretical reasons for believing that activity-based models should be better able to address complex pricing schemes such as time variant tolls or cordon pricing. On the other hand, as of the writing of this guide, toll road financing still relies more or less exclusively on trip-based modeling.

There are several ways in which activity-based models should be theoretically superior to traditional trip-based models for pricing scenarios, particularly complex ones. The synthetic populations of activity-based models allow the representation of a continuous distribution of values of time and deep integration with DTA could theoretically allow consistency between these values used in route choice and in ‘upstream’ choices. The more robust treatment of value of time may offer an advantage for simple pricing scheme but clearly provide an advantage in networks with complex pricing choices such as choices between multiple priced routes (e.g., a traditional fixed price toll road and an express lane with time varying tolls). The ability of activity-based model to represent shorter time periods and integrate with DTAs are also a clear advantage for evaluating time variant (including congestion sensitive) pricing scenarios. The ability of activity-based models to capture the likelihood of travelers to group activities into a single tour so as to only pay a cordon toll once is also a clear advantage of this model design for these type of pricing scenarios.

Despite these strong theoretical advantages, analyses using traditional trip-based models remain the mainstay for investment grade tolling analysis. There may be a number of reasons for this, including simply inertia of traditional practice which may fade as time passes. However, the reliance on traditional trip-based models may also reflect several of the other practical factors noted in the following section. Investment analysts may have more confidence in the calibration of trip-based models since there are fewer parameters to check or adjust. They may also feel they simply have a better handle on the limitations of traditional models. In some cases, runtime may also be an important factor because their analysis includes a large number of model runs in which different input assumptions (from land use to model parameters) are varied in order to better understand risk, and the longer run times of advanced models would limit the number of scenarios that could be tested in this type of analysis.

See also Section 5.1 for a discussion of forecast accuracy as it relates to toll projects.

4.6 Peak Spreading

Although some post-processing techniques attempt to account for peak-spreading, generally with relatively ad hoc heuristic and non-behaviorally based methods, traditional trip-based models do not capture or reflect the phenomenon of travelers shifting the timing of their travel in order to avoid peak congestion. Hybrid models can represent peak spreading in a more robust statistical way, within the demand model itself, thus offering some improvement over traditional trip-based models. Only activity-based models explicitly represent time constraints on activities and travel that impact peak-spreading behavior and hence, activity-based models offer a clear advantage to regions in understanding and predicting peak spreading.

4.7 Travel Demand Management

Traditional trip-based models also face significant challenges and generally struggle to evaluate travel demand management (TDM) strategies or policies such as telecommuting, alternative work schedules, employer provided transit passes, parking management strategies, etc. Hybrid model designs can offer some advantages over traditional trip-based models, but activity-based models clearly offer the most robust framework for the analysis of many TDM strategies. For example, employer provision of transit passes can generally only be addressed in traditional trip-based models by arbitrarily adjusting the alternative specific constants for different modes in the mode choice model; whereas, in some activity-based models, transit pass ownership is explicitly represented so that the model can actually predict likely behavioral responses to being provided a transit pass for non-work as well as for work-related travel.

4.8 Transit Investments

Although activity-based models may be better able to represent some transit-related policies such as employer provided transit passes or land use policies or patterns that favor transit oriented design, activity-based and hybrid models offer no advantage over traditional trip-based models in forecasting ridership for new fixed guideway transit services. FTA's own transit forecasting tool, STOPS, is of a trip-based design and the use of other models, regardless of model design, requires additional scrutiny for their Capital Investment Grants (New Starts) Program. Their before-and-after analyses have demonstrated that many MPO models are not able to produce reliable forecasts without further validation work, but that with this investment of effort, trip-based models have been able to produce reasonably reliable and accurate forecasts. Relatively few advanced models have been used to produce forecasts for New Starts projects, so similar conclusions cannot yet be drawn, but in summary, it is clear that trip-based models – with the investment of adequate validation effort – can produce reasonable transit forecasts, and the use of STOPS may offer further advantages in terms of streamlined FTA review. See also Section 5.1 as it relates to transit forecasting. However, it is worth noting that many enhanced activity-based models use stop-to-stop or station-to-station impedances and estimate demand in this format, which is in some ways similar to STOPS and may offer some added realism and reduction of aggregation bias.

4.9 Bicycle / Pedestrian Planning

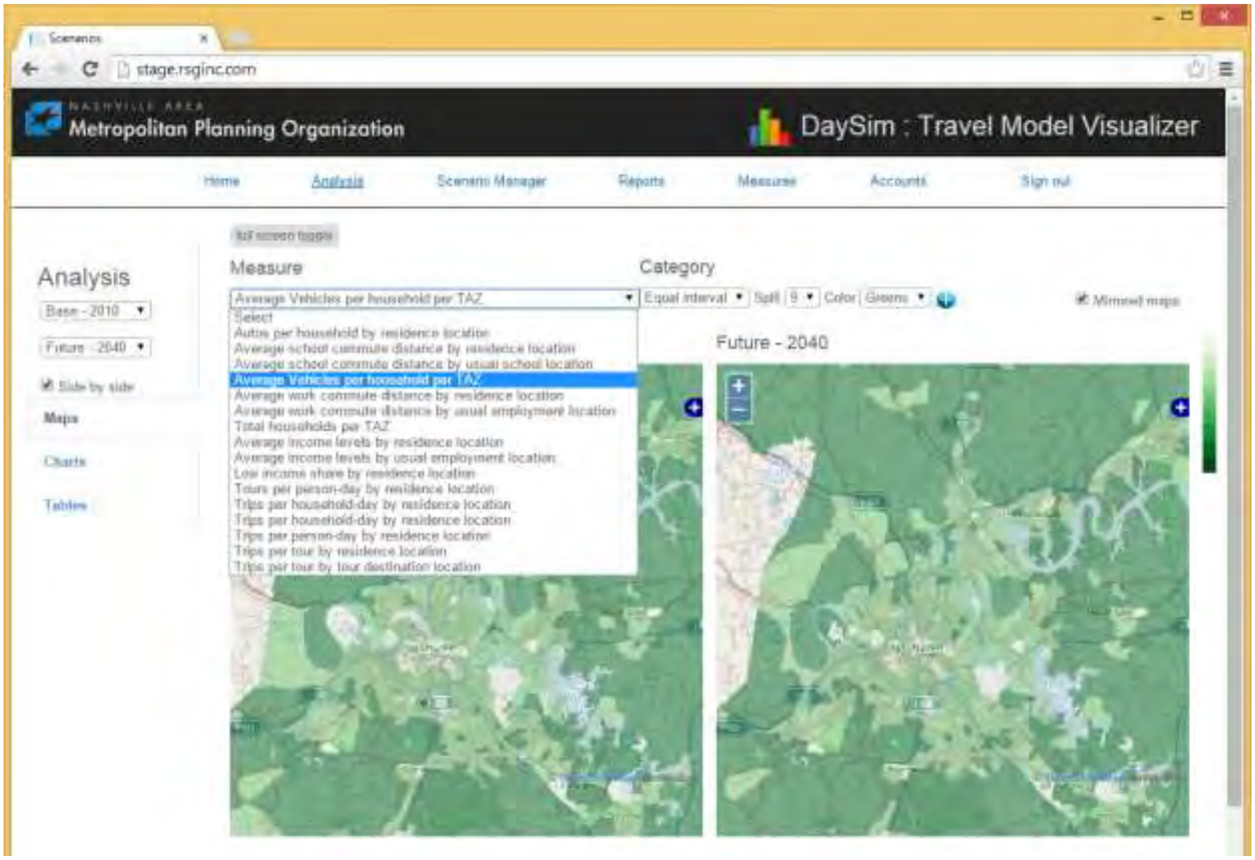
For several reasons, including their lack of spatial detail and typically their insensitivity to urban form, traditional trip-based models struggle to represent walk and bike trips. Hybrids do somewhat better because they do consider the urban environment (i.e., walkability/bike friendliness). Many standard activity-based models are able to do still better at forecasting pedestrian and bicycle trips through their use of microzones (or parcels) and small-scale impedances. The representation of non-motorized networks and level-of-service is also a factor in any model design. Trip-based models commonly don't model non-motorized accessibility or level-of-service at all. Many hybrids and standard ABMs represent non-motorized levels-of-service at a zone or microzone level (often based on GIS analysis of a simple non-motorized/all-streets network with few/no attributes). Only a small number of models have incorporated detailed non-motorized networks with facility types, grades, and other level-of-service variables that allow a model to respond to bicycle / pedestrian infrastructure improvements such as new bike lanes, cycle track, or multiuse trails, generally through the use of bicycle/pedestrian route choice models. Most of these models have been activity-based models although at least one trip-based model has also been integrated with this level of non-motorized network model.

4.10 Land Use Planning

Many agencies are interested in understanding the impacts of different potential land use scenarios on future travel patterns in their region. Traditional travel models are largely blind to urban design such as the density and connectivity of local street networks, the mixture of land uses at the scale of walk sheds, etc. In contrast, both hybrid and activity-based models consider and reflect the impact of these factors on travel patterns.

4.11 Equity Analysis

Concern for environmental justice or equity considerations has grown in recent years and lead some agencies to conduct increasingly complex analyses of the impacts of various projects and policies on specific communities of concern within their region. Traditional and hybrid models can only summarize results and produce performance measures for a small number of market segments (e.g., households with autos vs. households without autos). In contrast, because activity-based models produce results for individual travelers within their synthetic population, their results can be queried and summarized in any way desired. They can support analysis for special custom communities of concern such as low income single parent households or elderly minority households, etc., and these communities of concern can be defined after and independent of not only model development but even the model runs. However, it is important to acknowledge that the meaningfulness of these sort of detailed results is limited somewhat by sample size and variability in the base year (e.g., results for very small populations such as elderly Native Americans in a particular subarea of the model – like other small scale phenomenon – can be significantly impacted by simulation variation) and by the ability of the agency to forecast these demographic details in future year scenarios.



Source: Nashville Area Metropolitan Planning Organization.

Figure 6. Visualization of detailed and custom-defined impacts from an activity-based model.

4.12 Summary of Issues related to Model Applications

As noted in the Introduction/Executive Summary, different agencies use their models for different applications. Some applications which are the primary focus of one agency may be of little or no importance to another agency. Therefore, it is not possible to summarize the advantages and disadvantages of model design as relates to model applications or project/policy analysis in general, but only offer some indication of which model designs might offer some advantage for which sort of applications. Table 1 attempts to summarize and illustrate in a very simple way the relative advantages or disadvantages of the general model designs with respect to different common model applications. In referring to this figure, it is important to understand the limitations of the three-star scale or scheme to represent the complex issues involved. The goal of this and subsequent similar figures is to help the reader understand at a very high level some of the issues and pros and cons to be considered, not to serve as a scorecard.

Table 1. Relative advantages of model designs for common applications.

Model Application	Traditional	Hybrid	Activity-Based
Traditional Highway Projects	★★★	★★★	★★★
Air Quality Conformity Analysis	★★★	★★★	★★★
Complex Emissions Analysis	★	★	★★★
Traffic Impact Analysis	★★	★★★	★
Highway Pricing Projects	★★	★★	★★
Peak Spreading Analysis	★	★★	★★★
Travel Demand Management Strategies	★	★★	★★★
Transit Forecasting	★★	★★	★★
Bicycle/Pedestrian Planning	★	★★	★★★
Land Use Planning	★	★★★	★★★
Equity Analysis	★	★	★★★

5.0 Practical Issues related to Model Design

While theoretical concerns with traditional models can lead to very real problems in practice which generally provide motivation for more complex models, more complex models designed to address these theoretical concerns often face challenges of their own when it comes to their implementation and usefulness in practice. This section reviews the major practical issues that have been identified as being related to the design of travel models and their implications for the different families of model design.

5.1 Forecast Accuracy

There has been surprisingly limited analysis of the ability of travel models to accurately forecast travel as a response to changes. Much of the research that has been done has focused on fixed guideway transit forecasts (e.g., Pickrell, 1992; Button, 2009; Schmidt, 2016) or toll road forecasts (e.g., Bain, 2009) although there has been some more general research as well (e.g., Flyvberg et al., 2006; Parthasarathi and Levinson, 2010; Nicolaisen, 2012; Giaimo and Byram, 2013). Actual retrospective studies present evidence of an optimism bias in forecasts for fixed guideway transit and toll facilities. However, there is also some evidence that non-tolled highway forecasts are not biased (or slightly very slightly pessimistically biased) and the majority (possibly as much as two thirds) of highway forecasts are accurate to within +/- 20-25%, but a significant minority of projects (perhaps as much as a quarter) with accuracy worse than +/-40%. There is also evidence that accuracy and bias in transit forecasts may have both improved over time from errors frequently in excess of +/-70% before the mid-1990's to generally less than +/-50% or better since 2005. There have been no retrospective studies that have compared forecast accuracy across model designs as of the writing of this guide. Such studies could have significant value in informing the selection of model design.

