Modeling the Urban Continuum in an Integrated Framework:
Location Choice, Activity-Travel Behavior, and Dynamic Traffic Patterns

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INTERIM REPORT
TASKS 1 & 2: IDENTIFICATION OF ISSUES IN INTEGRATED LAND USE – TRANSPORT MODELING AND OVERALL CONCEPTUAL MODEL STRUCTURE AND DESIGN

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INTRODUCTION

The advent of microsimulation approaches to the analysis of urban land use and transport systems has ushered in a new era in urban systems modeling (Waddell, 2002). Microsimulation approaches allow one to represent the complex behaviors of individual agents in a system while recognizing the interactions, constraints, and decision mechanisms that drive their actions and choices (Kitamura et al, 2000). The implementation of microsimulation approaches has been made possible by advances along multiple dimensions. Advances in econometric and statistical modeling methods, numerical optimization techniques, computational hardware and software technology, and data collection and management systems have all contributed to making the implementation of microsimulation model systems a reality (Goulia and Kitamura, 1992; Goulia and Kitamura, 1997).

The primary motivation underlying this research project is the desire to integrate advances in microsimulation model development that have largely occurred in three (somewhat) independent streams of research. In the first stream, land use researchers have developed microsimulation models of land use development (Waddell, 2000). These models are intended to represent the behaviors of households and businesses as they make location choices (Waddell et al, 2007). Households make choices regarding residential location, individuals in households make choices regarding workplace location and school location (perhaps in consultation with other members of the household, resulting in interactions), and businesses make decisions about where to locate their enterprises and offices. Developers make decisions regarding the parcels of land that will be developed either for residential or commercial use. These location choices, coupled with demographic and socio-economic evolutionary processes, land regulations, and zoning policies, drive the development patterns in urban areas. More importantly, these location choices are often driven by transport accessibility considerations, thus calling for the feedback of transport level of service measures from transport models to submodels within the land use microsimulation model system. The land use microsimulation model system includes a series of submodels that mimic market clearing processes as different agents buy and sell building stock, relocate home and work sites, and participate in real estate transactions and development decisions.

The second stream of model development has seen travel modelers usher in a new generation of activity-based travel demand model systems (Miller, 2002). At the heart of the activity-based model paradigm is the microsimulation of daily activity-travel patterns of households and individuals within households (Kitamura and Fujii, 1998). These models consider household activity agendas, individual activity schedules that are formed through interactions among household members (as activities get allocated among household members or are undertaken jointly by a set of household members), activity linkages and trip chaining, and destination and mode choices at the level of the trip chain to explicitly account for interactions among trips in a chain. These models are intended to capture time-space interactions by considering time-space prism constraints, time allocation behavior represented by activity and travel durations, and history dependency in activity-travel behavior (Kitamura et al, 2000; Kasturirangan et al, 2002). At the end of the process, one would conceivably obtain a complete activity-travel pattern, with activities and trips simulated along a continuous time axis, for each individual in a synthetically generated population of the urban area. Different activity-based model systems incorporate the capabilities described in this paragraph to varying degrees (for example, tour-based nested logit model systems do not explicitly consider activity durations and treat time in discrete chunks), but the point remains that microsimulation models of activities and travel are seeing increasing acceptance in the modeling community. The activity-based model system has two major linkages that
are of interest in the context of this project. On the one hand, the model system needs land use information from the land use microsimulation model. On the other hand, the model system generates the travel plans of individuals that need to be assigned to networks and, in turn, utilizes network level-of-service measures to model activity-travel choices including activity time allocation, destination and mode choices, and travel durations.

The third stream of research that has had a major impact on the profession is that of dynamic traffic assignment (DTA). Dynamic traffic assignment models constitute a class of mesoscopic models wherein the route choices of individual trips/vehicles are modeled in order to simulate traffic flows along links in the network. In contrast to using microscopic car-following and cellular automata type paradigms to simulate vehicular movements and infer traffic flow parameters, the dynamic traffic assignment models use well-established macroscopic theories of traffic flow characteristics to compute capacities, travel times, and speeds on links in the network. Thus, individual vehicular movements (microscopic) are modeled and simulated using macroscopic traffic flow relationships, leading to the concept of mesoscopic dynamic traffic assignment models. These models route origin-destination (O-D) flows and update paths on a second-by-second basis depending on prevailing conditions on the network. Wardrop’s principle of user equilibrium holds at any point in time as travelers (individual vehicles) are routed along the shortest path prevailing when the trip is initiated. More advanced dynamic traffic assignment models are capable of simulating enroute path choice processes where individual travelers may modify their route plan along the way in response to congestion on one or more links. The dynamic traffic assignment models are related to activity-based travel demand models and land use microsimulation models in important ways. The dynamic traffic assignment model depends on the activity-travel model for time-dependent O-D flows. In turn, the dynamic traffic assignment model delivers time-dependent network conditions (level of service and accessibility measures) that influence activity-travel choices (mode and destination choices, for example) and longer term location choices in the land use model (residential and workplace location choices, for example).

Given the interdependency among these three model entities, there has been much interest in the profession to link these model systems together (Timmermans, 2003; Miller, 2006). Several researchers have developed conceptual designs of integrated model systems and others have attempted to operationalize joint model systems by coupling models through data exchange processes and feedback loops (Salvini and Miller, 2005). However, there is much to be done in the integrated land use – transport modeling arena. Virtually all attempts at integrated land use – transport modeling have generally focused on two of the three model systems noted in the previous paragraphs. There are models that attempt to link land use microsimulation model systems with activity-travel model systems (Waddell et al, 2008; Salvini and Miller, 2005) and there are other attempts to link activity-travel models with dynamic traffic assignment models and network simulators (e.g., Lin et al, 2008; TRANSIMS; Kitamura et al, 2008; Kitamura et al, 2005; Boyce and Bar-Gera, 2004). Rarely, if ever, has there been even a complete conceptual design that truly integrates all three modeling enterprises that together represent the urban continuum – from longer-term location choices to medium term vehicle ownership and activity lifestyle choices to short-term route choices.

The fact that much remains to be done in the integrated modeling arena has been articulated by several well-known researchers in the field. In his 2003 International Association for Travel Behaviour Research (IATBR) conference resource paper on integrated modeling, Timmermans (2003) confronted integrated modelers about the dreams that have been dreamt for more than 40 years and challenged the profession to wake up and take on the serious challenge of integrated model development. He argued that, while some notable progress has been made, the field of integrated modeling has simply not
advanced far enough or fast enough to make a difference in transportation planning practice and noted that there is no single integrated model system that is even close to serving as a true decision-support tool. Timmermans emphasized the lack of a solid theoretical foundation as one of the major reasons for the absence of progress in the development of truly integrated model systems. As a result, he noted that integrated model systems are nothing but ad hoc coupling of disparate model systems using statistical and data stitching techniques as opposed to truly behavioral representations of long-term to short-term location and travel choices. At the 2006 International Association for Travel Behaviour Research (IATBR), Miller (2006) presented the workshop resource paper for integrated modeling. Although Miller adopted a more optimistic view towards the profession in advancing the cause of integrated modeling, he acknowledged that Timmermans’ challenge concerning the absence of sound theoretical foundations for integrated model development remains. Miller goes on to state: “without a coherent and consistent conceptual framework (which has implicit within it a proper regard for behavioral fidelity and context), progress on developing a model system that “integrates” a variety of socio-economic processes, a multiplicity of actors, and a continuum of spatial-temporal scales stands little chance of being anything other than ad hoc in nature and difficult to defend, in either research or application contexts” (Miller, 2006).

The above discussion serves as the ideal backdrop for this research project which constitutes a major effort at developing a truly integrated model system of the urban continuum. Building on the work that has been done in the field to date, and leveraging model development efforts undertaken by the principal investigators themselves over the past decade, this research project is aimed at developing an integrated model system that represents the continuum of location and travel choices made by people across space and time. With advances in microsimulation methodologies, new database management technologies, computational and analytical tools, and software architectures, the time is ripe to develop an integrated model system that is behaviorally intuitive, robust, consistent, coherent, and operationally appealing. Once again, the dream is big and the vision is grand. Undoubtedly, compromises will have to be made within the scope and resources of the project, and limitations in behavioral theory will necessitate the adoption of simplifying assumptions. Operational considerations may result in having to find a middle ground between the ideal level of behavioral fidelity and what can be achieved in practice. However, the goal is to develop a set of procedures, methods, tools, and concepts that can significantly move the cause of integrated modeling forward.

The integrated modeling effort of this project is dubbed iMUBETA (IMUBETA) which stands for integrated Model(ing) of the Urban Built Environment, Travel, and Activities. The research project calls for the accomplishment of 15 tasks, including three specific tasks identified for facilitating exchanges with the peer review panel. The project tasks are:

Task 1: Identification of Issues and Challenges in Model Integration
Task 2: Development of Comprehensive Study Design (Scoping Study)
Task 3: Meeting with Peer Review Panel
Task 4: Development of Computational and Analytical Solutions to Address Issues/Challenges
Task 5: Development of Integrated Data Structures, Data Models, and Data Management Systems
Task 6: Meeting with Peer Review Panel
Task 7: Collection and Assembly of Databases
Task 8: Calibration of Microsimulation Model Systems in Test Area
Task 9: Development of Prototype Integrated Model System
Task 10: Calibration and Validation of Prototype Integrated Model System
Task 11: Policy/Scenario/Sensitivity Analysis Using Integrated Model System
This report covers the first two tasks of the project, namely, the identification of issues and challenges associated with the development of integrated urban models and the conceptual vision and grand model design for an integrated model system that leverages the previous model development efforts undertaken by the principal investigators. This report includes three main sections following this introductory section. The next section provides a discussion on the motivation for the development and implementation of integrated urban models. This section helps set the stage for the specification of the integrated model structure and specification. The third section provides a comprehensive discussion of the issues and challenges identified by the research team in the context of integrated urban model development. By identifying these issues and challenges upfront, it is possible to develop solutions and work around them prior to the actual model integration effort (tasks). Finally, the fourth section presents the conceptual design of an integrated model system that captures the continuum of choices of interest in this study. This section presents the vision of the team in terms of the design, specification, and feedback processes that define iMUBETA.

Two distinctive features characterize the approach to this project effort:

1. The research project is intended to result in the development of a generic and universally applicable integrated model design and system. In other words, the set of integrated modeling procedures and tools, data and model specifications, database management and handling systems, and all other aspects of the integrated model system (including, for example, feedback processes) developed in this project are not intended to be software-specific. The research team is charged with developing the model system in such a way that researchers and practitioners using a variety of software packages and tools should be able to incorporate the procedures and methods developed in this project into their modeling environment. While it is certainly inevitable that the model design and system will be influenced by the prior experience of the principal investigators in land use – transport modeling, every effort will be made to ensure the generic universal applicability of the methods, procedures, and data systems specified and developed in this effort. The prototype development and implementation effort within the context of this project will simply demonstrate how the model design/specification can be implemented and applied to an urban area.

2. The research project is completely operating in the open-source world, consistent with the notion that open source communities of model developers can help spur innovation and rapid enhancements to model systems. The source code for all models and submodels will be made available in the code repository for this project under standard open source licensing arrangements whereby any individual making enhancements to the code is required to deposit their enhanced versions in the open source repository as well. By keeping the source code and all programs in the open source public domain, it is envisioned that the cause of integrated modeling can be rapidly advanced in the years to come.