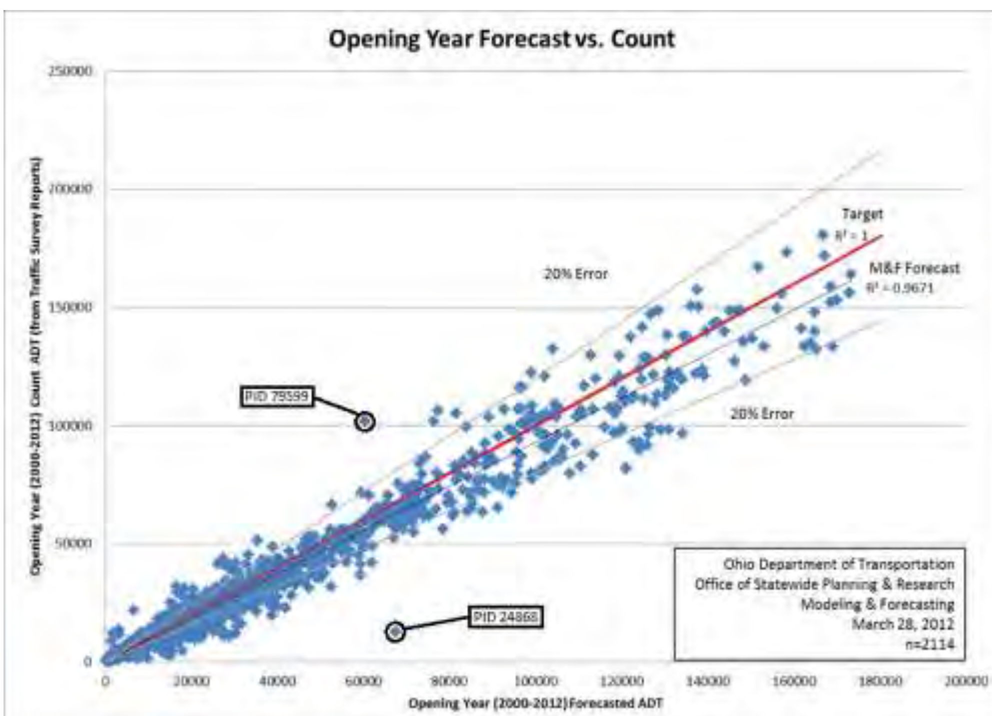


Figure 7. Historic accuracy of ADT forecasts.

Source: Improving Project Level Traffic Forecasts by Attacking the Problem from all Sides, presented by Greg Giaimo and Mark Byram at the 2013 TRB Transportation Planning Applications Conference.

Only a very limited number of studies have done experiments with real models and data comparing the forecast validity of different model designs. One study (Bernardin, 2008) did find that destination choice models developed from a 2000 survey were better able to predict OD patterns from a 2008 survey of the same region than gravity models developed from the same 2000 dataset. Although the improvement in forecast validity was modest, the data only spanned eight years and it may not be unreasonable to suspect that the margin of improvement may increase over time. This would suggest that hybrid (including advanced trip-based) or activity-based model designs including destination choice models may be better able to predict future travel patterns than traditional models using gravity trip distribution components. A significant number of sensitivity tests have also demonstrated that advanced models can produce more realistic elasticities or response properties than simple, traditional trip-based models, which also provides some basis for suspecting better forecast validity. However, the only study (Ferdous et al., 2011) to compare a traditional trip-based model and an activity-based model developed from the same data and validated to the same standards to predict local/project level changes in highway volumes found that the two models has basically equal predictive validity.

5.2 Data Considerations

One of the very important considerations in the development of any model is the data available to support the model development. “Garbage in, garbage out,” is a cliché and everyone knows that any model is only as good as the data used to develop and support it. However, it is easy, particularly in grappling with theoretical issues to lose sight of the data requirements implied by a particular solution. Data issues are therefore one of the important considerations for those who are seriously considering more complex model designs.

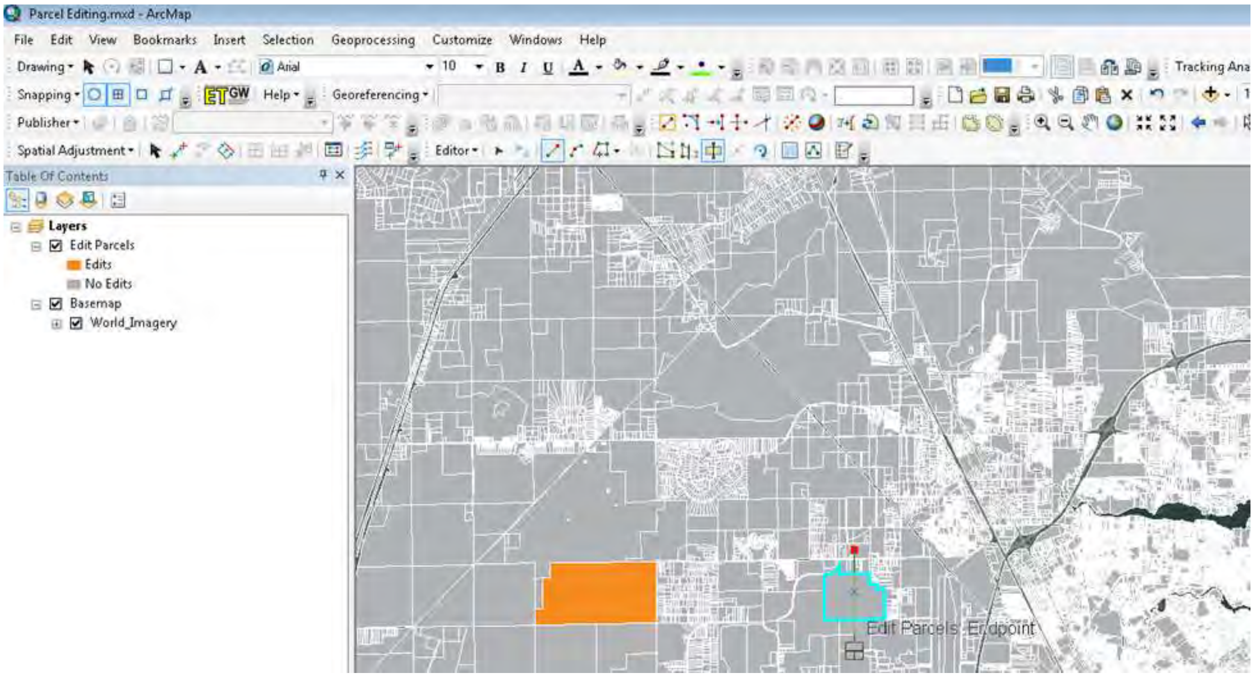
5.2.1 Spatial / Socioeconomic Data Work

When people think about data requirements for models, they often immediately think of household surveys and estimation data needs. However, as important as estimation data is, the basic spatial socioeconomic data required as inputs to the model are equally important and often overlooked until the model design has already been selected. Then, some agencies have been surprised by the data work required not only to get the base year model datasets prepared but also the work to develop inputs for alternative/future scenarios.

Traditional trip-based models, most hybrid models and even some activity-based models use traffic analysis zones (TAZ) to represent space and establish the population’s demographic characteristics and the characteristics of destinations such as the number of jobs. However, as is explained and illustrated in Section 6.1, the use of a zone system can be one source of aggregation bias, and can greatly limit the ability of a model to represent or understand small scale travel such as walk and bike trips.

For these reasons, most activity-based models and even one or two advanced trip-based models use both TAZ and microzones. Microzones are typically much smaller than TAZ. Individual census blocks are often used as microzones, although sometimes they are combined or split. A few models even use individual land parcels rather than microzones.

The use of census blocks as microzones is helpful since the Census Bureau provides block level estimates of both population and employment. However, finalizing base year microzone data is never as simple as just grabbing census data. Inevitably, the process of trying to synthesize a population reveals inconsistencies in the data which much be rectified. In recent years, the Census Bureau has been very conscientious about clearly acknowledging error in their estimates through the publication and promotion of confidence intervals for their data; however, many are still surprised when block level estimates of population from the decennial Census and block group estimates of households from the census ACS survey do not agree or other similar issues are encountered. Cleaning up and rectifying these data issues to the degree necessary to produce a synthetic population is often a cause of delays in the development of advanced models.



Source: City of Jacksonville, FL; ESRI

Figure 8. Editing parcel/microzone data in GIS.

Preparation of future year microzone data can also be challenging. Without census data for future scenarios, producing forecasts of demographics at the level of tens of thousands of microzones for a region can be understandably a daunting challenge. While many agencies simply use the base year distribution of population and employment within each zone to disaggregate future year TAZ level forecasts, this is obviously less than desirable in some cases, particularly where there is significant land use change within a zone. Moreover, manually adding to or adjusting the population is not entirely simple because it is easy to inadvertently introduce inconsistencies in the socioeconomic characteristics of the population (e.g., having more workers than people over age 15, resident population under age 10, but no households with children, etc.). Some agencies have recently begun developing tools to help with microzone data preparation for alternative land use scenarios, but these tools still make use of simplifying assumptions and cannot fully eliminate the additional work involved in developing alternative scenarios at the microzone level.

While none of the foregoing data needs are insurmountable, they amount to a non-trivial amount of additional effort both for the development and for the on-going day-to-day use of advanced models which use microzones. (For the few models that use parcels rather than microzones, the effort can be even more difficult.) So, it is important that agencies carefully consider the benefits of more detailed spatial resolution (e.g., better walk and bike modeling) with the real costs in terms of the additional data work required.

5.2.2 Parking Spaces and Costs

More advanced models typically also require the number of parking spaces and their cost as an input at either the zonal or microzone level. For some agencies, assembling this data for the base year can prove quite challenging, but even for agencies with good base year parking data, it can be difficult to develop reasonable forecasts of the number and price of parking spaces for future scenarios. Although simple assumptions are sometimes used such as holding parking fixed from the base year or scaling the number of spaces based on forecast employment, these methods can clearly prove unrealistic and problematic in many scenarios. While some traditional trip-based models also have component parking models with similar data demands, this is uncommon. Some may argue that ignoring parking in simpler model designs may be an important source of error in their forecasts, but as a practical concern, the need to forecast parking supply and cost is clearly a challenge for more advanced model designs.

5.2.3 Estimation Data Needs

Another important data consideration is the data required to estimate and/or calibrate the parameters of a model. While adding more detail is attractive to reduce aggregation bias, the more components and detail that is added to a model, the more data is required to support good estimates of the model's associated parameters. Having good estimates of model parameters is important because it is these parameters which determine the model's sensitivity to various types of changes, be they demographic or in the qualities of the travel options available.

Due to the large number of component models and detailed person and activity types in activity-based models, large sample household surveys are required to estimate the full set of model parameters. Although the actual data requirements depend on the details of the model specification, in general, a sample of roughly 5,000 households or more may be required to estimate a full set of activity-based model parameters. This can be difficult for many agencies to afford, although some agencies are addressing the need for data by establishing an annual budget and conducting continual or annual surveys.

Thankfully, many agencies do not need to re-estimate the full set of activity-based model parameters in order to implement an activity-based model for their region. Research by FHWA has provided strong evidence that of an activity-based model's parameters are generally transferrable across regions. This stands to reason, since once a model controls for many variables, the remaining random or unaccounted for variability is reduced (e.g., while aggregate trip rates may vary considerably from region to region, the trip rates for married couples without children with annual income between $80-100k, who live in a walkable neighborhood, etc., etc., do not vary much from region to region). So, as long as an agency is comfortable accepting a standard model specification estimated by another region, they can transfer or borrow many of the models parameters. Moreover, the model can still be calibrated to match survey observations from the local region through the adjustment of alternative specific constants. For this reason, this approach has become common for mid-sized and smaller regions that choose to adopt activity-based models.

While the evidence clearly supports the transferability of most model parameters, there are some component models / parameters which are not particularly transferrable. In particular, spatial / destination choice models are typically not transferrable due to the uniqueness of the geography and land use patterns of each region. Moreover, this is an important concern since the spatial distribution of travel is the most difficult to model and the mode and timing of travel depend importantly on it. Even more challenging is the fact that spatial / destination choice models can be among the most data hungry if the goal is to produce models that not only reproduce trip lengths but actually reproduce observed OD patterns. The good news is that new sources of passively collected big data offer hope for providing large samples of spatial travel data more economically than large scale surveys. The bad news, or challenge at least, is that integrating big data in activity-based models is still a very new and challenging task and methods of simultaneously estimating the full set of destination choice model parameters from both survey and passively collected (anonymous) data are still in need of development as will be discussed in the following subsection.

In summary, if a region feels it has unique factors or a unique policy or problem that will require a custom model specification, it will be necessary to budget for a large scale household survey. If a region is comfortable with a standard model specification, they can safely borrow many model parameters from another region, but they should still plan on collecting some survey data to support calibration of constants to local conditions optimally in conjunction with the purchase of passively collected OD data and budgeting for special analysis to incorporate this into the spatial model components.

5.2.4 Integration of Big Data

The advent of new passively collected big data on travel patterns fundamentally changes the methods available for travel forecasting. The availability of such data allows the employment of more data-driven forecasting techniques, and there are both strong theoretical reasons and growing evidence from practice that such methods can produce more accurate forecasts, especially in the short run, but potentially in the long run, too. The fundamental characteristics of these methods is that they rely on data for the spatial distribution of travel and only use models to predict changes to it rather than relying on models to reproduce the whole pattern. Even prior to the advent of big data, relying more on large household surveys, this type of data-driven forecasting has been standard in much of Europe for some time and even required in the United Kingdom. FTA's new STOPS transit forecasting model which pivots off of CTPP OD flows or user-supplied data, such as from an on-board survey, also falls into this category and has been shown to produce accurate transit forecasts.

With the increasing availability of observed base year trip tables, many agencies are opting for these types of data driven approaches. For agencies with trip-based or hybrid models which produce aggregate trip table matrices, it is relatively easy to adapt their existing models to adopt these procedures by using a simple pivoting scheme (e.g., Fox *et al*., 2012). However, it is fundamentally more challenging to incorporate these new sources of big data into disaggregate models such as activity-based models because the data is aggregate in nature, despite its large sample, due to privacy considerations. Activity-based models were developed to reproduce household surveys and so the incorporation of big aggregate data poses certain challenges.