Finally, it should be noted that this project only encompasses household and personal travel in an urban context. The scope of the model system does not include visitor travel, long distance travel, and freight and goods movement. These facets of travel demand merit their own model development efforts and are not included in this project.
MOTIVATION FOR INTEGRATED MODELING OF THE URBAN BUILT ENVIRONMENT, TRAVEL, AND ACTIVITIES (iMUBETA)

The design and specification of any model system is largely driven by the behaviors that need to be represented in the model system, the policies that need to be analyzed and evaluated, the planning applications for which the model may be used, and the computational and analytical resources available for model development and application. In this section, these aspects are briefly discussed to identify the primary forces that motivate the development of integrated urban models.

BEHAVIORAL MOTIVATION

The complexity of human behavior and decision processes underlying interwoven location and travel choices constitutes a major motivation for the development of integrated urban models. The past two decades has seen a tremendous body of research and literature devoted to understanding, explaining, modeling, and forecasting human activity-travel behavior and location choices. Much of this research has led to the development of new microsimulation model systems of land use and activity-travel choices. In these systems, the complex behavior of agents is simulated in such a way that emergent patterns of choices can be modeled in the time-space continuum.

As mentioned earlier, there are myriad choices that characterize location decisions and activity-travel behavior. In the longer term, people make decisions about where to live and work (thus defining their basic commute context) and go to school. In the medium term, people make decisions about their automobile fleet and overall lifestyle. In the shorter term, one deals with the week-to-week and day-to-day activity-travel patterns characterized by activity agendas, activity schedules, trip chains and tours, destination and mode choices, and route choices. Although these myriad choices occur potentially in different time steps and across different spatial contexts (say, household residential location choice may occur on a neighborhood level, while route choice and way-finding behavior occurs at the link/node level), they are highly inter-related with one another. It behooves the profession to consider integrating model systems that represent these behavioral dimensions in a robust and coherent framework founded on theories of behavior that have emerged over the past several decades of behavioral analysis.

The interactions among choice dimensions are critically important because many policy questions of interest have impacts across choice processes, and an impact on one choice dimension is likely to have a cascading effect on several other choices across the time-space domain. For example, consider a situation where congestion along a route from home to work is increasing. In the very short term, an individual may attempt to find an alternate route that is faster and less congested. The individual may shift departure time to work in order to arrive on time at the work place. The individual may attempt to telecommute once or twice a week to reduce the amount of time spent commuting, or shift working hours to facilitate travelling in a less congested period. These shifts may bring about secondary changes to the activity-travel pattern as discretionary activity durations may have to be changed, pick-up/drop-off routines may have to be altered, and trips previously linked to the commute (either to or from work) may have to be undertaken in separate trip chains or at different locations (possibly as a consequence of the route shift). In the longer term, the household may strategically choose to relocate home or work locations so that the commute is less arduous. This relocation may bring about an entire series of changes in lifestyle choices, vehicle ownership and fleet composition, and activity-travel patterns.
Essentially, it is inevitable that urban location and activity-travel choices are closely interwoven across the time-space domain.

While one can certainly attempt to model these relationships through a loose coupling of land use, travel demand, and transportation network models, it is likely that such loose coupling mechanisms will not have the richness or behavioral consistency that is warranted in such enterprises. For example, consider the situation often seen in practice where a tour-based microsimulation model system of travel that yields individual-level activity-travel patterns along a quasi-continuous time-axis is coupled with a traditional static traffic assignment model. The trips obtained from the tour-based model are aggregated into time-of-day based O-D matrices and then assigned using traditional static assignment methods. This loose coupling results in a loss of behavioral fidelity and is a poor representation of the dynamics that define network performance and the influence of the network attributes on activity-travel choices in the demand model. If one is moving towards a microsimulation-based behavioral framework for modeling choices, then such a framework should pervade throughout the model system so that there is consistency in representation of time, space, behavioral units, and behavioral processes (including feedback).

There are many behavioral aspects that warrant consideration in the development of a microsimulation-based integrated model system. In the context of this project, it is the intent of the team to develop a model framework and embed analytical methods that can account for several key emerging behavioral themes identified in recent research. These include, but are not necessarily limited to, the following.

- **Stochasticity**: Human activity-travel behavior and location choices are characterized by randomness and often best represented as stochastic processes. Random utility frameworks recognize that people do not often make the most rational or optimal choice and that people’s behaviors show variation from one context to another. Although such probabilistic utility-based framework offer convenient operational models for analyzing location choices and activity-travel demand, it may be appropriate to consider hybrid modeling methods that embed behavioral heuristics to represent stochastic outcomes.

- **Interactions**: Humans interact with one another, both within- and outside the confines of their households. Individuals communicate, socialize, travel together, depend on one another (particularly in the context of a child), and allocate vehicles, activities, and tasks among each another. People interact with businesses and institutions as they undertake various activities including work, school, social recreation, personal errands, shopping, and eat-meal. Virtually all of these interactions are characterized by space and time coordinates, thus bringing about time-space interactions in activity-travel patterns. If one were to consider activities or trips linked together in a chain, various choice dimensions such as destinations, modes, and times (activity and travel durations) are interlinked with one another.

- **Constraints**: There are a host of constraints that influence people’s location choices and activity-travel patterns. There are budgetary constraints that limit the types of homes that people can purchase or rent. There are household constraints that require individuals to be home (or at certain specified locations) at certain times of the day (say, to take care of children). Similarly, there are modal constraints (transit or vehicle availability) and institutional constraints (work, school, shop hours) that must be adhered to. Personal constraints (the need for sleep, for example) limit the amount of time that individuals can engage in other activities and travel.
Time-space (network) constraints limit how far individuals can travel within a given span of available time by any given mode. All of these constraints influence location choices and activity-travel patterns and need to be reflected in models across the urban continuum.

- **Dynamics**: The urban system is inherently dynamic in nature. Time never stands still and neither do urban systems. Households and businesses evolve (age and change) over time, relocate, and undergo structural changes (for example, when a child grows up and leaves home). Activity-travel behaviors show changes from day-to-day and week-to-week and there has been considerable research devoted to capturing longitudinal trends in socio-economics and activity-travel demand. While a traveler may have a preset route plan to execute a trip, it is possible that the traveler will make enroute decisions to shift to alternate paths based on emerging congestion and network conditions. All of these dynamics are extremely difficult to capture in the context of traditional survey data sets that capture a snapshot of behavior at one point in time. An integrated model system in which one is synthesizing a population over time and feeding network level of service measures from one simulation year to the next (for modeling location and activity-travel demand choices) would go a long way in representing dynamics in urban systems.

- **Uncertainty**: Forecasting is intrinsically fraught with uncertainty. While some of the uncertainty may be traced to stochasticity in behavior, there are several sources of uncertainty in urban system forecasts. Many of the inputs (influencing factors) are unknown, misspecified, or not measured. Forecasts of inputs themselves may be riddled with errors and these errors are likely to be propagated through the various components of a model system. Transportation planning models have traditionally focused on yielding a single answer to represent a future year context. However, it appears that the profession is ready to recognize that forecasts provided in terms of ranges or distributions of possible outcomes offer a useful mechanism for planning for the future while simultaneously accounting for uncertainty.

- **Heterogeneity**: People are different from one another. Different people respond differently to stimuli and value and perceive time and space differently. In considering traveler response to pricing scenarios, the variability in the value of travel time savings has been a topic of much interest in the profession. Behavioral heterogeneity may arise from observed factors or unobserved factors. Observed heterogeneity is that which is explained by land use, network, socio-economic, and demographic variables typically included in model specifications. On the other hand, unobserved heterogeneity is often captured using random error components that represent heterogeneity due to unknown factors. Again, in the context of microsimulation models of behavior, it is possible to simulate activity-travel patterns of individuals while recognizing the heterogeneity that may exist in the population. Advances in econometric model specifications and estimation methods make it possible to implement such models in practice.

- **History Dependence and Inertia**: While it is certainly important to recognize the presence of dynamics, it is equally important to recognize that humans are creatures of habit. Even when subjected to a stimulus, individuals may continue to exhibit a certain behavior (that they have been habitually devoted to) due to inertia or habit-persistence even when the behavior is no longer optimal. Similarly, there is history dependence in location choices, auto ownership, and activity-travel choices. If individuals completed shopping or social recreation earlier in the day or on a previous day in the same week, then it is less likely that they will engage in these
activities once again on the current day. Such history dependency effects can be captured in microsimulation models of individual activity-travel behavior and location choices. Recent work shows promise in the ability to capture dynamics and history dependence by treating one day of activity-travel data (or any snapshot of behavior) as one realization of a longer term stochastic process.

In summary, there are a host of behavioral aspects that motivate the development of microsimulation-based integrated urban model systems that offer the framework for representing such behaviors in a consistent and explicit fashion. Recent developments in the modeling and representation of these aspects of behavior provide an opportunity to realize such a behaviorally appealing integrated model system.

POLICY ISSUES AND PLANNING QUESTIONS/APPLICATIONS

The policy relevance of the development of integrated urban model systems cannot be more apparent than what has transpired in the global economy over the past few years. Over the past few years, fuel prices skyrocketed from about $2 per gallon to more than $4 per gallon, but have since fallen back to an average of about $1.75 per gallon, their lowest level in four years. At the same time, real estate values have plummeted, home foreclosures have soared to record highs, unemployment rate is the highest it has been in 15 years, and world stock markets have crashed to their lowest levels in years. In part due to these major real estate and economic phenomena, vehicle miles of travel (VMT) in the United States have reduced between 2007 and 2008 by about four percent, the single largest decline in VMT between consecutive years since the energy crisis of the early 1980s. Households are replacing larger gas guzzling vehicles with smaller, fuel-efficient and hybrid vehicles, thus contributing to dramatic shifts in household fleet compositions. Even though fuel prices have dropped once again to less than $2 per gallon, it appears that households are reluctant to revert to previous vehicle ownership and travel habits that prevailed at the dawn of the new millennium. This shows that there is hysteresis in behavior, where behavior does not revert to a previous state when the stimulus that caused a change in behavior in the first place is removed. Many agencies around the country are grappling with the profound changes in gas tax revenues, travel behavior, and real estate markets that have occurred in the past year.

In the absence of an integrated model system of urban land use markets, activity-travel behavior, and network dynamics, it is simply impossible to predict the cataclysmic cascading changes that have been witnessed by the country over the past year. This is not to say that an integrated urban model system could have forecasted these circumstances accurately or helped policy makers avert these series of events, but it is not a stretch to say that having a policy-sensitive integrated urban model system that links human choices and behaviors across temporal dimensions would have been a useful tool to have in the arsenal of planning agencies. Urban land use and activity-travel forecasting procedures serve as a critical component and backbone of short- and long-range land use and multimodal transportation planning processes around the world. The quantitative and qualitative information obtained from urban modeling systems provides planners the ability to identify problems in multimodal transportation networks, formulate policies and solutions, and monitor performance. Over the past several decades, the range of transportation planning applications for which travel demand forecasting procedures are used has considerably broadened. In the 1950s and 1960s, travel demand models were primarily applied to plan highway capacity expansions and determine route alignments, particularly in the context of the construction of the interstate highway system and major arterials serving metropolitan areas. Since then, the context of transportation planning has undergone a virtual revolution. In addition to traditional highway capacity and traffic congestion issues, planners are now grappling with such issues
as air quality conformity, land use – transportation interaction, transit- and pedestrian-oriented developments, competing for Transit New Starts funding, implementation of intelligent transportation systems (ITS), impacts of a range of travel demand management (TDM) strategies and transportation control measures (TCM) including variable pricing initiatives, social equity and environmental justice in the context of special populations, transportation and public health (obesity), and the effect of telecommunications on travel behavior (e.g., e-commerce, telecommuting, etc.). The geographic scope of transportation planning has also broadened to include statewide, rural, and inter-regional transportation considerations. Travel demand modeling procedures are now expected to be responsive to freight transport needs, non-motorized modes of transportation, and safety and security considerations. Figure 1 offers a concise look at the emerging scope of transportation planning and travel demand modeling applications in today’s context.

![Figure 1. The Expanding Scope of Transportation Planning](image)

Great emphasis is being placed in urban areas around the world on the notion of “sustainability”, characterized by development patterns and transportation systems that result in lower energy consumption, lower air pollution, healthier active lifestyles, and lower vehicle ownership and utilization levels. Land use policies including zoning restrictions, mixed use development incentives, transit-oriented development incentives, and so on are being actively considered in communities around the country as a means of promoting sustainability and green living. Automakers are developing and pushing new hybrid vehicles that pollute less and consume less fuel. One of the major challenges confronting the nation is that of the aging of America with a huge increase in the retirement age.
population over the next few decades. All of these developments are likely to have far-reaching consequences on people’s location choices and activity-travel behavior. Integrated urban models offer a mechanism by which socio-economic, land use, and transport phenomena can be modeled with explicit recognition of the inter-relationships among them.

METHODOLOGICAL AND COMPUTATIONAL FEASIBILITY AND TRACTABILITY

The development of integrated urban models is motivated further at this time by considerable advances in methodological capabilities and computational capabilities. Computational feasibility and tractability have been major roadblocks to the development of integrated urban model systems because of hardware and software limitations that precluded the ability to represent the interactions and feedback processes that characterize such model systems. As a result, urban modelers have continued to treat land use models, activity-travel demand models, and transportation supply or network models as separate entities, but each entity is loosely coupled with the other, with or without feedback loops. Land use model outputs serve as inputs to four-step travel demand models. Trip tables from the demand models are loaded onto networks using static traffic assignment models. Network level of service measures (usually travel times or other measures of impedance) from the assignment models may be fed back to trip distribution and mode choice models in the demand modeling system to reflect the effects of network performance on these aspects of behavior.

There is no question that the loose coupling of zone-based model systems across the land use, travel demand, and transportation supply dimensions has certainly served the profession well. With complex model structures difficult to estimate, and computing hardware and software what it was, there was no alternative but to resort to such loosely coupled model structures and frameworks. Even for such model systems, computational burden has not been negligible. Run times are easily exceeding several hours in large urban areas that deploy model systems encompassing thousands of zones, and associated model networks.

Given the state of affairs as described above, it is hard to imagine that the time is ripe for the development of truly integrated model systems of the urban continuum. What could motivate the development of integrated microsimulation models of the urban continuum that are likely to take days to run? There are three motivating factors that fall in the methodological and computational advances category that are briefly discussed in this section.

First, there have been key methodological advances in recent years that have made it possible to estimate very complex model structures efficiently without compromising on statistical robustness (desirable properties). If one were to consider the various behavioral aspects of interest including stochasticity, heterogeneity, and simultaneity, there is no question that more sophisticated model structures that reflect these aspects of behavior are called for. Over the past decade, the field of statistical and econometric modeling of travel behavior has experienced a quantum leap forward. The specification of sophisticated discrete choice models that accommodate and account for taste variations in the population is now possible through the use of mixing distributions such as that employed in the mixed logit model. The formulation of simultaneous equations model systems allows the representation of relationships among several activity-travel and land use variables in an integrated framework while explicitly recognizing the presence of common unobserved factors that affect them (error correlations). In the past, such model systems had to be estimated using cumbersome sequential estimation methods that resulted in model coefficients without desirable statistical properties (loss of efficiency due to limited information utilization). However, with the advent of efficient numerical integration methods.
that are characterized by intelligent draws over the domain space for the integration of distributions that do not offer closed form solutions, it has become possible to estimate complex specifications of simultaneous equations models of activity-travel behavior efficiently and accurately. More importantly, it has become possible to model aspects of behavior that were hitherto impossible to consider. It is now possible to model discrete choice processes characterized by multiple choices (as opposed to single choice processes), joint discrete-continuous model systems (combining a discrete choice process with a continuous choice process), and multi-dimensional choice model systems (incorporating more than two dependent variables of different types). The use of structural equations modeling methods has further facilitated the estimation and specification of integrated models of activity-travel demand and socio-economics. Thus, from a pure methodological perspective, the profession has reached a point where various aspects of behavior that were previously ignored can now be explicitly modeled using appropriate model forms and specifications. This has been made possible through methodological advances.

Second, the era of microsimulation as a means of modeling complex urban systems has arrived. The representation of stochasticity, variability, and heterogeneity in behavior calls for the use of microsimulation approaches. That is the only way by which individual differences in behavior can be reflected in urban systems models. In microsimulation approaches, the emergent behavior of agents in a system is modeled while giving due consideration to interactions that take place between agents. Microsimulation involves simulating the behaviors of these agents in space and time at the level of the individual decision-making entity. If residential location choices are made at the household level, then such choices are modeled for each household. If destination choice for a solo activity is made at the person level, then such choices are modeled for each individual. The disaggregate representation of the population in model systems allows one to virtually abandon the erstwhile zone configuration concept and treat each household or building (parcel) as a zone unto itself. As mentioned in the introductory chapter, the era of microsimulation has simultaneously impacted land use modeling, activity-travel demand modeling, and traffic network modeling. In the land use arena, microsimulation involves modeling market transactions at the level of the individual decision-making entity, whether that be a household or a business. In the activity-travel demand modeling arena, microsimulation involves modeling vehicle ownership, activity engagement choices, and trip making patterns at the level of the household and the person as appropriate. In the traffic assignment arena, microsimulation involves the representation of the movements of individual vehicles according to known characteristics and relationships that govern traffic flow. Microsimulation approaches can be easily implemented using software platforms available today and this finally leads one to the third major motivating factor in this category.

The third motivating factor in this category is that of advances in computational hardware and software platforms. In the past, concerns about software platform capabilities and computing power have hindered the move towards the development of comprehensive integrated model systems of urban enterprises. In the past few years, there have been major advances in computing and software programming that motivate a fresh attempt at developing an integrated model system. Modern computing systems are more powerful than ever and continue to become more powerful over time. More importantly, high power computing systems can now be run in parallel, thus contributing to substantial reductions in run times. Single desktop machines now come with four or more core processing units, thus facilitating parallelization of computations even within a single machine. With several machines of this nature running in parallel, the right software architecture, it is possible to run large complex model systems without undue computational burden. The right software architecture involves coding the system in a modular fashion so that different modules can be run on different
processors. Also, the system may be programmed such that the databases (population and networks, for example) can be carved into pieces and run separately on different machines. Information across subsets of data can then be integrated at the end of model runs that take place simultaneously. However, care should be exercised in doing this indiscriminately as loss of time may occur in read-write processes and data exchange across machines. The advent of the open source movement also falls within this category. Open source software provides the ability to make continuous improvements as a worldwide community of programmers constantly enhances and improves upon existing versions. As a result, although the prototype version may not be perfect in terms of run times, one can take comfort knowing that the day when a more efficient version becomes available, thanks to the open source nature of the enterprise, is not far away.

In summary, there are now methodologies that allow a behaviorally appealing representation of human choice and decision-making processes through the specification of sophisticated model structures. There are now microsimulation-based approaches that allow one to harness the full power of such behavioral model specifications by simulating human behavior and choices in the time-space domain at the level of the individual decision-making entity. Finally, computer hardware and software platforms and configurations now allow one to implement the methodologies and microsimulation approaches efficiently with run times that rival current run times experienced with aggregate and loosely coupled model systems.

**DATA AVAILABILITY AND DATABASE MANAGEMENT CAPABILITIES**

Although the data category is listed last in this chapter of the report, it is by no means the least significant. In fact, enhanced data availability and database management tools and capabilities are major motivating factors that have spurred the growth of interest in integrated model development. Large-scale travel surveys have been around for a long time; however, recent travel surveys have moved into the activity-based and time use arena. These enhanced travel surveys collect travel information in the context of activities that are pursued by people and, in some cases, collect detailed time use information for both in-home and out-of-home activities. Several surveys cover multiple days of the week, either for the same person or across the entire sample, thus facilitating the examination of day-to-day variability in travel behavior and weekday versus weekend travel demand. Activity information is being collected for all household members providing the ability to examine household interactions in the formation of activity patterns across all persons in the household. Repeated cross-sectional surveys (and at least two panel surveys) are now available in several metropolitan areas around the country and for the country as a whole, thus providing the ability to understand dynamics of behavior at the macro- and micro-level. The methodological advances referred to in the previous section offer the ability to estimate models of activity-travel behavior that harness the full information contained in these rich travel data sets. Many travel data sets are being enriched through the incorporation of stated preference data, transit samples, and sophisticated sampling schemes.

While advances in activity and time use data collection is certainly laudatory, the real significant quantum leaps have happened on two other major fronts. First, the use of GPS technologies to collect travel data by tracking people through space and time has made it possible to examine time-space paths and interactions in the context of real geographic locations and action spaces. Data on time-space paths and action spaces can be used to model time-space prism constraints, intelligently construct destination choice sets, and understand trade-offs people make between time and space (e.g., visiting a nearby destination, but spending more time at the activity versus visiting a far away location that is more appealing, but spending less time at the activity). GPS technology based surveys have, for the first time
ever, provided detailed information about people’s route choice behavior. Traditional travel surveys have offered virtually no information whatsoever about route and path choices. The GPS-based travel data sets have been examined to find out the extent to which individuals deviate from true shortest paths in traveling between origins and destinations. Complexity of path choice is further exacerbated by the large prevalence of trip chaining, and GPS-based travel data paint an accurate picture of path choice in the context of trip chains. Consistent with the collection of GPS-based data, geographic information systems (GIS) software have matured to a point that GPS data can be imported, analyzed, mapped, and visualized very easily and efficiently. The surveys are getting more sophisticated and low-cost and the software technology to collect, process, and analyze the data is consistently getting better.

On a second front, great strides have been made in the socio-economic and land use data arenas. It is now possible to analyze large census databases at the block or blockgroup level very efficiently using GIS. These systems allow one to decipher and analyze population distributions in space by age, vehicle ownership, transit accessibility, ethnicity, and income. Land use data is now available at the parcel level from property appraiser’s offices and other county and city databases in most jurisdictions. Having land use data at the parcel level provides the ideal environment for microsimulation of land use markets as people live and work in buildings, engage in transactions, and make decisions regarding future development tied to zoning policies and land use regulations. However, the management and analysis of parcel-level data is quite a daunting task given the size of such databases. Geographic information systems and open source database management systems such as PostgreSQL offer the ability to handle these databases and maximize the utilization of information contained in these databases.