Big data has now been used successfully to calibrate a rich set of constants for the spatial choice models for an activity-based model in Chattanooga, Tennessee, (Lee *et al*., 2016) and the technique is now being used to calibrate work location choice models to CTPP data for Philadelphia's activity-based models. While this technique does allow activity-based models to produce more data-driven forecasts that can reproduce observed OD patterns (see Table 2), it requires more effort than pivoting methods in aggregate models. Moreover, the initial methods currently in use are not ideal. Ultimately, the ideal solution would be not simply to calibrate but to estimate spatial choice models simultaneously from both aggregate and disaggregate data sets, but at this time, this remains a topic for research. Until such methods become standard and incorporated in the estimation software used to develop activity-based models, agencies should simply be aware that the cost to incorporate big data is greater in activity-based models than in four-step models or hybrids.

Table 2. Calibration of Chattanooga's activity-based DaySim model to AirSage data.

Origin Super District	Destination Super District 1	Destination Super District 2	Destination Super District 3	Destination Super District 4	Destination Super District 5	Destination Super District 6	Destination Super District 7	Destination Super District 8	Destination Super District 9	Destination Super District 10	Destination Super District 11	Destination Super District 12	Grand Total
1	0.5%	0.1%	-0.2%	0.0%	0.0%	-0.1%	-0.2%	-0.2%	-0.1%	0.0%	-0.1%	-0.3%	-0.6%
2	0.2%	0.2%	0.1%	0.0%	0.1%	-0.1%	0.0%	0.1%	0.1%	0.0%	0.0%	-0.1%	0.5%
3	-0.2%	0.0%	0.3%	-0.2%	-0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-0.1%	-0.3%
4	0.0%	0.2%	-0.2%	0.1%	0.0%	-0.1%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.3%
5	0.1%	0.1%	-0.1%	0.0%	0.4%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.7%
6	-0.2%	-0.1%	0.0%	-0.1%	0.0%	0.2%	0.2%	-0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
7	-0.1%	0.0%	0.1%	0.0%	0.1%	0.0%	0.3%	0.1%	0.1%	0.0%	-0.1%	0.0%	0.5%
8	-0.1%	0.0%	0.0%	0.0%	0.0%	-0.1%	0.1%	0.3%	-0.1%	0.0%	0.0%	0.1%	0.2%
9	-0.1%	0.0%	0.0%	0.0%	0.0%	-0.1%	0.1%	0.0%	0.6%	0.0%	0.0%	0.0%	0.5%
10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.1%	0.0%	0.3%
11	-0.1%	-0.1%	0.0%	-0.1%	0.0%	0.0%	-0.1%	0.0%	0.0%	0.2%	0.1%	-0.2%	-0.2%
12	-0.3%	-0.4%	-0.2%	-0.2%	0.0%	-0.1%	-0.3%	0.0%	-0.1%	0.0%	-0.2%	0.0%	-1.8%
Grand Total	-0.1%	0.0%	-0.1%	-0.4%	0.5%	-0.3%	0.2%	0.2%	0.5%	0.4%	-0.3%	-0.7%	0.0%

5.3 Calibration

The calibration of a travel forecasting model is always a challenging task. Even relatively simple trip-based models have a non-trivial number of parameters and components interacting with each other to produce ultimate measures of interest. The challenge of calibration grows with complexity of a model where complexity can mean the number of variables, the number of component models, or the number of connections between component models. Activity-based models are very complex in each of these dimension, particularly the lattermost. The calibration of activity-based models is therefore challenging in several ways.

One of the key challenges of calibrating an activity-based model is diagnosing what is wrong or choosing what parameter is in need of adjustment when aggregate model results do not agree with observations. Even relatively simple issues become more complex. In a trip-based model if highway assignments reveal the model is low versus counts, there are already several but a relatively short list of things to check – input socioeconomic data, trip rates, trip lengths, mode shares. In the same scenario in an activity-based model, the list becomes much longer – input data, synthetic population, day patterns, number of tours, number of intermediate stops, primary destination “trip” lengths, intermediate stop trip lengths, tour mode shares, trip mode shares. Moreover, the number of parameters or variables that could be at fault in each of these component models are greater than in their traditional counterparts. Diagnosing more subtle problems like why there are too few transit trips to downtown in the morning from the northern suburbs becomes even more complex.

Another challenging aspect of calibrating activity-based models is the high level of integration between the component models. Although as this is clearly a good thing from a theoretical perspective, as discussed in Section 6.2 and 6.3, it makes calibration more difficult because adjustments to one model component also affect other model components. If the analyst suspects that trip lengths may be too long, they adjust destination choice models to shorten trip lengths, but this adjustment also has the effect of lowering tour rates or intermediate stop rates which then necessitates compensating adjustments to those components. As a result of the high level of integration of the components, it rarely possible to adjust just one model component or parameter, but rather calibration must generally proceed in iterations through the entire model system.

Finally, the difficulty of calibrating activity-based models is exacerbated by their generally long run times. The time it takes to run the model to test each adjustment can be substantial and significantly limit the number of adjustments that can be tested during a set amount of time such as a week or month. For testing many components, thankfully model run times can be reduced by running the activity-based model with only a sample rather than the full synthetic population. However, some calibration tasks such as adjustments to the spatial models require a large sample or full population run to ensure that sampling does not lead to non-representative results.

None of the foregoing challenges have stopped a significant number of activity-based models from being calibrated. However, these challenges do entail that the calibration of activity-based models takes more time and therefore if done by consultants, costs more, than to calibrate traditional models. Moreover, some still might question whether being able to replicate base year conditions and perhaps produce apparently reasonable forecasts or sensitivity tests guarantees that the right parameters were adjusted.

5.4 Cost

The cost of developing, maintaining, and applying travel models is always an important consideration. All transportation agencies operate in an environment of constrained funding and as such it is important to weigh the benefits of any investment of funds against the costs.

Moreover, the cost of forecasting models can be significant in absolute terms. However, at the same time, they can more than justify their costs if they help avert a costly project that would prove ineffective, help right-size projects to avoid excess right-of-way or construction costs, or help a region improve its roadway safety or its public health.

There are several factors that have significant impact on the costs for a model. Some of the most significant drivers for any model development or improvement project are how much of the new model will be taken from the old model and how much the new model components will make use of standard scripts/software versus being custom programmed from scratch.

Although it seems obvious once stated, it can be easy for agencies to sometimes overlook the fact that an incremental improvement to a subset of the components of the existing model will usually be less expensive than developing a whole new model (although there is an exception to every rule, and sometimes updating a highly customized model may involve more effort than implementing a new standardized model). If a model has good networks that have been validated to real travel time data, so that only the demand components need to be updated this should cost less than if both network and demand components need updating. If only select updates are made to the demand models, e.g., replacing gravity models with destination choice models and linking the non-home-based distribution to the home-based distributions, this should also generally cost less than a complete new set of demand model components. In terms of the implications for model design, in some cases this can mean that a hybrid advanced trip-based design may be less expensive than an activity-based model because it would only require the update/replacement of a subset of the model components. Advanced trip-based models and to some extent hybrid model designs in general can generally be achieved through one or more incremental updates to an existing trip-based modeling system; whereas, to move to an activity-based model necessitates replacing all the resident demand components.

The use of standardized (and to a similar but lesser extent, borrowed) software or scripts can also result in important cost savings. Any time a project involves new scripting/coding it entails significant extra effort and cost for debugging which can be avoided by using standard or borrowed scripts. Currently, standardized software/scripts exist for several traditional trip-based designs (in different software packages) and for standard activity-based models. There are some standard scripts for hybrid models/advanced trip-based components in some modeling platforms but not others. In general, this can mean that if an agency is updating all of their demand components that a standard activity-based model or standard trip-based model may offer cost savings versus competing model designs.

The size of the modeled area and model complexity do also play an important role in the price of model development, but often not as significant a role as the foregoing issues. The size of the modeled area can factor into the cost of model development in several ways. One of the crucial issues is that the time for traffic assignment is longer for larger and more congested areas, and this added model runtime translates in to added time for calibration because it limits the number of test runs that can be completed in a given set of time such as a week (particularly when the results of each test are important in determining the next test). The size of the modeled area also effects runtime through the number of zones (even for standard activity-based models, due to the use of zones in skimming), although this effect is usually less significant than the assignment run times. Larger model areas also often face more complex travel patterns (due to more diverse travel options and more competition/congestion on the network) which can require more effort to validate that a model is correctly reproducing.

Although it is far from the only driver, the complexity of a model is also still an important factor in the cost of a new model. As mentioned in the previous section, more effort is required to calibrate activity-based models than simpler model designs with fewer components and parameters.

However, it is important to note than the cost of standard activity-based models has decreased significantly in recent years due to economies of scale, so while five to ten years ago almost all activity-based model implementations cost more than $500,000 and some more than $1,000,000; in some circumstances (e.g., small/mid-sized areas with good existing networks and auxiliary demand models, etc.) agencies can now implement standardized activity-based models for $300,000 or even less, although re-estimating a full set of parameters or developing new software will still generally require $500,000 or more.

5.5 Staff Skills and Training

Many agencies do recognize that staff skill and training in general are important issues in considering their model design. However, this consideration often remains rather vague and sometimes amounts to a suspicion that activity-based models require some mysterious special domain knowledge. The knowledge / skill set that is required for basic maintenance and use of an activity-based model need not be mysterious and can be broken down into four categories.

The first skill or knowledge-based is knowledge how to maintain and use the network model and associated software package it is implemented in (e.g., Cube, EMME, QRS2, TransCAD, Visum, etc.). This skill is required of all travel model designs from traditional trip-based models to activity-based models and therefore does not pose a special requirement for any of them.

The second skill required is a basic understanding of logit discrete choice models and perhaps how to make basic calibration adjustments to them. This requirement often looms large in people's perception of the necessary skills required for advanced modeling. However, many modelers have some level of familiarity with logit models from the mode choice component of a traditional trip-based model, and can often pick up the requisite basics for most model maintenance and analysis. Estimation of choice models does require special expertise, but this is not a routine task once a model has been developed. So, while this remains a consideration for advanced model designs, whether activity-based or hybrid, it may not be as significant a requirement as some fear.

More important in many cases than knowledge of discrete choice modeling is knowledge and skill with the programming language(s) used to implement the model. Although programming is usually thought of as being only necessary for model development, in depth analysis for major projects often requires at least some programming to add special new reporting functionality or diagnostics for project level validation, etc. A modeler who does not understand the programming language in which the model is implemented will generally have a limited understanding of their model and require more assistance for various modeling tasks. There is an important difference in the programming skills required by different model designs. Traditional trip-based models and hybrids both generally require only one programming language – typically the scripting language associated with the network modeling software package. Activity-based models, in practice (with one or two possible exceptions), require the knowledge of a second programming language in addition to the network modeling software's scripting language. While many modelers have a working knowledge of two or more programming languages, finding candidates who have working knowledge of exactly the two a particularly agency's activity-based model uses (e.g., GISDK and C# or Cubescript and Java) becomes more challenging. A staff person without skill in both languages will either need to learn one or both or remain limited in their ability to do in-depth analysis or "get under the hood".

The final category of knowledge required for advanced model systems is knowledge of that particular modeling system. Some of this knowledge is general to a model design (e.g., knowledge of activity-based models in general) but much of the pertinent knowledge is specific to the actual system (e.g., knowledge of DaySim or CT-RAMP or TourCast, etc.). This level of knowledge must often be acquired simply by becoming familiar with an agency's model; however, some ability to find and hire staff with this knowledge is slowly developing with the standardization of activity-based modeling platforms and the growth of their associated user communities discussed in the Section 5.9.

5.6 Runtime

The runtime of a model is another key practical concern. Runtime limits the usefulness of a model. Long run times can prevent an agency from being able to provide timely answers to important policy questions and can limit the number of analyses that can be performed during a given period of time. Moreover, longer runtimes increase the risk associated with user errors or other problems. Any modeler who has worked for long will have ample examples of cases when a model was run only to discover an incorrect input file was used or something was wrong with one of the inputs, etc. If the model runs in an hour, an hour is lost. If the model runs for two days, two days are lost. The difference is significant.

While parallel processing and 64-bit memory have helped reduce model runtimes to some extent, there are also a significant number of travel modeling processes that are order dependent and do not lend themselves to parallelization. Even with a relatively large array of processors and ample RAM, travel models remain computationally challenging applications that can require significant runtime.

It is important to recognize that the runtime for most models tends to be largely dominated by the assignment step, and to the extent that this is true for a region, the choice of demand model architecture or design may have only a marginal effect on overall runtimes. However, in many regions, although assignment may still be the largest component of runtime, the demand models still have a significant runtime contribution.

In relation to demand model design, as might be expected, more complex models tend to require more runtime. Traditional trip-based models tend to be fastest. Hybrids tend to offer intermediate runtimes, and activity-based models tend to take the longest, although differences can vary depending on the size of the modeled population, the number of zones, and a few other factors. Trip-based models with a very large number of zones, coupled with significant market segmentation can sometimes be as computationally intense as activity-based simulations.

There have been some real improvements to activity-based model runtimes in recent years from software optimization of some activity-based model software packages, but despite these improvements and gains from having more processors, activity-based models still often require significant runtime. At the fast end, an activity-based model for a region with less than 500,000 people, with limited congestion so feedback converges in three iterations, might run in just under three hours on a high-end machine. Activity-based models for areas with several million residents and a large degree of congestion could generally be expected to run for a day or more, although trip-based models for such regions may also require relatively long runtimes.