A couple of additional developments in the data arena are noteworthy. There is a need for comprehensive network data to support microsimulation model systems of land use and transport. Network data should include the layout and geometry as well as a comprehensive set of attribute data. Network data has been consistently getting better and more accurate thanks to new mapping and routing publications such as Google Maps and Google Earth. Many jurisdictions have now obtained new and up-to-date data about their networks including all attributes of interest to land use – transport modelers (speed, travel time, number of lanes, capacity). Many areas have traffic count stations and traffic counting programs that provide vehicle classification counts by time of day in 5 or 15 minute blocks of time. All of this data is available for freeways and is becoming increasingly available for arterials as well. This information is critical to the calibration of land use models, activity-travel models, and dynamic traffic assignment models. This data is also critical to the validation process as model predictions are checked against true ground conditions for a base year.

There are concerns whether large parcel-level land use databases and detailed networks that include all links and nodes of an urban area transport system would entail prohibitive memory and storage requirements, and computer processing times. While these concerns continue to be valid, recent advances in database management systems and computational technologies offer much promise and it is unlikely that these concerns will prove to be a stumbling block on the road to the development of integrated urban systems models. Computing power and memory/storage capacity are constantly increasing while their costs continue to come down, thus making it possible to harness disaggregate data sets for microsimulation of urban systems.
ISSUES IN THE DEVELOPMENT OF INTEGRATED LAND USE – TRANSPORT MODELS

The first task in the project involved the identification of key issues and challenges in the development of an integrated model of the urban built environment, travel, and activities. Many of these issues have received attention in the literature and have been resolved in various ways by researchers and practitioners dealing with integrated modeling. This chapter is intended to provide an overview of these issues and the considerations that the research team is taking into account as it moves forward with resolving the issues.

CHOICE OF BEHAVIORAL UNIT

In the microsimulation model development context, an issue that arises is that of defining the behavioral unit at each stage of the simulation. Although this is somewhat of an issue in the context of model specification and estimation for disaggregate models that lie at the heart of traditional aggregate model systems, the issue is amplified in the context of microsimulation model systems that purport to explicitly model and simulate patterns of behavior and choices at the level of the individual behavioral unit chosen for the microsimulation.

Different model systems generally do not simulate behavior for the same behavioral unit. Table 1 provides an illustration of how different model systems and components are likely to use different behavioral units to represent choice processes.

<table>
<thead>
<tr>
<th>Model Component</th>
<th>Behavioral Unit</th>
<th>Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential location choice</td>
<td>Household</td>
<td>Household interactions</td>
</tr>
<tr>
<td>Workplace location choice</td>
<td>Person</td>
<td>Household interactions</td>
</tr>
<tr>
<td>Vehicle ownership</td>
<td>Household</td>
<td>Household interactions</td>
</tr>
<tr>
<td>Vehicle type choice</td>
<td>Household, Vehicle</td>
<td>Household interactions</td>
</tr>
<tr>
<td>Time-space prism constraints</td>
<td>Person</td>
<td>Household interactions</td>
</tr>
<tr>
<td>Activity type choice</td>
<td>Person</td>
<td>Household interactions</td>
</tr>
<tr>
<td>Activity timing (time of day choice)</td>
<td>Person</td>
<td>Household interactions</td>
</tr>
<tr>
<td>Activity linking/trip chain formation</td>
<td>Person</td>
<td>Time-space interactions</td>
</tr>
<tr>
<td>Joint versus solo activity engagement</td>
<td>Person</td>
<td>Household interactions</td>
</tr>
<tr>
<td>Vehicle allocation</td>
<td>Person</td>
<td>Household interactions</td>
</tr>
<tr>
<td>Activity location (destination choice)</td>
<td>Tour, Trip</td>
<td>Time-space interactions</td>
</tr>
<tr>
<td>Activity duration (time use)</td>
<td>Activity</td>
<td>Time-space interactions</td>
</tr>
<tr>
<td>Mode choice</td>
<td>Tour, Trip</td>
<td>Time-space interactions</td>
</tr>
<tr>
<td>Vehicular route choice</td>
<td>Driver, Vehicular Tour, Trip</td>
<td>Time-space interactions</td>
</tr>
<tr>
<td>Traffic simulation</td>
<td>Vehicle</td>
<td>Traffic flow characteristics</td>
</tr>
<tr>
<td>Transit assignment</td>
<td>Rider, Transit Tour, Trip</td>
<td>Transit schedules</td>
</tr>
<tr>
<td>Land use policies and regulations</td>
<td>Government agents, agencies</td>
<td></td>
</tr>
<tr>
<td>Land use development</td>
<td>Developer, Business Establishment</td>
<td></td>
</tr>
</tbody>
</table>
The fact that different model systems use different behavioral units is not a problem per se. It is, in fact, necessary and desirable to have different submodels operate on the behavioral unit that is appropriate to each submodel. What is necessary, however, is to ensure that adequate book-keeping is done throughout the model system so that the model system keeps track of households, persons, vehicles, riders, and other agents throughout the model system. By keeping track of all agents (perhaps in an object-oriented approach), one can ensure that the spatio-temporal location of each agent is known at all times and that interactions among agents (objects) can be adequately captured. The research team will need to make final decisions regarding the choice of behavioral unit for all model components and these decisions should be made with some consideration for consistency and transparency.

IDENTIFICATION OF CHOICE DIMENSIONS OF INTEREST

An integrated model system purports to represent the entire gamut of choices that characterize the urban continuum. These include location choices by households and businesses that occur on longer time scales and second-by-second turning movement choices made by drivers as they navigate their path between an origin and destination. In between, one has to consider vehicle fleet ownership and composition choices, workplace and school location choices, and the entire range of activity-travel choices. The first column of Table 1 provides an initial list of basic model components that would be included in the integrated model system. Accounting for inter-person interactions and group decision-making in households is gaining increasing attention in the activity-based modeling arena and therefore models of solo versus joint activity engagement and vehicle allocation will be included in the model system. Similarly, recent trends in which households have moved away from larger vehicles in favor of smaller fuel-efficient vehicles in response to rising fuel prices motivate the development of vehicle fleet composition or vehicle type choice models.

Each of these choice dimensions may include a series of submodel components that need to be identified and specified. For example, the land development model may include a real estate price model, an expected sale price model, a development choice model, and a building construction model. As the research team makes progress on the design and specification of the model system, the various submodels in each of the choice dimensions will be specified in detail.

REPRESENTATION OF SPACE

The representation of space is a major issue in the context of the development of integrated urban models. Many of the choice dimensions that are considered in integrated models are, by their nature, spatial. Traditional travel demand models have generally treated space at an aggregate level using the concept of the traffic analysis zone (TAZ). However, in moving to the microsimulation paradigm of modeling choice behavior and given the increasing availability of rich data sets, the profession has continually strived to move away from this aggregate representation of space and move towards a more disaggregate representation of space – in the extreme, space would be considered as a continuum.

There are many different geographical units of space that are captured in various data sets, and by extension, in model systems. Census data is available at the level of census tract, block group, and block. Land use data is available at the parcel level and parcels can be aggregated up to map to census geographies or TAZs. Also, one can map census geographies to TAZ boundaries. Within each parcel, one is considering the housing unit, building unit, or vacant real estate. Thus, there are many different ways in which space has been viewed and represented in data sets.
From a behavioral modeling perspective, data limitations may automatically impose constraints on how space is represented in the integrated model system. However, many choices remain. Should residential location choice be modeled at the level of the zone, group of zones (neighborhood), census tract or block, or parcel? How do people perceive and view space when making different types of location choices? For example, in the context of residential location choice, it is plausible that households first choose among regions based on affordability, type of housing, socio-economic characteristics, age of building stock, land use opportunities and accessibility, and proximity to job centers. Then, after choosing a region, households may choose among neighborhoods. Then, within a chosen neighborhood, households may choose among subdivisions or residential communities. Within a subdivision, a household will then choose a parcel (building unit). In other words, it is plausible that households go through a multi-stage process of residential location choice in terms of viewing space.

For tours and trips, destination locations may likewise be represented by zones at the one extreme and points or parcels at the other extreme. If an individual is going to visit a specific shopping center, then the representation of space using the parcel as the unit is appropriate. On the other hand, if the individual is going window shopping and wants to just browse around shops in an area, then a zone or tract may be the appropriate spatial unit of analysis.

The representation of space also has important ramifications for the definition and size of networks. As the spatial resolution increases, so does the fidelity of the transportation network that must connect all points in space. If origins and destinations are represented by parcels, then one would need to have all parcels or points connected by links and represented as appropriate nodes in the network. Vehicles will need to be routed between pairs of parcels that constitute origins and destinations. It is not clear if the activity-travel model and the traffic assignment model systems can yet support such a high level of spatial resolution. While the land use microsimulation model may operate at the level of the individual parcel, it is likely that land development and socio-economic characteristics would have to be aggregated to a higher spatial agglomeration for activity-travel location choice modeling and network assignment.

One of the issues associated with this approach is the need to feedback accessibility measures from the network assignment model to the land use development and location choice models. An assignment is likely to offer skims or network level of service variables for origin-destination pairs that are at a higher aggregation level than individual parcels. If, however, land use models are operating at the level of the individual parcel, then parcel-level accessibility measures are desirable. Desire for consistency in the feedback process will necessitate the introduction of algorithms that reconcile these differences in spatial representation.

**REPRESENTATION OF TIME**

Much of the inconsistency across models in the representation of space is likewise encountered in the representation of time, except that the trend is reversed. When one considers the time dimension, land use development patterns, business location and labor force choices, and household residential and workplace location choices tend to evolve over annual or multi-year time frames. At the other extreme, vehicular movements are simulated on a second-by-second basis. In the middle, vehicle ownership and fleet composition tend to be medium-term choices (but also multi-year in time frame), while activity and travel choices tend to be short-term choices. However, some activity-travel choices may also be considered longer term choices that are linked to household residential location and worker location choices. Thus, aspects of the commute trip may constitute a longer term choice, although the time of
departure, mode, and trip chaining pattern associated with the commute may constitute short term choices that vary from day to day. Activity engagement patterns, activity durations and time use allocation, solo and joint activity engagement, destination and mode choices, and time of day choices are day to day choices that could vary if the traveler wished to do so. What is important here is to recognize that the time dimension is not defined by the duration of constancy in behavior. For example, in the US context, it is conceivable that people have changed homes and jobs more often than they changed their mode choice to work (many have probably drove alone to work for several decades). However, that does not mean that the commute mode is a long term choice while household and work location choices are medium term choices. The definition of the temporal scale is based on the ability of an individual to change or modify the choice behavior. While an individual can change mode choice to work (if he or she wishes to do so) in the short term (for example, consider an alternative if the car breaks down or another household member needed to use it), it is generally implausible to think that an individual could change homes or work places at the drop of a hat. Thus, it is the transaction cost or duration that defines the temporal scale of a choice dimension.

Time-space interactions dictate the distances that people can cover by various modes within specified periods of time. The explicit consideration of time-space interactions provides the ability to intelligently sample destination choices for modeling activity location choices. Time-space prisms represent the constraints that influence and govern activity-travel patterns that are measured and observed in travel surveys. Activity durations and travel durations are generally constrained by the prism boundaries as these boundaries represent time-space coordinates that a person must adhere to; otherwise, the activity-travel pattern is infeasible as it violates a constraint that must be satisfied.

In considering time, the research team is clearly interested in recognizing the differences in temporal scale across choice dimensions. As long as different choice processes are modeled within their appropriate time scales, problems should not arise in model development and execution. Land use choice processes and vehicle ownership and fleet composition can be modeled at the annual time step, activity-travel choices can be modeled at the day-level along the continuous time axis (resolution of one minute), and traffic dynamics can be modeled at the resolution of one second.

**REPRESENTATION OF TIME-DEPENDENT MULTIMODAL NETWORKS**

The representation of networks has received considerable attention in the context of microsimulation models of land use and transport systems. Networks are typically represented by a set of nodes and links that connect nodes to one another in accordance with the geometric alignments prevailing in the system. Nodes representing zonal centroids are connected to the rest of the network using centroid connectors that represent average accessibility connections between the zone and the model network. Network conditions are typically based on the number of time of day slices that are considered in the travel demand modeling system. Similarly, transit networks are characterized by links and nodes, although additional elements are included in the system to account for transit access by walk and auto. Rarely, if ever, is explicit consideration given to transit schedules in traditional models where individual travelers (transit riders) are not followed through the course of a day.

In the microsimulation modeling context at the heart of this project, it is necessary to develop and use time-dependent multimodal networks that are of high fidelity and resolution. Highway and transit networks will continue to be represented by sets of nodes and links in space. Each of these nodes and links will have a series of attributes associated with them. Nodes will have information about turning movements, turning penalties, and if possible, traffic control devices and signal operations. Inclusion of
traffic control places a heavy burden on the development and definition of networks and may be beyond the scope of the resources available within this project. However, what is critical is to have a methodology and approach that can take advantage of such information were it available in the network files. Link attributes including number of lanes, traffic volumes, posted and operating speeds, capacity, geometric attributes (shoulder widths), percent trucks, and so on must be included in the network files. Cost information such as transit fare, parking pricing, and tolls would also have to be part of the network files.

Initial network attributes will allow the microsimulation process to get started. Then, as the simulations proceed and feedback processes are executed, the network attributes (generally, link travel times) are constantly updated, thus yielding a time-dependent network. At any point in time, one can get a snapshot of network conditions and those conditions are what drive activity-travel choices (activity agendas, activity and travel durations, destination choices) in the activity-travel demand model. Peak or average network conditions can be used to influence land use development and location choices in the next simulation year. Once again, the issue of network fidelity or resolution arises. The development and coding of extremely detailed networks with turning lanes and bays, driveways, and so on is an extremely cumbersome process that is likely to make the implementation of integrated microsimulation models practically infeasible for large urban areas. The research team is likely to start with the model networks and enhance model networks with additional detail as appropriate to reflect local streets and higher levels of spatial detail considered in the parcel-level land use microsimulation model system and destination choice models. Early experience and prototype testing of a dynamic traffic assignment and simulation model using the Puget Sound region model network shows great promise suggesting that greater levels of resolution may be introduced as the study matures.

Transit adds a challenging dimension in the microsimulation modeling context. When activity-travel patterns are simulated, there is no guarantee that the time of day choice will be consistent with the availability of transit as dictated by transit schedules. A high resolution transit network with full stop information, route information, and schedule information must be developed and integrated with the highway network to reflect the influence of transit on highway performance and vice-versa. In most instances, regular local buses ply on the same roads as the rest of the traffic and congestion affects transit travel times, leading to time-dependent skims for transit as well. Activity-travel agendas have to be adjusted to be consistent with transit, requiring additional feedback loops that may not be necessary in the context of auto travel. Transit schedules, transfer points, constraints, and access and egress opportunities need to be coded into transit networks so that individual riders can be simulated through their transit tour or trip. Not only do transit schedules affect activity timing, but transit route alignments and networks affect destination choices and mode choices, particularly in trip chaining contexts. The good thing is that much of this can be handled in a microsimulation context; however, suitable heuristics need to be embedded in the transit modeling process to keep track of riders, adjust their activity-travel patterns to be consistent with transit schedules and network performance, and track them through their tours to completion (for example, a traveler should not be left stranded at a time and place when transit is not available).

**REPRESENTATION OF BEHAVIORAL CHOICE PROCESSES AND DECISION HIERARCHIES**

Recent research in activity-travel behavior has focused on decision processes that result in the observed travel patterns reported in travel surveys. The idea is that revealed travel patterns are a manifestation of underlying choice processes and that it is important to attempt to replicate the appropriate decision process in model systems so that the resulting model predictions are appropriate manifestations that
one is likely to observe in the real world. In the traditional trip-based modeling paradigm, a sequential process of trip generation, destination choice, mode choice, and route choice is assumed to drive travel demand. While this simplification of the travel decision process has served the profession well for many years, the move to microsimulation based approaches affords the opportunity to consider more robust behavioral choice processes that reflect aspects of travel behavior that have hitherto been ignored.

Many activity-travel choices interact with one another. As mentioned throughout this report, activity type choice affects destination and mode choices, solo versus joint activity engagement, and time of day choice. Activity duration affects timing and vice versa. Travel durations affect activity durations and vice versa. Vehicle ownership affects mode choice and destination choice. Mode and destination choice may be considered a package of choices made jointly or a sequence of choices made separately. In all of these instances, multiple dependent (endogenous variables) affect one another calling for the adoption of simultaneous equations model systems that reflect the simultaneity in many choice processes. Even within simultaneous equations model systems, one needs to determine the appropriate model specification, error correlation structure, and dimensionality of the model system (Pendyala and Ye, 2005). If one were to consider the classical self-selection problem in residential location choice modeling, residential location choice is endogenous together with vehicle ownership and mode choice for the commute (for example). Then, these three variables have to be modeled simultaneously. While the decision hierarchy in this simultaneous equations model may be quite obvious, it may not be as clear in other multi-dimensional choice models of behavior. For example, is mode choice motivated by a complex activity pattern (characterized by substantial trip chaining) or is trip chaining motivated by the use of the automobile (that makes it inherently easier to trip chain)? These types of questions pervade the simultaneous modeling of longer term location choices and shorter term vehicle ownership and activity-travel choices. Recent work in this area has shed light on appropriate decision hierarchies and the activity-based microsimulation model system in this project will embed state-of-the-art simultaneous equations model systems estimated using the most efficient simulation-based estimation methods. These choice dimensions may best be modeled as a lifestyle package that reflects people choosing a certain lifestyle characterized by neighborhood traits, vehicle ownership, and activity-travel choices taken together.

In this regard, it is worth noting that behavioral heterogeneity may be prevalent even in the context of decision processes (Senbil and Kitamura, 2004). For the same individual, the behavioral choice process may vary from one context to another, and behavioral choice processes may be different across individuals. In other words, not only will a certain parameter or coefficient (say, reflecting the value of time) be different across behavioral units, but the actual model structure and decision hierarchy may be different across behavioral units. It is critical to identify such market segments using latent segmentation approaches as these segments are not explicitly known a priori by the researcher.

**REPRESENTATION OF STOCHASTICITY**

As noted earlier in this report, human behavior is characterized by considerable randomness that is best represented as a stochastic process using probabilistic model forms and specifications. Virtually all disaggregate choice models recognize this stochasticity through the introduction of error terms with suitable distributional assumptions imposed on these terms and error correlation matrices. The error terms represent the randomness in behavior and the influence of unknown factors.

The representation of stochasticity becomes easier in the context of microsimulation models of land use and transport systems. In a microsimulation model system, a random seed is used to run the simulation...
through the series of models and submodels and obtain one realization of the stochastic process represented by the model system. From this standpoint, the microsimulation paradigm is very appealing and offers substantial benefits in the modeling of human activity-travel behavior in the urban built environment.

The issue that needs to be resolved is that related to the number of model runs that need to be performed. There are two related concepts here. First, many runs can be performed and the results can be averaged across all runs so that one represents an average outcome or forecast. Second, many runs can be performed and all outputs can be reported in distributional form to capture the stochasticity that is embedded in the choice process. The distributions that result from many model runs may, in part, represent the uncertainty associated with the outcome of the choice process. Thus, in this study, it is envisioned that considerable testing will be undertaken to determine the appropriate number of runs of each model system and the entire integrated model system as a whole. It is not clear if the activity-travel demand and traffic network models embedded in the integrated model system have to be run many more times or the same number of times as the land use microsimulation model to obtain stable results, and consequently infer an average and a distribution of outcomes. New Bayesian approaches for evaluating uncertainty effects need to be considered to see if efficiency in model performance can be gained through the use of such techniques (Sevcikova et al, 2007).

**REPRESENTATION OF ACTIVITY TYPES**

The field of integrated land use - transport modeling often involves grappling with decisions about the fidelity or resolution in the representation of space and time. However, an issue that has consistently been debated in the context of activity-travel demand modeling (even in the trip-based four-step modeling paradigm) is that of the definition or resolution of activity types or trip purposes. The activity-based modeling literature is replete with examples of models in which activity types or purposes are simply categorized as mandatory (subsistence), flexible (maintenance), or discretionary in nature. Those that are mandatory are considered fixed in time and space, those that are flexible must be done but can be shifted in space and time, and those that are discretionary can be foregone all together. Traditionally, researchers and practitioners have considered work and school as mandatory activities, shopping and personal business as flexible activities, and social recreation as discretionary activities. Serve passenger activities are either mandatory or flexible and eat-meal activities are either flexible or discretionary. Although this categorization has served the profession well in the research arena, it does not provide the richness of information that is necessary for modeling travel in the context of the activities that are actually being pursued by people.

More recently, there has been discussion about the appropriate classification of activities and their treatment in terms of the levels of flexibility that may exist (Doherty, 2006). In today’s connected world, work and school are increasingly becoming anywhere-anytime activities, work follows individuals on vacations, and work is no longer as rigidly fixed in time and space. Also, the level of fixity varies from individual to individual and across contexts. On the other hand, some social recreation activities that have been traditionally considered discretionary may, in fact, have high levels of fixity. A child’s team sports event is often mandatory in nature with high level of fixity in time and space. A ball game occurs at a certain place and time, but may be foregone. Does this mean that it is discretionary or mandatory?

The above discussion points to the need to identify activities not only by the purpose (which remains an important characterization of activities), but also by the levels of time-space flexibility and fixity that may exist. An activity is now associated with several dimensions in addition to purpose – spatial
flexibility, temporal flexibility, and activity engagement flexibility (can it be foregone). In the activity-based model system embedded in the integrated model system of this project, activity purposes will be used similar to those postulated by Miller (2002). This is shown in Table 2. In addition, explicit attributes representing spatial, temporal, and activity flexibility will be attached to each activity. These attributes will be deciphered using rule-based heuristics developed on travel survey data sets, but this will remain a very challenging task and the research team will play close attention to this issue in the model development effort. The research team is trying to find a simple solution to address this issue.