5.7 Simulation Variation

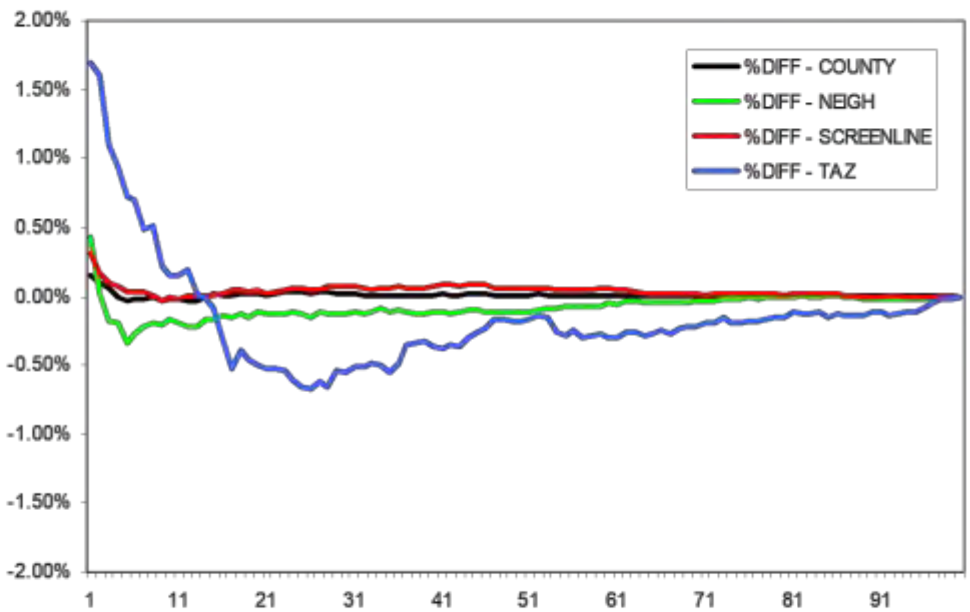
Because activity-based models use Monte Carlo simulation which involves random number draws to realize probabilities, an element of random variation is introduced in their results. As a consequence, their results can be expected to vary from run to run. Although technically, a model can be made to reproduce a run by fixing the random seed, this does not eliminate issues related to simulation variation because it does not guarantee that a single run is a representative or average result.

The practical significance of simulation variation depends greatly on the application. As can be seen in Source: email correspondence with Joe Castiglione

Figure 9, testing has shown that even moderate scale results are only modestly impacted by simulation variation (e.g., TAZ level Peak VMT varied less than 2% in this example). So, for many applications with higher to medium scale performance measures, simulation variation may not be a significant issue.

However, for some applications, simulation variation can pose a significant challenge. The most problematic applications are those that involve small scale results (e.g., intersection turning volumes) and measuring change between two runs or alternatives (as in benefit cost analysis). In cases such as these, multiple runs of the model, varying the random seed, may be required to ensure that results are stable and representative rather than simply an artifact of random variation in results.

Alternatively or in addition, simulation variation can be reduced by over-sampling in the demand simulation. This is essentially equivalent to making multiple runs of the activity-based demand model and averaging them to produce the demand used in the network assignment. This approach entails some additional run time, but significantly less than making multiple full model runs (because assignment is large portion of a full model's runtime). This approach was recently successfully applied in BKR's activity-based model to help reduce simulation variation and its impacts on traffic impact analysis.



Source: email correspondence with Joe Castiglione

Figure 9. Simulation variation: PM peak period volumes by geography - % difference from final mean.

Thus, the importance of simulation variation can vary widely for different agencies. An agency which uses their model mostly for regional planning analysis may not find simulation variation much of an issue, while on the other hand, an issue that routinely uses their model to examine traffic impacts of developments on intersections (e.g., to determine the need for a new turn lane, etc.) may find simulation variation a very significant problem.

5.8 Staging

Another difference in model designs that can be important for some agencies in planning the funding of their new model is the ability or inability to update their model through a series of projects or phases over more than one year. The difference in this regard is that an agency with an existing trip-based model can upgrade their model to convert it into a hybrid model in one or several steps which can be spread over several years, with a working model available at each stage. This incremental approach to model improvement can be used to accomplish significant model design improvements without requiring a large expenditure in a single budget year. The incremental improvement of a model from a traditional to a hybrid design also has the advantage of providing a more graduated learning curve for agency staff who need only familiarize themselves with more limited updates at each stage rather than adapt to an entirely new modeling system. In contrast, if an agency has an existing model but wants an activity-based model, the new activity-based model will need to be developed (or borrowed) in full, using only the network/assignment models from the existing tool. This effort can be spread over multiple years, but there will not be a useable product until the end of the project and at that point, agency staff and other model users in the region will need to transition to an entirely new demand modeling framework.

5.9 User Communities

The number of people or size of the community working with a particular model design is also worth considering when thinking about model design. The existing user community for a model design can be beneficial to others joining that community in at least a couple different ways.

First, a larger user community helps ensure that a model is well tested. Any responsible model developer will engage in various sorts of basic testing before delivering a model, but it is often impossible to anticipate and test every possible use case and for that reason it is not uncommon to only discover certain kinds of subtle issues with a model through its actual application. This can apply both to a model framework as well as its implementation in particular software. The more people who have used an approach the more likely errors or issues will have been found and fixed or at least addressed.

In terms of general frameworks, standard trip-based models clearly have the largest user community and it should be clear from the rest of this document that the issues with trip-based models are well documented and understood. No other model design has seen the magnitude of applications as traditional trip-based model. However, standard activity-based models have now been used in over a dozen metropolitan areas, in some cases for as long as 15 years, so their user community is not only growing but also increasingly well established and understanding of the limitations and issues with standard activity-based models has developed at least enough to provide motivation for the development of both hybrid models and advanced or next generation activity-based models.

In terms of implementation of a model design in software, there is more variation. There are many traditional trip-based models which despite relying on a well-established framework were implemented from scratch and for that reason are not as well tested as some other models. Some states (such as Ohio and Florida) have developed standard trip-based model implementations in code for a particular software. The user community for these models ensures a high level of testing. Standard activity-based models have tended to be more standardized than trip-based models as many agencies have attempted to mitigate development costs by borrowing code from other agencies. The result is that some standard activity-based model implementations have more than half dozen agencies using not only the same framework but also the same code base. As a result, these agencies models have been 'tested' in a way that agencies with unique/custom models have not. There is also one hybrid model code base which is in use by four MPOs, which offers similar benefit.

Second, a larger user community also helps ensure an adequate pool of experienced professionals for hiring as agency staff and/or hiring as consultants. In this regard again, the user community could refer to either a general framework (e.g., four-step) or an actual implementation (e.g., Florida's FSUTMS). Professionals familiar with a model framework offer one degree of relevant experience while professionals familiar with a particular implementation offer another degree of relevant experience. With reference to general model designs or frameworks, it is clear that the user community for traditional models is still by far the largest, while there is an established and growing community of standard activity-based model users, and much smaller user communities for other model designs.

5.10 DTA Integration

While the focus of this guidebook is specifically on the design of the demand components of travel forecasting models, the representation of supply or networks is equally important. The challenges of increasing congestion and new potential solutions such as express lanes with time varying tolls coupled with the limited ability of traditional static assignments to address these scenarios is leading some agencies to explore the use of dynamic traffic assignment (DTA) tools. Despite advances in computing power, DTA remains extremely computationally challenging for large, regional networks, and these computational challenges still generally prevent agencies from using DTA as part of their standard regional model. However, DTA is seeing increasing use for project level and subarea analysis and may eventually prove more feasible for regional applications.

While DTA can be used with demand models of any design, the level at which DTA can be integrated with the demand components of a model are limited by the complexity of the demand model design and specifically its treatment of time. When DTA is used with a traditional trip-based model, the DTA can only provide large multi-hour peak period travel times to the demand model just like the static assignment model and the demand model provides only trip-tables for these same periods which must be disaggregated by some means prior to input into the DTA. Standard activity-based models can share information with DTA at much finer time slices. For instance, the DTA may be able to provide travel times for 30-minute periods and the ABM may be able to produce trip tables for the same period or even more finely. With communication at this level, congestion patterns in the DTA can have some impact on timing of activities and travel in the demand model; however, travelers in the demand model still only see average travel times for a particular time period. Advanced next generation activity-based models are now being designed for even deeper integration with DTA so that individual travelers are represented consistently between the two models so that some travelers experience and react to travel times faster and slower than the average. At the time of the writing of this guide, given the computational challenges of regional DTA, the ability to achieve deep integration with DTA may be a somewhat more theoretical concern, but for at least the handful of agencies developing these next generation systems, there is hope this will ultimately prove a practical consideration.

It is, however, also important to note on this issue that while behaviorally appealing deep integration of ABMs and DTAs is theoretically possible and has been demonstrated at some level in some limited cases, the practical evidence over the past decade or two between TRANSIMS and the multiple SHRP2 C10 projects suggest that successfully achieving deep level integration may be possible, but only with very significant investment of effort. Moreover, important questions about the equilibration of supply and demand in these systems remain, so it may be some time before this becomes a truly practical issue.

5.11 Summary of Practical Issues

Table 3 summarizes the relative advantages or disadvantages of the general model designs with respect to key practical considerations. As noted above, the reader should not rely solely on the figure but refer to the full discussion of these issues later in this guide for a more complete understanding of these issues. Again, it is important to understand the limitations of the three-star scale or scheme to represent the complex issues involved. For instance, in no way should the reader infer or assume that all issues are equally important such that average star score would represent something meaningful.

Table 3. Relative advantages of model designs with respect to practical issues.

Practical Consideration	Traditional	Hybrid	Activity-Based
Forecast Accuracy	★★	★★	★★
Data Needs – Spatial/Socioeconomic	★★★	★★★	★
Data Needs – Parking	★★★	★★	★
Data Needs – Estimation/Surveys	★★★	★★	★
Data Integration – Big OD Data	★★★	★★★	★★
Calibration	★★★	★★	★
Cost	★★★	★★	★
Staff Skill / Training	★★★	★★	★
Runtime	★★★	★★	★
Simulation Variation	★★★	★★★	★
Staging	★★★	★★★	★
User Communities	★★★	★	★★
DTA Integration	★	★★	★★★

6.0 Theoretical Issues related to Model Design

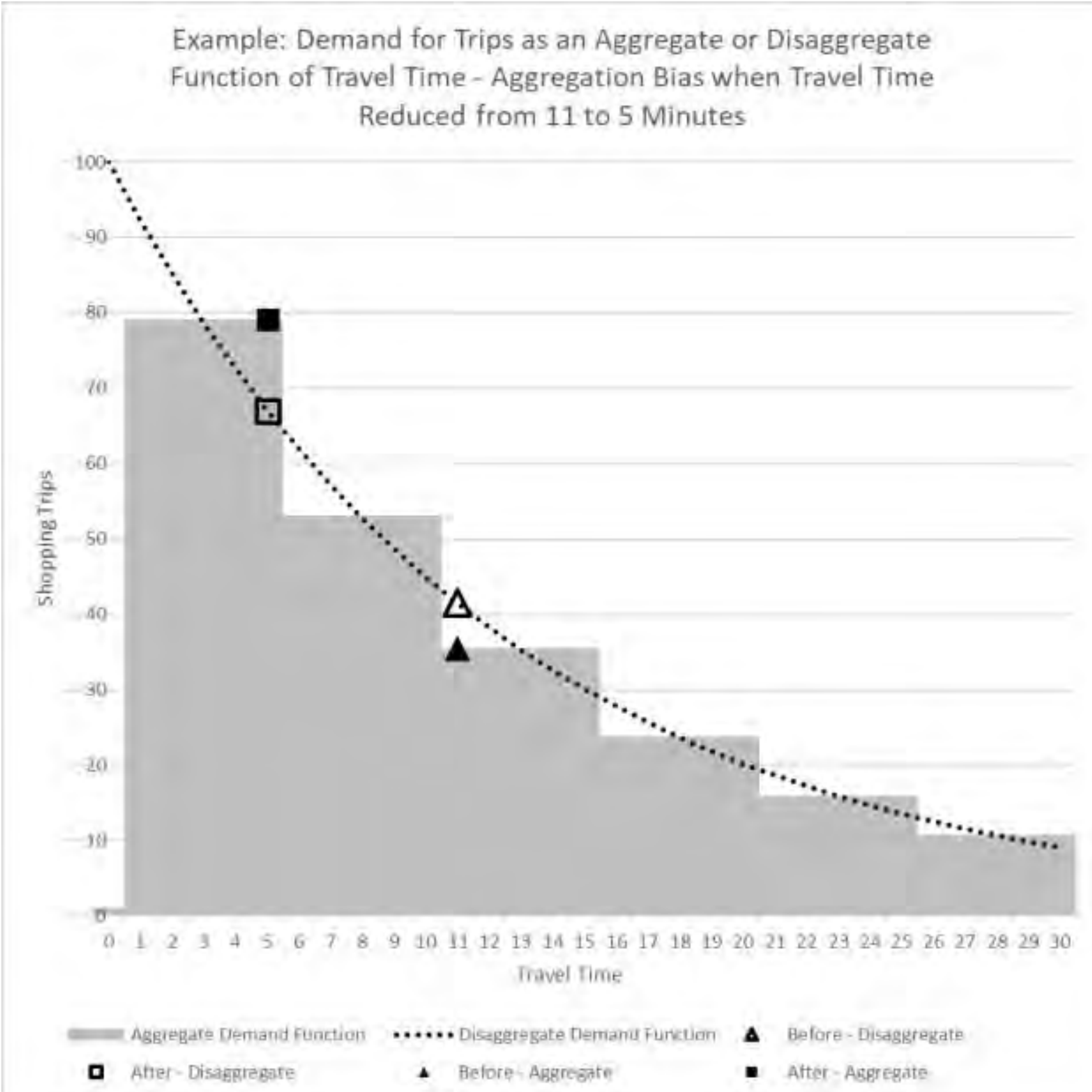
While travel models developed initially and remain primarily practical tools for forecasting travel, academics and other researchers including some practitioners have had important insights into the ways in which these tools represent travel and some of the issues that they have identified can have important practical impacts on the forecasts that models produce. This section reviews the major theoretical issues that have been identified as being related to the design of travel models and their implications for the different families of model design. These issues were primarily identified as limitations or inconsistencies implied in traditional trip-based models and have served as some of the key motivations for more advanced model designs. For an example which uses most of the following to argue for the adoption of activity-based models, see for instance, Vovsha *et al*., 2005. For the purposes of this report, these issues are presented in terms of aggregation and consistency, as these are often used following Vovsha *et al*., 2005, even in arguing for simpler model designs.