Table 2. Representative Activity Types

<table>
<thead>
<tr>
<th>Activity</th>
<th>Possible Categorization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entertainment / Recreation</td>
<td>In-home, personal</td>
</tr>
<tr>
<td></td>
<td>In-home, joint</td>
</tr>
<tr>
<td></td>
<td>Out-of-home, personal</td>
</tr>
<tr>
<td></td>
<td>Out-of-home, joint</td>
</tr>
<tr>
<td>Formal Group Activity</td>
<td>Team sport game / practice</td>
</tr>
<tr>
<td></td>
<td>Attend religious service</td>
</tr>
<tr>
<td></td>
<td>Religious / community group meeting</td>
</tr>
<tr>
<td></td>
<td>Religious / community group activity</td>
</tr>
<tr>
<td>Household Maintenance</td>
<td>Household dwelling unit</td>
</tr>
<tr>
<td></td>
<td>Household vehicle(s)</td>
</tr>
<tr>
<td></td>
<td>Food preparation / clean-up</td>
</tr>
<tr>
<td>Informal Gathering</td>
<td>By project</td>
</tr>
<tr>
<td>Personal Business</td>
<td>Doctor</td>
</tr>
<tr>
<td></td>
<td>Dentist</td>
</tr>
<tr>
<td></td>
<td>Lawyer</td>
</tr>
<tr>
<td></td>
<td>Bank / Financial</td>
</tr>
<tr>
<td>Personal Maintenance</td>
<td>Sleeping</td>
</tr>
<tr>
<td></td>
<td>Eating (in-home; out-of-home)</td>
</tr>
<tr>
<td></td>
<td>Personal grooming (in-home; out-of-home)</td>
</tr>
<tr>
<td></td>
<td>Exercise (in-home; out-of-home)</td>
</tr>
<tr>
<td>Serve-Dependent</td>
<td>Supervise dependent</td>
</tr>
<tr>
<td></td>
<td>Chauffeur dependent</td>
</tr>
<tr>
<td>Shopping</td>
<td>Grocery</td>
</tr>
<tr>
<td></td>
<td>“Other consumables”</td>
</tr>
<tr>
<td></td>
<td>“Durables”</td>
</tr>
<tr>
<td>Socialize with Friends / Relatives</td>
<td>In-home</td>
</tr>
<tr>
<td></td>
<td>At their home</td>
</tr>
<tr>
<td></td>
<td>Out-of-home</td>
</tr>
<tr>
<td>Work</td>
<td>Desk-based (working independently)</td>
</tr>
<tr>
<td></td>
<td>Internal meetings (interaction with co-workers)</td>
</tr>
<tr>
<td></td>
<td>External meetings, local clients, conferences, etc.</td>
</tr>
<tr>
<td></td>
<td>External meetings, out-of-town clients, etc.</td>
</tr>
</tbody>
</table>

INDIVIDUAL TRAVEL CHOICES VERSUS SYSTEM EQUILIBRIUM

Following the seminal work by Beckmann, McGuire et al. in 1956, research advances in transportation system-demand equilibrium analysis has established a solid foundation for the traffic assignment procedure to serve as the critical modeling step to map travel demand to transportation system networks. The outcome of traffic assignment now often serves as the principal inputs for the development of metropolitan transportation plans (MTP) and project-level analyses (Chiu et al, 2007). Research advances in dynamic traffic assignment (DTA) in the last two decades have created a renewed opportunity to properly extend the Wardrop’s user equilibrium principle in a dynamic time-varying manner, rendering a more realistic modeling approach to study the changing transportation system performance dynamics resulting from time-varying travel decisions.

Several early studies have extended the User Equilibrium (UE) problems to the so-called dynamic user equilibrium (DUE) problem (Mahmassani and Herman 1984; Wie et al, 1987; Ran and Shimazaki 1989; Boyce et al, 1995). One category of DTA formulations commonly seen in the literature assumes that the time-dependent origin-destination trip departure pattern over the simulation (analysis) period is known a priori, thereby removing the departure time choice dimension. This leads to time-dependent user equilibrium traffic assignment (TDUETA) models. The objective of this type of model is to obtain a TDU flow pattern by equilibrating time-varying experienced trip times given time-varying O-D trips within a modeling period.

One of the first contributions to the TDUETA problem was a heuristic proposed by Yagar (1975), which was one of the earliest approaches to recognize the importance of adequately capturing queuing phenomena in this problem. Since the late 1980s, the TDUETA modeling approaches have begun to branch out into analytical and simulation-based methods. These two approaches differ in the network loading as well as the associated assignment solution algorithms. Within the class of general analytical DTA problems, a wide range of studies can be found in literature. Most of these approaches relied on link exit functions to represent traffic congestion. Several studies specified functional forms for the link exit function and most of these assumed certain mathematical properties (Wie et al, 1987). Ran and Boyce (1994) formulated a continuous TDUETA model in which the link outflows were treated as a set of control variables rather than as functions to overcome difficulties presented by the non-linearity of the link exit function for multiple origin-destination networks. A common challenge associated with analytical TDUETA models is that the First-In-First-Out (FIFO) property, used as a proxy for model tractability, is problematic and/or is not explicitly addressed in most analytical TDUETA models.

Existing time-dependent TDUETA formulations mostly fall into two categories based on how the temporal dimension is treated: discrete time mathematical programming formulations and continuous time optimal control formulations. Friesz et al (1989) proposed a time-dependent generalization of Beckmann’s equivalent optimization problem (for a static UE) in the form of an optimal control problem. Following Ran and Shimazaki (1989), Boyce et al (1995) formulated a convex optimal-control model for TDUETA by defining inflows and outflows on links to be control variables. They discussed a methodology to solve the discretized version of the problem using the Frank-Wolfe algorithm and an expanded time-space network representation. No implementation or illustration of the procedure has been reported. In addition, the use of static link performance functions may preclude adequate modeling of the dynamics of congested traffic behavior.

Because of the limitations of analytical performance functions in capturing FIFO and traffic congestion phenomena, simulation-based approaches have been developed. Mahmassani and Jayakrishnan (1991)
computed a stochastic DUE in a corridor network where traffic performance was represented with a traffic simulation model using the Method of Successive Averages. In their model, the simulation based algorithm consisted of an iterative procedure in which a mesoscopic traffic simulation model, DYNASMART, was used to represent the traffic interactions in the network, thereby evaluating the performance of the system under a given assignment (Peeta, 1994; Peeta and Mahmassani, 1995). The use of a traffic simulator to evaluate the objective function and model system performance circumvented the need for link performance functions and link exit functions, ensured the FIFO rule was met, captured link interactions, and precluded unintended holding of traffic, thus ensuring consistency with realistic traffic behavior. The procedure assigned vehicles to various paths directly, obviating the need to infer a path assignment from the solution to a link-based formulation. An excellent review of DTA models has been given by Peeta and Ziliaskopoulos (2001).

Due to its modeling flexibility, the simulation-based DTA has become the paradigm for most commercially or academically available simulation-based transportation planning software tools, such as INRO’s DYNAMIC (INRO, 2005), VTG’s VISTA (VTG, 2007), DYNASMART-P (Chiu and Mahmassani, 2000; Mahmassani et al, 2007), DynusT (Chiu et al, 2009a; Chiu et al, 2009b), and MALTA (Villalobos et al, 2008; Villalobos et al, 2009). Due to computational burdens, most of the existing transportation planning projects using DTA are limited to corridor based analysis for peak hours only (Mahut et al, 2002; Ziliaskopoulos and Chang, 2004; Ziliaskopoulos et al, 2004; Balakrishna et al, 2005; Mahut et al, 2005; Zhou et al, 2008). No regional traffic assignment over a long (full day) period is found in the literature. Chiu and Nava proposed the Method of Isochronal Vehicle Assignment (MIVA) that provides a significant breakthrough in advancing the computational efficiency of DTA algorithms (Chiu and Nava 2009a; Chiu and Nava, 2009b). A case study in El Paso, Texas applying the MIVA technique demonstrated that MIVA enables the DTA model to be able to analyze daily traffic patterns (Chiu and Villalobos, 2008).

One important issue that remains for further consideration in this research study is the incorporation of heterogeneity across individual travelers in the equilibrium analysis framework. Considering heterogeneity seems to be trivial in the context of microsimulation of travel and activities. However, the fundamental entity in equilibrium analysis is usually flow comprising a homogeneous group of entities that make the same choice (route or departure time, for example) without needing to differentiate their other individual decisions under various conditions due to personal attribute differences. This is because equilibrium analysis explicitly jointly establishes and estimates the conditions at which the demand-supply states are stabilized. Heterogeneity introduces added modeling and solution algorithm complexity and therefore, elevates the intractability for computing solutions.

On the other hand, if one is to apply agent-based type of simulation models that allow stochasticity to dominate the outcome of the modeling process, then the stability, consistency, and robustness of the model outcomes become questionable. Unstable model outcomes may not be acceptable from a policy-making standpoint. As a result, it is paramount to seek a balanced modeling approach that properly incorporates heterogeneity and stochasticity while ensuring stable, consistent, and robust system performance states.

**CRITICAL FEEDBACK PROCESSES: BEHAVIORAL AND COMPUTATIONAL**

Integrated model structures call for the incorporation of feedback processes to reflect behavioral processes at play and to ensure consistency in link attributes between those used in the destination and mode choice model components and those obtained through the dynamic traffic assignment procedures.
of the model system. There are numerous feedback processes that reflect the behavioral adjustments and adaptations that may be warranted as a result of network conditions. In an activity-based modeling paradigm, congestion on the network may result in longer travel durations than originally anticipated by the traveler. When travel durations increase, various types of adjustments are possible. First, the traveler may delete an activity episode (presumably, a discretionary one is deleted first) from the activity agenda simply because there is not enough time to pursue that activity. Second, a flexible activity may be shifted in space or time to accommodate the increased time spent traveling. For example, if it is likely that a time-space prism constraint is going to be violated, an activity may be shifted to another open time-space prism period, thus shifting the activity in time. Alternatively, the activity may be pursued at an alternative destination which is closer to the current location of the traveler thus resulting in savings in travel time and adherence to time-space prism constraints. Another possibility, particularly for those activities where spatial and temporal fixity is quite rigid, includes a modification of the activity duration of the activity. For example, if one is running late for work, a movie, or a restaurant, the duration of that activity may be shortened by the amount equal to the excess travel time. The converse is also true; when travel times are less than anticipated, then a new activity may be inserted into the agenda, an activity originally scheduled for a different time period may be shifted in time to fill up the excess time available in the current time-space prism, a traveler may visit a more desirable destination that is farther away, or an existing activity may simply be prolonged in duration to fill up the extra available time.

The above discussion points to the impact that network travel times and conditions can have on activity generation, activity scheduling, time of day choice, destination choice, and activity linking or trip chaining. It is critical then to incorporate feedback loops from dynamic traffic assignment back to the components of the activity-based travel model system dealing with these choice dimensions. While there is certainly a behavioral motivation for the incorporation of feedback loops as noted here, there is also a key computational consistency motivation for the inclusion of feedback loops (Siegel et al, 2006). At the end of the process, it is desirable to ensure that network travel times resulting from the dynamic traffic assignment are consistent with those used to generate activities, destination choices, time of day choices, and trip chaining patterns. Consistency in link attributes between assignment and trip distribution and mode choice steps in the context of current models is a notion that has been addressed by Boyce and Bar-Gera (2003, 2006) in detail. They suggest the use of averaging techniques as a means of implementing efficient convergent feedback processes and find that it outperforms more naïve feedback processes where no such averaging techniques are deployed. Figure 2 constitutes a representation of the convergent feedback process depicted by Boyce and Bar-Gera (2006). In this context, it is necessary to establish convergence criteria for each feedback loop in an integrated model system. It is not clear as to what appropriate convergence criteria are, and how they can be established in a consistent and intuitive (as opposed to ad hoc) way.