6.1 Aggregation

Aggregation bias is perhaps the single most cited critique of traditional travel models by academics and researchers, and perhaps the least well understood in practice. The effects of aggregation bias, can be quite significant, however, in practice. At the same time, aggregation affords many of the practical benefits of simpler models discussed in the previous sections. The issue of aggregation is one dimension, therefore where there must be a sort of trade-off analysis between the practical advantages of aggregation and the issue of aggregation bias.

Examples may prove helpful in elucidating aggregation bias. Mode choice is one dimension where aggregation bias can often be problematic because some of the items of interest (mode shares for active modes) are small, so even relatively small effects of aggregation bias can have large impacts relative to the items of interest. Consider the probability of transit use for a zone (an aggregation) with 100 households with an average of 2.2 cars per household. Most forecasters and their models would assume almost no transit demand from such a zone. However, if it is also known that those 100 households are comprised of 5 households with no cars, 15 households with one car, 50 households with two cars, 20 with three cars, 5 with four cars, and 5 with five cars, either a model or forecaster might reasonably expect that the five carless households might generate some transit demand.

Examples like this are helpful both because they illustrate the practical implications of aggregation bias in terms of poor forecasts and because it illustrates the basic nature of aggregation bias. Aggregation bias ultimately is simply a way of describing forecasting errors that arise from the loss of information when things are grouped together. Mathematically, aggregation bias can generally be understood as arising from the fact that for non-linear functions the average over the results of the function applied to a disaggregate distribution of data is not equal to the results of applying the function to the average of the distribution (i.e., $f(avg(x)) \neq avg(f(x))$). Since demand function, including travel demand functions, are almost always non-linear in practice, aggregation of inputs to the demand model (including intermediate inputs from one component of the model to the next) results in errors.



Source: FHWA

Figure 10. Example of aggregation bias from spatial aggregation of a demand function for shopping trips.

A second example is provided to illustrate spatial aggregation bias (Figure 10). The aggregation in the example could arise simply from using a zone system to represent space or it could be the result of model specification (e.g., the use of friction factors). The example compares the forecast demand for travel between OD pairs (or travel to a destination for a given origin). The curve in blue illustrates a continuous/disaggregate function. The aggregate step function is illustrated in red. The demand prior to a network improvement is shown by triangles, green based on the continuous function and black based on the aggregate function. The demand after the network improvement reduces the travel time from 11 to 5 minutes, is shown with squares, again with green based on the continuous function and black based on the aggregate function. The disaggregate function predicts 41 trips before the improvement and 67 trips after the improvement for an increase of 26 trips; while the aggregated function predicts 36 trips before the improvement and 79 trips after the improvement for an increase of 44 trips. Despite what could at first glance be thought a reasonable aggregation/step function to represent the actual continuous function, the aggregation error is 70% in this example.

Examples like these have made many academics deeply concerned with the large degree and many types of aggregation in traditional models. Traditional models aggregate continuous space into zones, aggregate discrete individuals into very few, large market segments, and aggregate continuous time into very broad periods of several hours or an entire day. These aggregations certainly cause some degree of aggregation bias. Spatial aggregation likely causes some error in the spatial distribution of trips and also greatly limits the ability of traditional, zone-based models to represent walk, bike, and walk access transit trips which typically depend significantly on the cost of travel within zones. Demographic aggregation of travelers can bias models when demographic characteristics of travelers that significantly affect their behavior are omitted from the specification of component models. This can affect the generation of travel (e.g., when cross-classification limits the specification to just two or three explanatory variables) but tends to be even more of a concern in later components such destination, mode, and time-of-day choices. Temporal aggregation does not allow the model to represent the temporal distribution of travel well and causes insensitivity to policies or scenarios (e.g., congestion, time specific parking costs/tolls, aging population) which might change it.

At the same time, the amount of aggregation bias depends significantly on the curvature of the demand function(s) and the aggregation scheme(s). It is also possible to construct examples in which aggregation introduces relatively little error. Thus, while examples like above and some more realistic ones (e.g., Koppelman, 1974) are certainly enough to establish aggregation bias as a real concern for traditional travel models, some may argue that before and after analyses, or at least very detailed sensitivity analyses, would be required to truly understand the level of significance of aggregation bias in a particular travel demand model. It is generally not possible to understand aggregation bias from base year validation alone since both aggregate and disaggregate models can be calibrated to represent the base condition. However, this calibration does not mean that the model will necessarily respond reasonably to changes in land use, transportation improvements, or other assumptions.

In summary, it is clear that aggregation bias is a concern and a cause of some error and various limitations in traditional models, but the amount of error and its significance may vary somewhat depending on the particulars of individual models (e.g., the resolution of the zone system, market segmentation scheme, etc.). Concern for aggregation bias has motivated improvements to trip-based models (e.g., increases in the number of zones, adding market segmentation) as well as the move by some to disaggregate or partially disaggregate demand models.

6.2 Consistency within Trips

Beyond aggregation bias, most of the theoretical issues with bearing on model design have to do with inconsistencies in the way that traditional models represent travel. As with aggregation, consistency or integration may be thought of as a dimension of tradeoff which the practical advantages of less consistent and integrated models (in terms of the ease of calibration, etc.) must be traded off against the theoretical concerns regarding consistency.

The first type of inconsistency in travel models are inconsistencies within the modeling of individual trips. These inconsistencies arise from the fact that while each component model or step in traditional trip-based models depends on the preceding step(s), the earlier components or travel decisions (generation – whether to make a trip, destination choice – where to go, etc.) are independent of the later components or choices. Sometimes this issue of consistency within trips is discussed in academic literature in terms of vertical integration or integrity of the model.

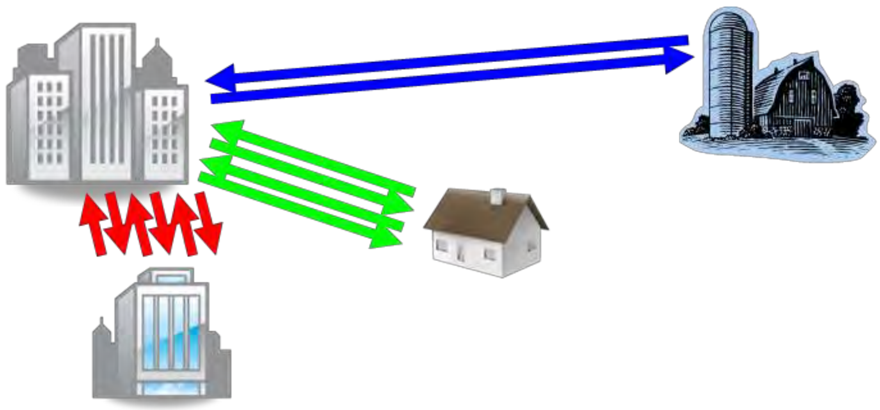
The best known issues related to within-trip consistency is the potential for the travel times used in trip distribution/destination choice and mode choice to be inconsistent with the travel times resulting from the final assignment. This obvious inconsistency has been widely addressed by the addition of feedback loops in which all or parts of the demand model are iterated with the assignment component. So long as the feedback loop includes a valid averaging mechanism, this can guarantee the model converges on a consistent solution (see Boyce and Bar-Gera, 2005; Boyce *et al*., 2008, etc.). (Integrated models in which demand components essentially run within assignment iterations have also been demonstrated but have seen limited adoption.) Activity-based and hybrid models also generally adopt this feedback loop approach to dealing with this issue. Thus, this issue, while well-known, has little bearing on the decision between trip-based, hybrid, and activity-based frameworks.

Another issue that some modelers have faced in practice is that in trip-based models as they were originally and still often implemented, destination choices (or trip distribution) are independent of mode choices. Thus, a traveler with no access to a car can choose to visit a location to which they cannot walk or take transit. This can happen if trip-distribution or destination choice is based only on highway travel time and/or distance. This has been addressed in practice in two ways. Some have addressed this issue using less formal generalized costs approaches (e.g., Bhat *et al*., 1998), but most have implemented nested logit models of destination and mode choice (e.g., Lawton *et al*., 1999) or equivalently, incorporated the mode choice logsum as a variable within destination choice. There are several problematic issues, however, with this approach. The most common being that the nesting hierarchy is asserted (as mode under destination choice) and likely as a result the parameter on the mode choice logsum in destination choice must also be asserted. It is also difficult to estimate the nested joint mode and destination choice model simultaneously and so the components are often estimated sequentially which can cause additional problems (particularly if shadow prices or accessibilities are included/required in the destination choice model specification). Some models, mostly hybrids, have dealt with some of these issues by reversing the choice hierarchy as discussed in Section 2.3 above. Activity-based models typically include mode choice logsums in their destination choice models and thus have all the same advantages and disadvantages of this approach, but offer no advantage over advance trip-based models which have adopted the same approach. Hybrid models which reverse the choice hierarchy may actually offer the best solution to this issue, although there is no reason ABMs could not also adopt the reverse hierarchy or even more comprehensive latent class approaches.

There can also be issues related to the inconsistency of the time-of-day with other aspects of the trip. The most common of these encountered in practice occurs when a model assigns transit trips to a time of day during which there is no transit service. Various models fix this in different ways, typically with rules. Although errors are rarely clear enough to be caught in practice, models can also assign times of day to trips that do not provide the activity/trip purpose at that time of day. For instance, shopping trips to a particular zone may be assigned to the night period even though all of the shops in that zone are only open during the day. Although in practice, activity-based models still use some ad hoc rules similar to trip-based models to address some of these issues, there can be no disputing that in general, activity-based models do offer superior treatment of and consistency of temporal choices with other dimensions of travel when compared to simpler models designs.

6.2.1 Sensitivity to Land Use

The final issue of consistency within trips does not necessarily appear immediately to be a problem of consistency, but from a theoretical perspective is helpfully understood this way. Traditional trip-based models do not consider accessibility in trip generation. In other words, in four-step models, how long it takes a traveler to get to a store, whether they can walk, or take a bus, etc., has no impact on how frequently the traveler goes shopping. In reality, people who can walk to a store or make a quick stop to shop on their way home from work, etc., often do and shop more frequently. People who live in relatively rural areas that have to drive longer distances to get to a store tend to plan their shopping trips and make them less frequently. This ultimately boils down to the consistency between generation and the destination and mode choices. If there are no destinations you like nearby, you are less likely to travel in the first place.



Source: Bernardin, V., An Accessibility-based Approach in the New Knoxville Travel Model. Presented to the Northwestern University Transportation Center, February 2009.

Figure 11. Trip frequency and length by area type/urban form.

Since urban form in terms of density, walkability, etc., is an important aspect of urban planning, there is a general desire and need for travel forecasts to be sensitive to urban form or land use patterns. Traditional models will predict the same number of trips generated by a two-person, middle income household regardless of whether that household lives in a walkable urban environment or a sprawling suburban development. In reality, the household in the urban area is likely to make more, shorter trips which are more likely to be by non-motorized modes. The household in the suburban area is likely to make less trips, but those trips will likely be longer and almost certainly by private auto. The implications of these different travel patterns in terms of the travelers' physical health and environmental impacts such as emissions are substantially different. Traditional trip-based models' blindness to these realities is a very legitimate critique, and one which more advanced models can address. However, the key to addressing these issues is the incorporation of accessibility variables in component generation and distribution models, and this can be done within a trip-based framework as well as in an activity-based or hybrid framework.

6.3 Consistency of Trips within Tours

In reality, all person travel must take place in continuous trajectories through space-time which are bound to form closed circuits or tours to the extent that travelers return home to sleep every night. Although travel can be broken down into trips from one location to the next, the location, mode, and timing of each trip is importantly related to the trips prior to and following it on the same tour from when the traveler leaves home to when they return home. If a person travels from A to B, they cannot then travel from C to D without first making a trip from B to C. If a traveler drives their car to work in the morning, it is highly unlikely that they will take transit home in the evening.

However, because the traditional trip-based approach models each trip independently, it is capable of predicting highly improbable or even physically impossible sets of trips. While this inconsistency of traditional trip-based models with tours is widely cited as a motivation for hybrid and activity-based modeling frameworks, the implications of this general inconsistency are not always immediately clear. Therefore, the importance of the consistency of trips within tours is explored in the following subsections for each dimension of travel.

6.3.1 Spatial Consistency of Trips within Tours

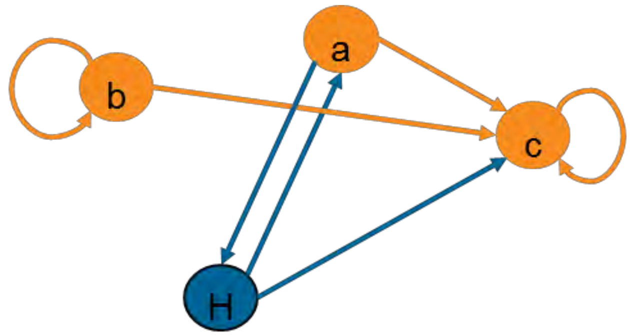
The spatial independence of trips within traditional models is perhaps their most serious criticism because it implies that their predictions can be physically impossible. It is helpful to illustrate this, however, as it is not necessarily immediately obvious that treating trips independently can result in the prediction of physically impossible open tours. This can be demonstrated (as in Bernardin, 2008, which contains a more complete discussion for the interested) most simply by considering that the trip tables produced by traditional models do not observe any properties. Neither singly or doubly constrained gravity models actually impose any special structure on their resulting trip table since trip generation can produce any row and column vectors which bear no special relationship to each other beyond the basic requirement (for doubly constrained models) that their sums are equal. Thus, basically any matrix, such as illustrated in Figure 12, could be produced by a gravity model given some production vector, attraction vector, and impedance matrix.

	H	a	b	c	
H	0	1	0	1	2
a	1	0	0	1	2
b	0	0	1	1	2
c	0	0	0	1	1
	1	1	1	4	7

Source: Bernardin, V., An Accessibility-based Approach in the New Knoxville Travel Model. Presented to the Northwestern University Transportation Center, February 2009.

Figure 12. Possible trip table from a traditional model.

The figure presents seven trips (H-a, H-c, a-H, a-c, b-b, b-c, c-c). There is no way that all seven of these trips can be arranged into one or more tours. Real travelers could not produce this travel pattern, but a traditional trip-based model can. It can be helpful to illustrate the pattern, as in Figure 13.



Source: Bernardin, V., An Accessibility-based Approach in the New Knoxville Travel Model. Presented to the Northwestern University Transportation Center, February 2009.

Figure 13. Illustration of the seven trips from the previous figure.

Taking H as the zone and a, b, and c are destination zones, it is clear that one traveler does not return home. A traveler departs from b despite never having arrived there. People travel to c but never from it – a frightening black hole. The ability of trip-based models to produce patterns like this is clearly a significant problem.

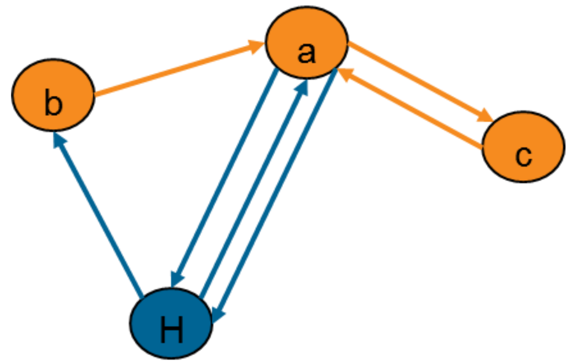
In contrast, trip tables produced by hybrid and activity-based models observe a special property that their row and column sums are identical as in Figure 14.

	H	a	b	c	
H	0	1	1	0	2
a	2	0	0	1	3
b	0	1	0	0	1
c	0	1	0	0	1
	2	3	1	1	7

Source: Bernardin, V., An Accessibility-based Approach in the New Knoxville Travel Model. Presented to the Northwestern University Transportation Center, February 2009.

Figure 14. Trip table consistent with tours.

Like the previous example, seven trips are presented (H-a, H-b, a-H, a-H, a-c, b-a, c-a). These seven trips could be produced by either of two different sets of tours: [H-a-H & H-b-a-c-a-H] or [H-b-a-H & H-a-c-a-H]. As before, it is helpful to illustrate the pattern in Figure 15.



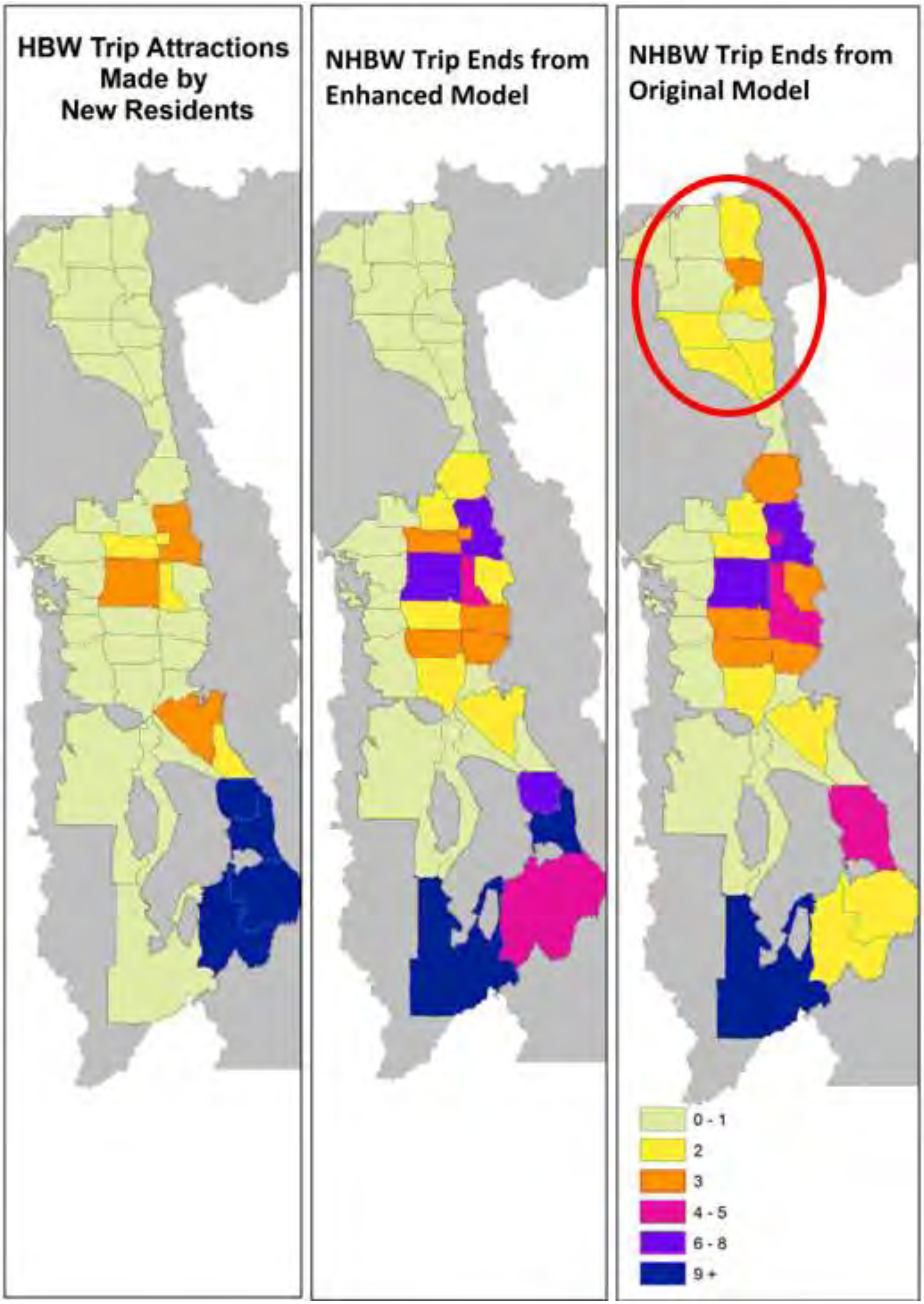
Source: Bernardin, V., An Accessibility-based Approach in the New Knoxville Travel Model. Presented to the Northwestern University Transportation Center, February 2009.

Figure 15. Trips from the previous figure consistent with tours.

It is clear that travelers could indeed generate this pattern, in contrast to the prior example, and it can be proved (Bernardin, 2008) that any model that generates total trip tables with identical row and column marginal sums is consistent with some set of tours. Both hybrid and activity-based models can demonstrate that they meet this criterion, albeit in different ways (and further, that the probability of "pathological" tours of only non-home-based trips approaches zero). Hybrids ensure consistency at some level of aggregation (zone, district, or the entire population) by creating non-home-based trips as the product of two distribution or spatial choice models; while activity-based models build individual tours by choosing a primary destination and then inserting intermediate stops.

Another aspect of the spatial consistency trips within tours is that travelers choose their destinations to minimize the travel cost of their entire tour, rather than trips independently. Activity-based models closely approximate this with their sequential process of tour building. Hybrid methods are also capable of incorporating this effect, but it requires the use special accessibility variables in their destination choice models (Bernardin *et al*., 2009).

It is sometimes helpful to illustrate the issue in practice as well as in theory. In another issue of TMIP's How-to series, illustrating simple methods for improving non-home-based trips in trip-based models (and thereby make them hybrid advanced trip-based models), a examples scenarios were run with the model for the Salt Lake City MPO, the Wasatch Front Regional Council, to compare predictions of the original, traditional trip-based model with the hybridized advanced trip-based model in response to major new residential development in the far south of the model area. In Figure 16, at the left, the reader can observe that most HBW trips from the new residential growth in the far south of the model are attracted to the jobs in the south of the model, near Provo (in blue) and some are attracted to downtown Salt Lake City (orange and yellow). In the center of the figure, it can be seen that the hybrid or advanced trip base model predicts NHBW trips in consistent locations, in Provo and downtown Salt Lake City and a few in areas in between. In contrast, at the right of the figure, the original trip-based model predicts new NHBW trips in Ogden in the far north of the model area despite the fact that none of the new HBW trips are attracted there. These NHBW trips in the Ogden area (circled in red) imply a physically impossible travel patterns in which travelers goes to work in Provo or Salt Lake City and then magically appears and makes trips in Ogden despite never going there.



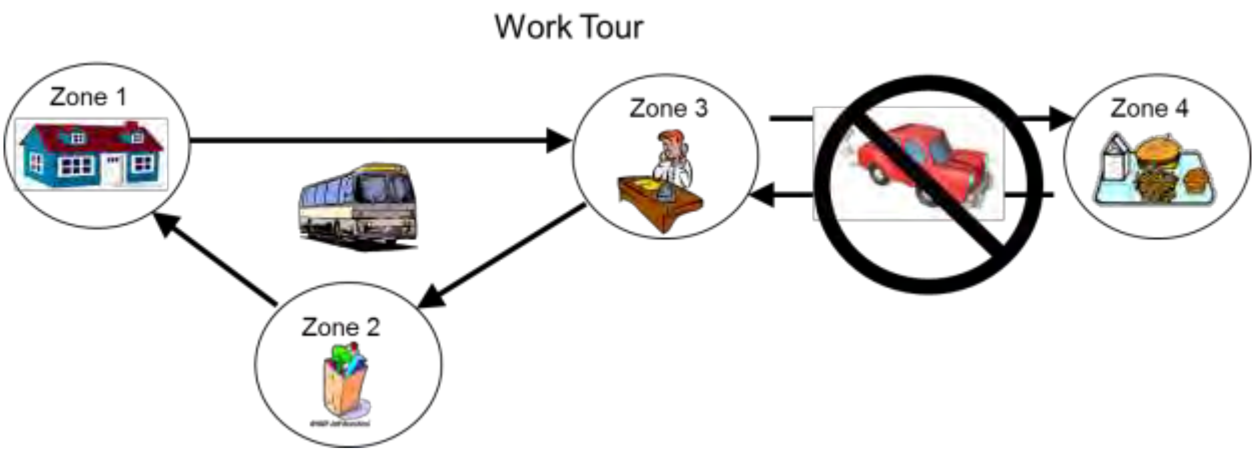
Source: FHWA. How-to: Improve Non-Home-Based Trips, March 2017.

Figure 16. New HBW and NHBW trips from hypothetical residential development in the Salt Lake City model.

It is clear from the Salt Lake City example that the inconsistency of traditional trip-based models with tours and their ability to produce physically impossible results is not just a theoretical concern, but one with very real practical implications.

6.3.2 Modal Consistency of Trips within Tours

The independence of mode choice for different trips within the same tour in traditional trip-based models also can lead to highly improbable mode choices. Despite occasional exceptions related to car sharing, company cars, etc., it is generally necessary for an SOV NHB trip to be associated with HB auto trips from the same household. In general, a traveler cannot take the bus to work and then drive to lunch, or at least, such patterns are fairly improbable. Perhaps even more improbable is a scenario in which a person drives their car to work in the morning and then leaves it at work and takes transit home. Yet traditional trip-based models evaluate mode choice probabilities independently for each trip, allowing for improbable choices, particularly for NHB trips.