Finally, it should be noted that accessibility measures from the dynamic traffic assignment model in one year feed into the land use microsimulation models of the following year. Land use choices including household residential location choice, workplace location choice, and business location choices are influenced by accessibility and network level of service. This connection between dynamic traffic assignment model and the land use microsimulation models is not feedback and does not involve an iterative process until stability or consistency in values is achieved. This connection represents an evolution of the system over time where network accessibility of one year affects land use development patterns of the following year. This is described further in the model design chapter of this report.
CONSISTENCY AND PARSIMONY IN DATA STRUCTURES

An integrated model system utilizes large amounts of data, particularly in the context of microsimulation approaches. In a microsimulation model system, land use at the parcel level, activity-travel plans for each and every person in the population, network files with link attributes and node information, and route paths for each trip generated in the system are just some of the databases that are used as inputs or obtained as outputs. All of these databases include information at a disaggregate level and are inevitably going to be large. Many of these databases can be organized, stored, managed, and manipulated using GIS.
Computational efficiency concerns require that consistency and parsimony in data structures be adopted in the context of the development of the integrated model system. Mode choice and destination choice models use network level of service measures to model choice behavior. Similarly, land use microsimulation models use network level of service measures from one year to model development and location choices of the following year. Socio-economic data is used by the population synthesizer and in modeling location choices in the land use microsimulation model system. The dynamic traffic assignment model and model calibration and validation steps involve the use of traffic volume information. In other words, there are multiple model components that use the same data items as inputs to model different choice behaviors of interest. There is no reason to have and maintain multiple databases with multiple sets of the same information. Not only is this inefficient from a database management standpoint, but it also increases the risk of inconsistency in data values of the same variables across disparate databases. It is desirable to have parsimony in databases where different model components can access the same information from the same database as needed.

The research team plans to define databases in the context of Task 5 of the research project. The databases will be defined in detail to ensure both parsimony and consistency in definition. Intermediate databases that will be generated by the model system, presumably in binary format to speed up operations, will also be identified and decisions will be made as to how and when they will be stored. In the spirit of open source software development, the research team plans to use open source platforms for maintaining and handling the large databases that are part of the integrated model system. Database platforms such as MySQL and PostgreSQL and open GIS platforms such as qGIS are just some of the platforms that the research team is considering for database handling, management, and visualization.

**MODEL CALIBRATION AND VALIDATION**

Model calibration and validation is an important process in the development and implementation of any model system. These issues get amplified in the context of an integrated model system that includes several model systems embedded within it. In model calibration process, the outputs of the model are compared against observed trends and distributions in the travel survey data set that was used to estimate the various model components. This is primarily applicable to the activity-based travel demand model system where such survey data is available and comparisons can be made to calibrate the model to replicate behaviors seen in the surveys. Model validation cuts across all model components and involves comparing aggregate outputs from the model systems against ground counts, link traffic volumes, transit route ridership and stop boardings, and land use population and business/employment characteristics to ensure that the model system is capable of replicating true real-world conditions. This is done for a chosen base-year and is consistent with standard practice in model validation.

The research project includes two tasks devoted to model calibration and validation in this study. This is because model calibration and validation has to be done for each model system individually, and for the entire model system as a whole. In other words, just because each individual model system is calibrated and validated in its own right, it does not mean that the entire integrated model system is automatically validated. When one integrates model systems and incorporates feedback loops, results are no longer the same, processes are different, convergence criteria are re-established, and different numbers of simulation runs may be necessary to obtain stable results. As a result, it is necessary to re-calibrate and re-validate the integrated model system even after individual model components are subjected to their own calibration and validation processes.
The model validation process is not straightforward. For each model, appropriate knobs that can be used to adjust models to replicate ground conditions need to be identified. At what point should models be re-specified and re-estimated? At what point is it sufficient to tweak model parameters and coefficients to replicate ground conditions for the base year? What are the model parameters and coefficients that can be adjusted without compromising the integrity of the model system itself, and without having secondary adverse effects on other components of the model system? Are there automatic or semi-automatic calibration and validation processes that can be programmed into the system so that the degree of manual adjustment necessary to validate a model is minimized? For example, a process can be set up where model outputs are compared against select base year volumes and counts, and depending on the difference, models adjusted and re-adjusted through a series of iterations until these values are close enough to meet a preset convergence criteria. Guidelines on model validation that specify the degree to which model outputs ought to replicate ground counts are available and can be brought to bear on this project. Nevertheless, the research team will have to establish appropriate calibration and validation targets for various entities within the context of an integrated model system. What are the validation targets for links, zones, paths and routes, household and person travel plans, and so on?

Although calibration and validation is often done at the aggregate level (comparing model outputs against ground conditions for the base year), it is possible to incorporate a series of logic checks within the context of a microsimulation model system. What good is a model that replicates ground conditions in the aggregate, but provides illogical results at the disaggregate level? For example, household and person travel plans have to be logical and consistent. Children cannot be abandoned, a person cannot be at two places at one time, joint activities across household members should be consistent in terms of destinations, modes, and activity/trip times, and so on. Similar simple logical rules apply for the land use microsimulation model and the dynamic traffic assignment model. The research team will set up a series of logic checks for each component of the model system and subject the model system to these logic checks. Any failure of logic will call for an appropriate revision to the model system.

MODEL ASSESSMENT AND SENSITIVITY ANALYSIS

One of the key motivations for the development of a truly integrated model system that is consistent in terms of behavioral representation and links the entire gamut of choices constituting the urban continuum is the ability to analyze policies and impacts of socio-economic changes in an integrated and robust modeling environment. The integrated model system provides the ability to capture the primary, secondary, and tertiary impacts of changes in the system as effects are felt throughout the model continuum. Land use development choices may be impacted; these impacts, in turn, affect household and business location choices, the entire range of activity-travel choices, and dynamic traffic patterns. As such, the integrated model system constitutes a major leap forward in the ability to analyze policy impacts and capture the entire set of changes brought about by changes in system conditions.

Although the model system will be subject to calibration and validation routines as described previously, the research team feels that this is not sufficient to assess a model system. A model must eventually be responsive to a host of policy changes, socio-economic conditions, network attributes, and travel demand management measures. The model system should be able to respond to land use policies including those that promote transit-oriented development along new major transit routes and light rail lines and zoning policies that promote new mixed use development in an area. The model system should be able to reflect the impacts of corridor or area-wide pricing policies, fuel price shifts, parking
Modeling the Urban Continuum in an Integrated Framework

Tasks 1 & 2: Identification of Issues and Conceptual Model Design

pricing, and the entire range of network level of service impacts. These include anything from simple
capacity expansion to more sophisticated dynamic tolling methods that can be analyzed using dynamic
traffic assignment models embedded within integrated model systems. The model system should be
capable of responding to shifts in socio-economic conditions in the area. Shifts in population and
employment characteristics bring about shifts in activity-travel demand. All of the changes noted here
may happen at the macro- or micro-level and the model system should be able to respond to these
changes appropriately.

Model testing and sensitivity analysis is being done by model developers as a means of assessing the
reasonableness of model forecasts. The research team will test and assess each model component and
subcomponent in addition to the entire model system as a whole. The set up of a careful experimental
design to facilitate the model testing and sensitivity analysis process is not a challenge in itself. The
challenge comes in determining whether the model responds appropriately. For example, if population
or income levels are increased by a certain amount, it is not clear as to what the correct model response
ought to be. Although there may be some qualitative expectations regarding the direction and
magnitude of changes in activity-travel patterns and land use patterns that such changes would bring
about, it is generally unclear what the exact quantitative impact should be.

In this context, the research team is exploring the possibility of using information from an ongoing study
funded by the Ohio Department of Transportation to help inform the model assessment and sensitivity
analysis task of this project. In that effort, the Ohio DOT is comparing forecasts of the tour based model
against those obtained from the traditional trip-based model. Forecasts are being compared for real
projects on the ground where before and after data is available and before and after conditions are
known with certainty. As the principal investigator is a member of that project team, he is in discussions
with the Ohio DOT to explore the possibility of obtaining the before and after data from that project to
assess and test the sensitivity of the model system developed in this project. The research team will
also explore alternative sources of such data where the actual change in travel brought about by a
system change is known and can be used to assess the integrated model system.

SOFTWARE ARCHITECTURE AND COMPUTATIONAL ISSUES

The development of integrated microsimulation model systems has been stymied, at least in part, by
computational limitations. Many individual microsimulation model systems (land use, activity-travel
demand, or dynamic traffic assignment) have been reported to take several hours, and sometimes days,
to run. This is particularly true for large urban areas where one is dealing with millions of parcels in
land use model systems, millions of persons in activity-travel demand model systems, and tens of
millions of trips in dynamic traffic assignment. Add a few feedback loops to the mix and the
computational burden can be staggering indeed.

The research team is cognizant of the sensitivity that the community has expressed over the years to
computational burden and model run times. There is also considerable concern in the community about
the hardware and software resources required to run model systems of this nature. The research team
therefore understands that the need for computational efficiency is important. The research team has
extensive experience with the development of open software architectures that take advantage of
parallel processing. By distributing a model system across processing units, the computational burden
and run times can be drastically reduced. This parallelization can be accomplished in several ways. A
geographic area can be divided into regions and each region can be run separately on different
processors. The population of a region can be divided up into several parts and each subset of the
population can be simulated on different processors. The same can be said for networks. On the other hand, the model system can be divided into parts where certain model components are run for the entire area on one process and other model components are run on other processors.

Several issues arise in the parallelization of the process and in giving due consideration to computational efficiency and burden. It is likely that some compromises will have to be made to reduce run times and enhance computational efficiency. What compromises can be made without defeating the purpose of the development of the integrated model system? Would the relaxation of convergence criteria on feedback processes make a substantial difference in run times? Does the level of resolution along the time or space dimensions need to be made more coarse to speed up the process? What are the implications of breaking up the geographic area, networks, or the model system across processors? What kind of parallelization would yield the greatest benefits in terms of run time without compromising consistency across the different parts running on different processors?

The research team believes strongly in the development of comprehensive user documentation. All of the principal investigators have had a history of preparing user documentation in the context of their own respective model development efforts. Among the final deliverables for this project is a comprehensive users guide for the integrated model system methods and tools developed in this project. The research team is also wedded to the concept of open source code so that the community can access, use, enhance, and share the source code over time. It is hoped that these aspects of the model development effort will ease the burden associated with trying and deploying integrated model systems, and help accelerate the movement towards the implementation of such models in practice.
DESIGNING AN INTEGRATED MODEL OF THE URBAN BUILT ENVIRONMENT, TRAVEL, AND ACTIVITIES (iMUBETA)

The concept of integrated modeling of the urban built environment, travel, and activities is not new. Such large scale model systems have been considered and envisioned for at least 40 years. Nearly 35 years ago, Lee (1973) provided a harsh critique of first-generation land use models and noted the seven deadly sins of such large scale models including hypercomprehensiveness, grossness, data hungriness, wrongheadedness, complicatedness, mechanicalness, and expensiveness. He also criticized such models for their lack of theory. Nearly 20 years later, Lee (1994) once again took a look at attempts to develop large scale urban models and, although noting some progress, criticized the model systems for their lack of theory and for falling between the cracks in the sense of being neither scientific in their foundation nor particularly useful in practical application. In 2003, Timmermans (2003) continued to admonish the profession for making inadequate progress in moving the integrated modeling agenda forward and bemoaned the lack of a fundamental understanding of behavioral processes to drive the structure and specification of such model systems.