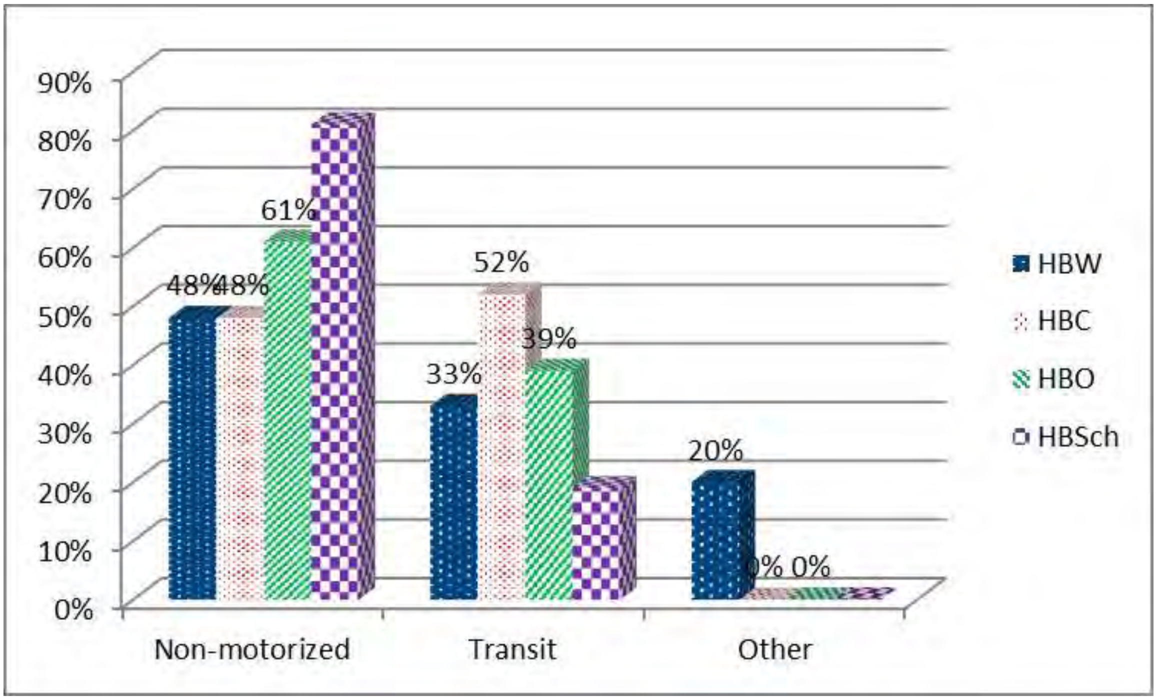


Source: Stabler, B., email correspondence.

Figure 17. Improbable mode choices for trips within a tour.

Both hybrid and activity-based model have mechanism to ensure that the probability of mode choices for trips within the same tour are linked and correlated in reasonable ways. Source: FHWA. How-to: Improve Non-Home-Based Trips, March 2017.

Figure 18 uses the Salt Lake City model again to illustrate how the NHB trips on tours where the HB trips are by transit are most likely non-motorized, possibly by transit, and rarely if ever by auto.

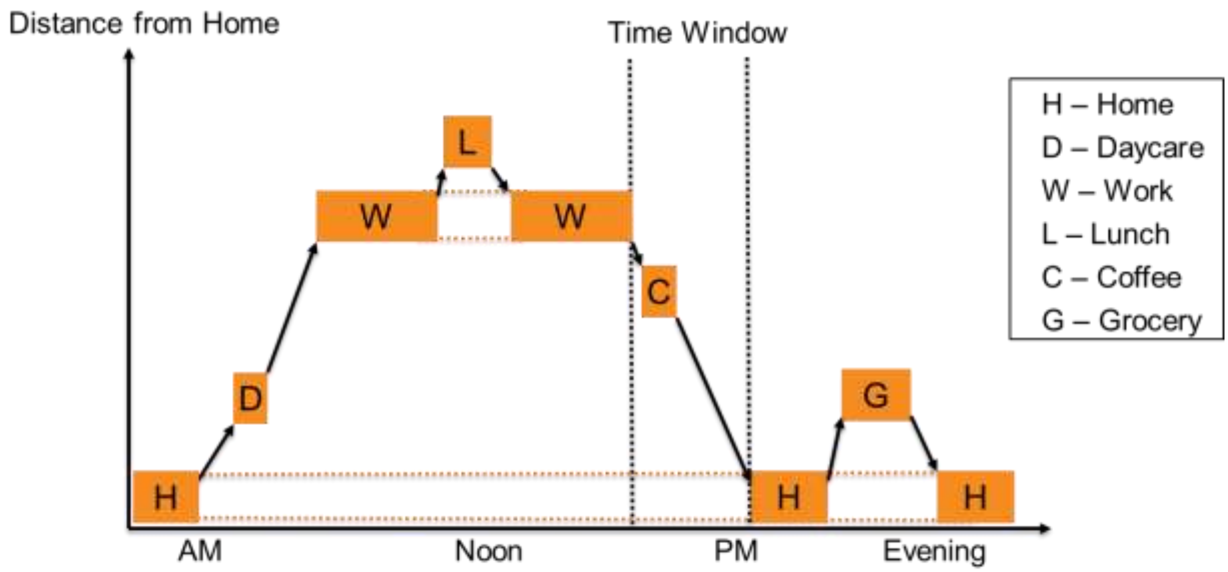


Source: FHWA. How-to: Improve Non-Home-Based Trips, March 2017.

Figure 18. Mode Shares of NHB trips associated with transit HB trips in Salt Lake City advanced trip-based (hybrid) model.

6.3.3 Temporal Consistency of Trips within Tours

Just as in the spatial dimension travelers cannot depart from a location that they never arrived at, temporally travelers cannot depart from a location until after they arrive there, or more simply put, travelers cannot be in two places at once. Traditional trip-based models have little understanding of time, and while hybrid models offer some improvements, they are fairly marginal. The temporal dimension is one where the activity-based framework clearly outshines its alternatives. As only the activity-based model can ensure reasonable temporal relationships and consistency. Activity-based models assign clear activity start and end times which impose constraints or time windows into which other activities and travel must fit. These constraints within the general tour building process of activity-based models ensure that they generate proper trajectories through space and time as illustrated in Figure 19.

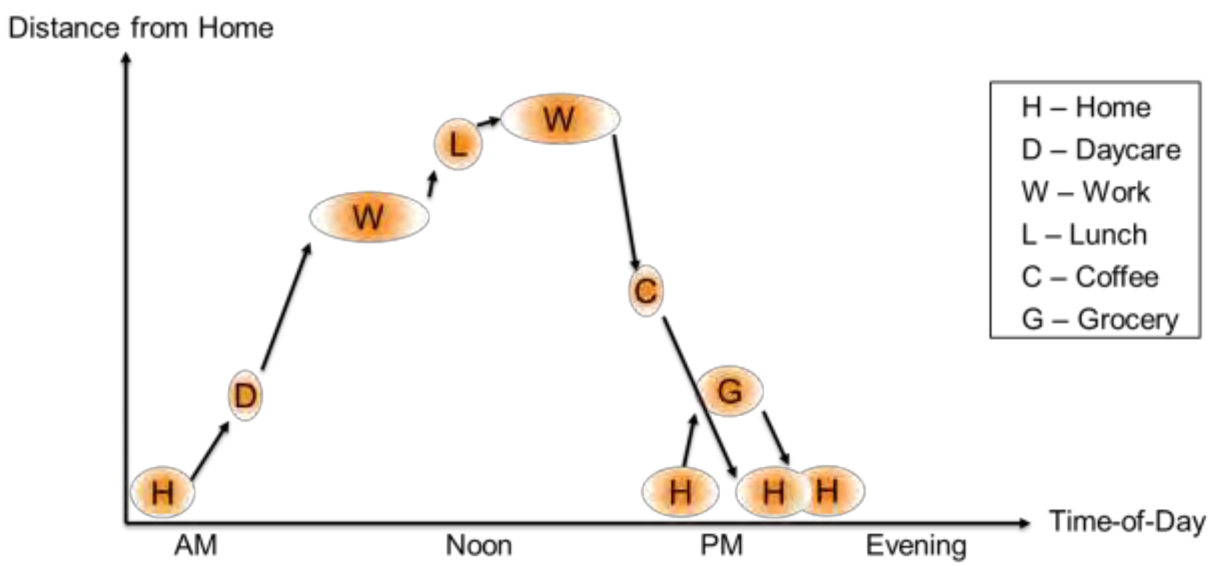


Source: RSG

Figure 19. Space-time trajectory from activity-based model.

While hybrid models can ensure that trips form closed tours in space, there can still be some inconsistencies in the space-time trajectories they imply, particularly in timing, because time windows are not clearly defined. Source: RSG

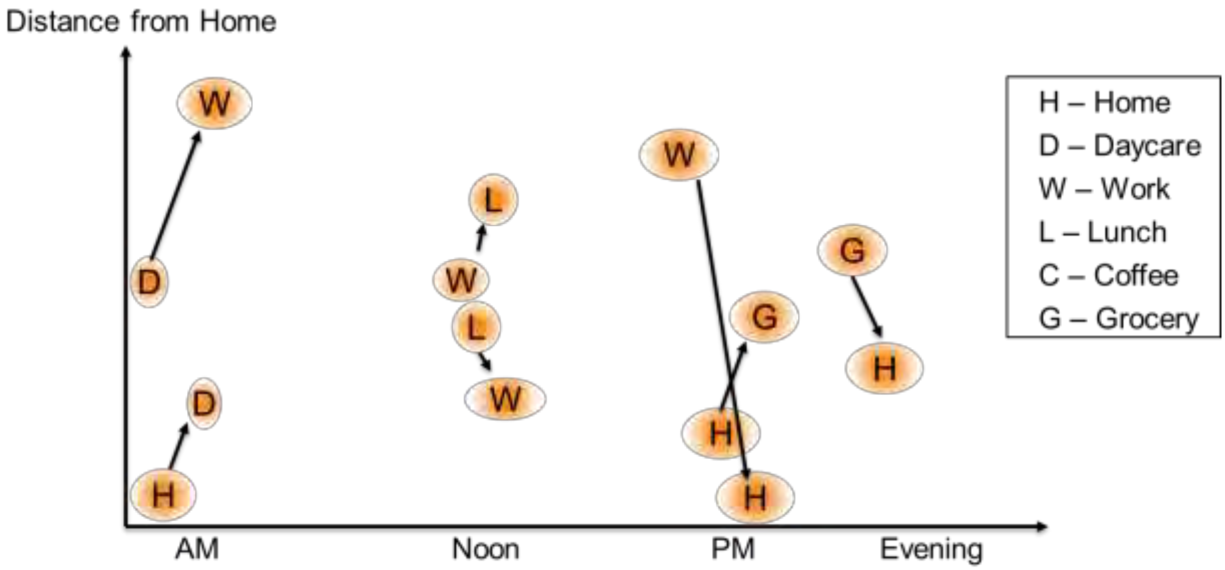
Figure 20 illustrates some of the potential inconsistencies. For instance, the traveler leaves home to go grocery shopping before they arrive home from work and their coffee stop. Spatially, there is also a small inconsistency because the traveler does not return from lunch to the same work location that they were at before lunch but rather another work location nearby.



Source: RSG

Figure 20. Space-time trajectory from hybrid model.

The trips predicted by traditional trip-based models cannot generally be connected into any sort of space-time trajectories. Although the model does predict basically the right overall number of trips, with the correct trip lengths, at more or less the right distances from home, and generally the correct times of day, there is no way to connect these trips into a feasible travel pattern. As was already illustrated in section 6.3.1, trips can depart from locations the traveler never arrived at. They can also occur simultaneously or before the traveler arrives from their previous trip.



Source: RSG

Figure 21. Space-time trajectory from traditional trip-based model.

From these illustrations, it should hopefully be clear that only the activity-based framework allows the consideration of whether future congestion would cause the traveler to omit their coffee stop on their trip home or other complex questions related to the timing of trips.

6.4 Inter-Personal Consistency of Trips

The consistency of trips within the same tour focuses on different trips made by the same individual. However, there are also some ways in which trips made by different people must also be consistent. For instance, in a household with one car, two workers cannot both drive alone to work. If a student is dropped off at school, an adult from the household has to make this stop – at the right school and the correct time.

Only enhanced activity-based models begin to strictly enforce these sort of inter-personal consistencies between trips by different travelers and even they still do not enforce all types of inter-personal consistency, but focus on consistency of travel between members of the same household. While it is difficult to illustrate that simpler models are actually inconsistent in this way, there has been at least some evidence (Gupta and Vosha, 2013) that enhanced activity-based models incorporating these considerations produce different results than simpler models which ignore them.

6.5 Summary of Theoretical Issues

Table 4 summarizes the relative advantages or disadvantages of the general model designs with respect to key theoretical considerations. This summary is meant simply as a prompt to help the reader consider together, the various theoretical issues related to model design discussed in more detail above.

Table 4. Relative advantages of model designs with respect to theoretical issues.

Theoretical Considerations	Traditional	Hybrid	Activity-Based
Aggregation Bias	★	★★	★★★
Within Trip Consistency	★	★★★	★★★
Spatial Consistency of Trips with Tours	★	★★★	★★★
Modal Consistency of Trips in Tours	★	★★★	★★★
Temporal Consistency	★	★	★★★
Interpersonal Consistency	★	★	★★

7.0 The Model Design Process

Given that agencies typically only perform major updates to their travel models once or twice in a decade, the selection of a model design for a region's new travel model is an important decision that will have consequences for the agency's analysis capabilities for some number of years. The design of the model will affect not only the modelers charged with maintaining and applying the model to various studies, but also the planners and ultimately, decision-makers, who will use the model's forecasts. For this reason, a robust process for selecting a model design for a region's new travel model should involve all the relevant stakeholders affected.

Stakeholder outreach to determine the questions the agency is likely to face in coming years is important for informing the model selection process. Involvement of decision-makers and consumers of planning analysis data can also be helpful in securing adequate funding and ensuring that planners and decision-makers expectations for agency analysis capabilities are in line with the level of investment they are willing to make.

An important part of stakeholder outreach is some level of education to familiarize them with the various issues and considerations discussed in this guide. Ultimately, stakeholders should consider the relative importance of these various theoretical and practical issues and the particular applications their model will be used to evaluate together with their available resources including time, budget, staff, and data in order to make an informed and thoughtful decision. In addition to this guide, agencies may want to refer to the NCHRP 08-94 decision support tool and associated report for help, particularly in the selection of components and details of model design.

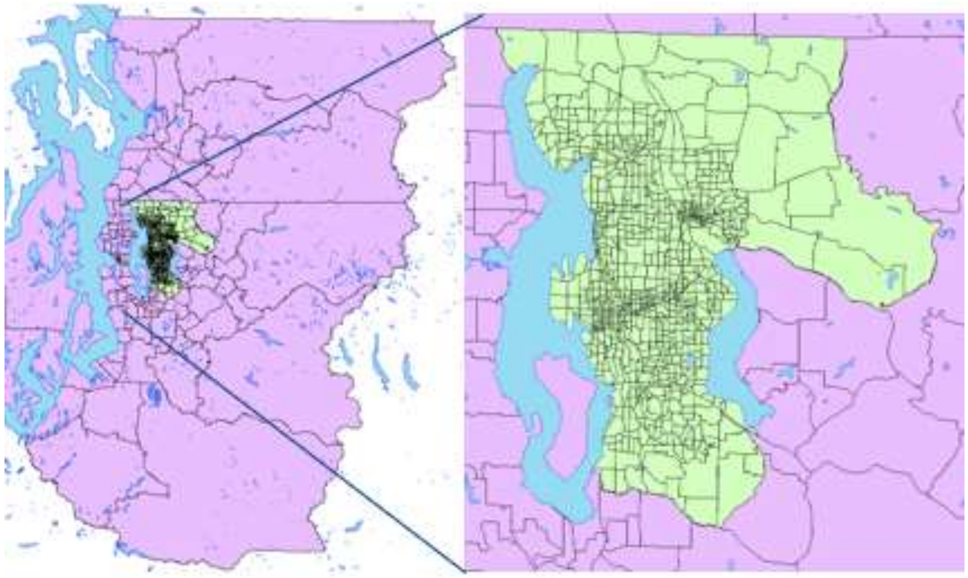
The following sub-section provides an overview of the process engaged in by the cities of Bellevue, Kirkland, and Redmond, WA, in selecting a design for their new model. Although the needs of every agency are different, the example may be helpful for other agencies considering what a good model design process might look like.

7.1 The Bellevue-Kirkland-Redmond, WA Case Study

The cities of Bellevue, Kirkland, and Redmond (BKR) occupy the east side of the Puget Sound region and are home to approximately 300,000 people. (See Figure 22.) The region is known for its high income and highly educated households, and includes the global headquarters of international corporations such as Microsoft, Paccar, Expedia, Zillow, and others. In the early 1990's the three cities entered into an inter-local agreement to develop the BKR Model to help carry out various planning activities. Since then, the model has undergone many rounds of minor to moderate updates, but the model construct and vehicle oriented nature remain unchanged.

The BKR cities are part of the Puget Sound Regional Council which is the MPO for the larger Seattle/Puget Sound region. They are therefore, also covered by its regional travel model. Traditionally their local model has provided more detail than the regional model, but been similar in design. With PSRC's investment in an ABM, a decision had to be made whether or not to similarly switch to this framework or continue with a different model design.

In recent years, the Puget Sound region has clearly focused its transportation planning efforts in investing in smart sustainable communities and mobility options such as light rail transit, bus, bicycle, and walking. The BKR region is also known for its collaborative effort in managing growth at a regional scale, in long range planning to keep the region economically competitive, and in implementing projects that promotes neighborhood livability. As the region continues to grow, the cities decided that it was an opportune time to design and implement a new travel demand model that supports scenario planning applications through proven methodology and travel behavior data while making use of existing regional investments.



Source: City of Bellevue, WA

Figure 22. Bellevue-Kirkland-Redmond area.

Recognizing the value of expert input, stakeholder input, and independent review, BKR engaged in a process including the following key elements:

1. Staff consultation with national experts in model design
2. Stakeholder engagement through two open, full day workshops
3. Development of refined design options and recommendations
4. An independent review by experts not previously involved
5. Final evaluation of options and selection of model design

BKR engaged with consultants to support steps 1-3 of this process, coordinated with TMIP to facilitate the independent peer review, and reserved the ultimate evaluation and selection of model design for their own agency staff and decision-makers.

Initial consultation between agency staff and consultant experts helped the agency identify and review many of the issues discussed in this guide, and this guide benefited greatly from these efforts, although for BKR, issues were organized based on model components/steps or dimensions of travel rather than as in this guide.

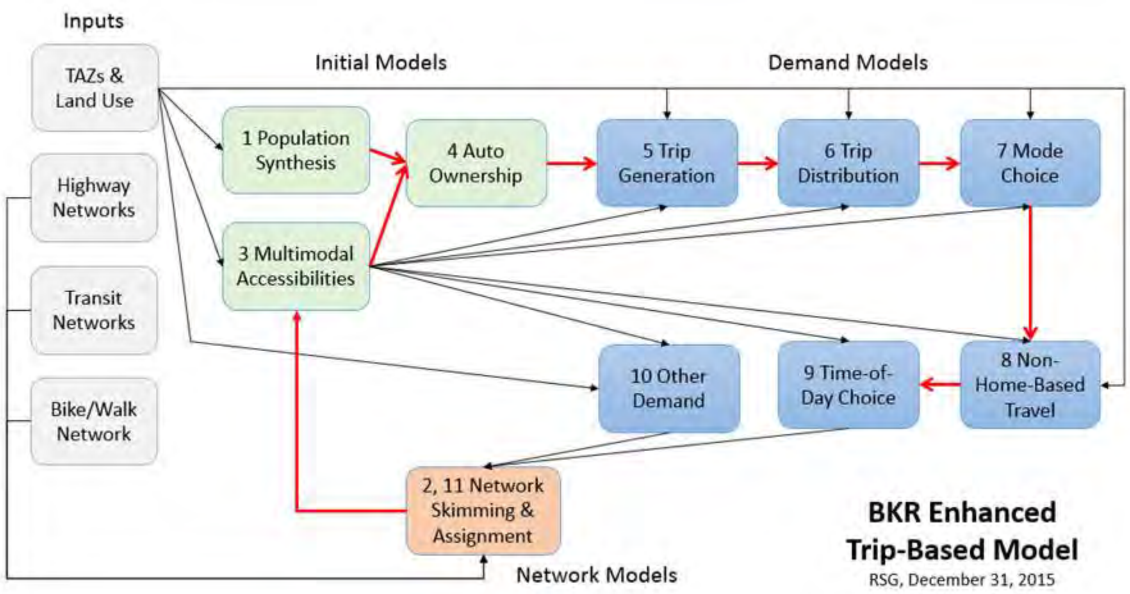
The morning session of the first workshop began with reflections and remarks from local decision-makers on pertinent local planning issues, followed by discussion by those in attendance, notably including many local planners. Following the workshop and based on input from local planners and decision-makers, the consultants coordinated with agency staff to develop the following requirements for the new BKR model:

1) Responsiveness to changing household characteristics is important. This means producing forecasts along various demographic markets such as household vehicle availability, incomes, household sizes, and person ages.
2) Responsiveness to changing employment characteristics in the region is essential. This means producing forecasts that are sensitive to changes in industries and are segmented by many different types of employment.

3) Responsiveness to changes in multimodal accessibility for all travel modes and land uses is required. This includes ensuring the model is sensitive to changes in density, diversity of land uses, congestion by time-of-day, and relevant costs by mode (parking, tolls, fares, etc.).
4) Producing forecasts by different travel purposes is required – work, university, K-12, shopping, recreation, etc.
5) Planning for non-motorized travel options such as bike, walk, and transit access are very important to the BKR region.
6) Planning for travel options by time-of-day (early morning, AM peak, midday, PM peak, and night) is required. This is especially true now that I-405 and SR-520 are variably priced.
7) Accounting for non-BKR resident traffic is important since it accounts for a significant share of auto and transit network utilization.
8) Produce reasonable intersection level forecasts for operational analyses and traffic impact studies (such as Level-of-Service (LOS) estimates).
9) The model should be implemented in familiar technologies to BKR and others in the region. It may use model components already programmed in other languages if open source, proven, and configurable in order to minimize revisions. This means the model should, at least in part (assignment and skimming), be implemented in EMME.
10) The model should be easy to use and maintain. This means the modeling system has a proven track record, is modular and upgradable, is easy to use, is supported by a good support ecosystem, has an upgrade path, and interoperates well with other tools such as GIS.
11) *Built-in sensitivities to transportation demand management (TDM) strategies such as employer-sponsored transit passes, planning for working at home, sensitivities to flexible work scheduling, and sensitivities to CBD parking constraints are all desired but not required.*

Following the discussion of local planning needs and priorities in the workshop, the consultant team reviewed the basic families of model designs including traditional trip-based, enhanced trip-based and hybrid, and activity-based models, providing a high-level overview of the advantages and disadvantages of each approach similar to that provided in this guide. In the afternoon, the consultant team focused on describing in detail what an enhanced trip-based model and activity-based model might look like for the BKR region with a smaller group of stakeholders with more technical interests and background. The BKR region already has a traditional trip-based model and many present were familiar with it, so it was not reviewed in detail.

Following the first workshop, the consultant team worked with agency staff to further develop design options for the new BKR model. (See Figure 23 for an example.) The second workshop was then used to review and refine these options. Based on the input from the second workshop, the consultant team then finalized its design options and recommendations.



Source: RSG

Figure 23. One model design option for the new BKR model.

BKR then tasked the TMIP peer review to review the draft model design that was developed by BKR with the help of the consultant team by:

- Reviewing model components, their subcomponents and data requirements,
- Identifying opportunities for improvement,
- Discussing uncertainties of inputs and assumptions and advise on how they can be managed, and
- Estimating resources required for implementation.

In reviewing the draft model design, BKR desired for the panelists to focus their recommendation on answering the following question: "What are proven, best practice modeling techniques that can be cost effectively incorporated into the next BKR model?"

The peer review discussed many of the details from the proposed model design options including the TAZ system and BKR model boundary, land use and socioeconomic data, bicycle network and assignment, transit modeling, highway network and assignment, the incorporation of multimodal accessibility measures, the auto ownership model, the segmentation/definition of trip/activity purposes, mode choice, trip distribution, the number of time periods, and the interface with the larger PSRC model. They also discussed issues of concern including simulation variation, runtime, and model complexity as well as the benefits of leveraging PSRC's investment in an activity-based model.

The peer review panel provided recommendations suggesting that the hybrid/advanced trip-based model presented by BKR to the panel could be reasonable approach, but as a stand-alone model with limited interaction with PSRC's activity-based model, and they did express some concerns about the advanced trip-based design, particularly given the option to simply refine PSRC's activity-based model which may be more cost-effective. If BKR chose to pursue this this model design, they suggested an incremental approach to improving the existing model and converting it into a hybrid design, but they encouraged BKR to further investigate the option of refining the PSRC activity-based model.

In part in response to the recommendations of the peer review panel, BKR staff engaged with PSRC staff to further evaluate the PSRC activity-based model and examine its validation specifically for the BKR sub-region. BKR staff found that they were able to develop proficiency and comfort in using the activity-based model and that the preliminary validation for the BKR sub-region was promising, although further refinement would be necessary for their purposes.

Therefore, informed by their consultant recommendations, the peer review recommendations, and their own staff review efforts, including efforts to test PSRC's model and its validity in their region, BKR ultimately chose to adapt and refine PSRC's activity-based model. Although they recognized the advantages and disadvantages of either this or an enhanced trip-based approach, because of PSRC's prior investment in an activity-based model for the region, this approach was more cost-effective than the development and maintenance of a separate model platform. It also had the benefit of greater consistency with PSRC and easier integration with the PSRC model for travel to and from the wider region.

Although BKR's final decision regarding model design is of some interest, many of the unique circumstances such as the availability of a preexisting activity-based model for the region will not obtain for other regions. Even with this important local consideration, there was considerable deliberation by BKR and some of the most important lessons for other agencies can be drawn from their process, rather than simply their conclusion:

- First, each stage of the process added value.
  - The initial consultation helped identify both nuanced options and issues that were not necessarily clear beforehand.
  - Stakeholder input helped clarify needs and priorities for transportation planning in the BKR region.
  - Formalizing well-defined options helped clarify the decision and the advantages and disadvantages of each option relative to BKR's own priorities
  - Independent review helped provide additional perspective and identify potential refinements of the options.
  - The entire process helped to bring the staff to a point where they were able to conduct their own final investigation to inform the agencies' final decision.
- Second, what seemed at certain points in the process what might be a clear decision – of different options at different points in the process – ultimately proved challenging as the real advantages and disadvantages of each approach became clearer to all involved. The process helped proponents of each option understand its limitations and the detractors of each process understand its strengths. It seems reasonable to think that as a result all involved will have realistic expectations going forward with the new model.

Just like with the model designs themselves, no process is a one-size-fits-all solution for all agencies. The example of BKR's process can and should be adapted to fit the needs of individual agencies, but hopefully the example helps illustrate key elements that will likely prove helpful for many agencies, just as the foregoing sections identify key issues to be considered within the process.

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