Despite these misgivings and concerns, there is no doubt that considerable progress has been made in the conceptualization of integrated modeling frameworks – frameworks that integrate land use, activity-travel demand, and transportation networks or supply in a unifying paradigm. In some instances, not all three entities have been considered simultaneously. Such frameworks consider the integrated land use – travel demand modeling paradigm or the integrated travel demand – transportation supply modeling paradigm. Nevertheless, these frameworks attempt to link model systems in a consistent and behaviorally robust manner, employ microsimulation approaches, and incorporate feedback loops to represent behavioral processes and ensure consistency in network attributes between the demand side and the supply model of the modeling enterprise.

This section presents some of the progress that has been made and then presents an overview of the model design that is envisioned and planned for this project.

CONCEPTUAL FRAMEWORKS FOR INTEGRATED MODEL DEVELOPMENT

Miller (2006) defines an integrated model as that which tries to “model the spatial evolution of a given study region system state over time as a function of various socio-economic, demographic, and political processes”. He notes that the region’s system state is highly multi-dimensional and usually includes the spatial distribution of the region’s resident population over time, the spatial distribution of the region’s employment and other out-of-home activities over time, the personal travel that occurs from point to point within the region over the course of a representative time period, and the flow of goods and services from point to point within the region over the course of a representative time period. The concepts of space, time, networks, and socio-economics/demographics are central to the development and implementation of policy-relevant integrated urban model systems. These concepts are embodied in the ILUTE (Integrated Land Use, Transportation, Environment) modeling framework proposed by Miller (Salvini and Miller, 2005). Figure 3 presents the overall structure of the ILUTE modeling framework. The shaded box represents the ILUTE model components while those outside the box constitute exogenous factors. Demographics, regional economics, government policies, and transport system attributes are considered exogenous to the system; however, the two-way arrows suggest that these entities are informed by and influenced by outcomes of the ILUTE model system. Similar relations
exist with traffic flows and travel times, and external impacts (e.g., air quality). More notably, within the context of the ILUTE model system itself, appropriate feedback processes are put in place to reflect the influence of travel choices on auto ownership, location choices, and land use development patterns. Location choice models embody household and business location choice processes while the activity/travel and goods movement entity includes the entire gamut of activity-based travel demand model components and freight transportation models. This fundamental framework offers a simple, yet useful, overall conceptualization of the integrated urban modeling enterprise.

Figure 3. Structural Overview of the ILUTE Model (Salvini and Miller, 2005)

A special issue of *Transportation* published in 1996 contains noteworthy papers relevant to the development of integrated urban model systems. In fact, the conceptual frameworks presented in several of those papers have played a major role in shaping the model structures that have been developed more recently and in shaping the model vision of the research team. One of the papers, by Stopher et al (1996), presents a Simulation Model of Activities, Resources, and Travel (SMART). Figure 4 presents the overall conceptual structure for SMART. It can be seen that Stopher et al (1996) envisioned a model system that included consideration of market prices for land, land use policies and constraints, and household resources and constraints. These are aspects of the urban modeling enterprise that the research team plans to explicitly consider in the integrated model system developed as part of this project. In the SMART model structure, land uses are endogenous to the model system, household characteristics including resources and constraints influence the formation of activity-travel patterns, and appropriate feedback loops are incorporated to reflect the influence of network performance measures on land use, socio-economics, regional change, and infrastructure investments.
In the same issue of *Transportation*, a paper by Kitamura et al (1996) presents a comprehensive Sequenced Activity Mobility Simulator (SAMS) that constitutes a sequential model system of the entire urban system. This model structure is one of the key drivers of the model system that is envisioned to be developed in this project. The comprehensive model system included an Urban Systems Simulator that predicted land use development patterns, land transactions, and building stock. Land use policies and network level of service or accessibility measures explicitly influenced land use transactions and development, similar to that in the model system proposed in this project. The Urban Systems Simulator interfaced with a Socio-Economic/Demographic Simulator that essentially served as a population synthesizer and population evolution model. Through this interaction, location choices were predicted. These fed into a Vehicle Transactions Simulator. Most model systems include simplistic vehicle ownership models that simply predict the number of vehicles in a household. Such models do not provide any information about the age or composition of the fleet. The Vehicle Transactions Simulator determines vehicle holding durations and the types of vehicles owned by the household. The Activity-Mobility Simulator (AMOS) is at the heart of the model system and constitutes a full-fledged activity-based travel demand model system that simulates activity-travel patterns along the continuous time axis. This model system has since been enhanced to incorporate time-space prism constraints (Kitamura et al, 2000). Finally, the Dynamic Network Simulator interfaces with the Activity-Mobility Simulator to route trips and determine link flows and link travel times along the continuous time axis. Figure 5 presents an overview of SAMS, with explicit consideration of feedback from the Dynamic Network Simulator to the Activity-Mobility Simulator, the Vehicle Transactions Simulator, and the Urban Systems Simulator.

Another paper that appeared in the same issue is that by Ben-Akiva et al (1996). That paper constitutes one of the early presentations of the tour-based modeling paradigm that has begun seeing implementation in practice in several metropolitan areas around the country. Several of the tour-based
model systems in practice can be traced to the original conceptualization by Ben-Akiva et al (1996). The overall model structure that they proposed is shown in Figure 6.

Figure 5. The Sequenced Activity-Mobility Simulator (SAMS) (Kitamura et al, 1996)
It can be seen from their model structure that they too considered longer term choice processes that define mobility and lifestyles. These include choices of employment, housing, activity program, auto ownership, and information technology accessibility. The activity-travel scheduling model constitutes the activity-travel simulator where activity-travel patterns are predicted for each individual in the microsimulation. The tour-based travel models implemented in practice have essentially involved deeply nested logit models of primary tour formation, secondary tour formation, time of day choice, destination choice, and tour-based mode choice with log-sums feeding from one level to the upper level to reflect the impacts of one dimension (accessibility) on another. Some of the more recent tour-based models are also reflecting household interactions in activity engagement and vehicle allocation (Gliebe and Koppelman, 2005; Bradley and Vovsha, 2005).
The modeling paradigm embodied in the Ben-Akiva et al (1996) paper may be considered a precursor to the integrated model system that has been proposed by Bradley et al (2008) for implementation in the Puget Sound region. The integrated model system combines the tour-based travel model systems with other model components. For example, UrbanSim constitutes the land use microsimulation model while existing network traffic assignment models constitute the supply side of the enterprise. The existing network assignment models can presumably be replaced with dynamic traffic assignment models in the future. Feedback processes provide for the influence of accessibility measures on land use development patterns and location choices. The proposed integrated model design for the Puget Sound region is shown in Figure 7 (Bradley et al, 2008).

Figure 7. Proposed Integrated Model Design for the Puget Sound Region (Bradley et al, 2008)
The proposed PSRC model design is a simple and practical operational model design that can be implemented relatively quickly and easily, and builds on some of the recommendations of a comprehensive model design developed previously for the agency (Waddell et al, 2001). From the standpoint of practical implementation, it has several merits and serves as an excellent starting point for the operationalization of integrated model systems with feedback processes. The intent of the current research project is to go beyond what can be accomplished with the model design depicted in Figure 7. Instead of a tour-based travel model, a full-fledged activity-based travel model system that considers time-space constraints and simulates activities and trips along the continuous time axis will be employed. Instead of aggregating trips into origin-destination matrices for static traffic assignment, dynamic assignment of trips through appropriate routing and simulation will be undertaken.

More recently, Bhat has proposed a comprehensive model system of the urban environment called the Comprehensive Econometric Microsimulator of Urban Systems (CEMUS) (Eluru et al, 2008). CEMUS constitutes an integrated model system much like what the research team envisions and plans to implement as part of this research project. CEMUS includes various model components including a Synthetic Population Generator, a land use microsimulation model system called CEMSELTS (Comprehensive Econometric Microsimulator of Socio-Economics, Land Use, and Transportation System), and a full-fledged activity travel simulator called CEMDAP (Comprehensive Econometric Microsimulator of Daily Activity-travel Patterns). Aggregate-level base year socio-economic data are first fed into the synthetic population generator to produce a disaggregate-level synthetic dataset describing a subset of the socioeconomic characteristics of the households and individuals residing in the study area. Additional base-year socioeconomic attributes related to mobility, school, employment, residential/vehicle ownership, and any other variables that may be difficult to synthesize directly from the aggregate socio-economic data for the base year are simulated by CEMSELTS. The base year socio-economic data, along with activity-travel environment attributes, are then run through CEMDAP to obtain individual-level activity-travel patterns. The activity-travel patterns are then subsequently passed through a dynamic traffic assignment model to obtain path/link flows and level of service measures. These measures are fed back into CEMSELTS to reflect the influence of accessibility measures on location and mobility choices, thus indirectly impacting activity-travel patterns simulated by CEMDAP. Upon reaching a stable state, forecast year outputs are obtained. The overall framework is shown in Figure 8.

Several additional model systems that attempt to integrate land use and travel models are worthy of note. These model systems do not explicitly include all three modeling entities – land use microsimulation, travel demand, and transportation supply. Instead, these models often consider the land use microsimulation model to be exogenous, although it is clearly evident that network accessibility measures from the transport model system would influence land use development patterns in a future year. These model systems offer valuable frameworks, particularly in the context of integrating travel demand and transportation supply models.

A more recent structure is that proposed by Gliebe (Waddell et al, 2007). The model structure is quite appealing in that it represents a practical model system that can be implemented in the context of tour-based travel demand models that are finding their way into practice today. At the same time, it incorporates elements of dynamic activity generation as tours are built dynamically through stop-making choices within the activity-travel pattern simulator. The model includes specific elements to capture long term location choices and has an explicit component to represent initial conditions. In most model systems, initial conditions are not modeled explicitly and the feedback from assignment to the initial conditions module offers an appealing way of adjusting times at which people start their
travel day to account for network conditions. The model system saves both trip lists and origin-destination matrices, thus facilitating an interface with either static or dynamic traffic assignment models. Figure 9 presents the structure proposed by Gliebe.

![Figure 8. Comprehensive Econometric Microsimulator of Urban Systems (CEMUS) (Eluru et al, 2008)](image)

Lin et al (2008) report on an attempt to integrate an activity-based travel model with a dynamic traffic assignment model in the context of Bhat’s CEMDAP and Waller’s VISTA. These packages constitute activity-based travel demand and dynamic traffic assignment microsimulation model systems respectively. The objective of the Lin et al (2008) study was to develop a conceptual framework and explore practical integration issues for combining the two streams of models. Technical, computational and practical issues involved in the demand-supply integration problem are discussed in the paper. While the framework is general in nature, specific technical details related to the integration are explored by employing CEMDAP for activity-based modeling and VISTA for the dynamic traffic assignment modeling. Solution convergence properties of the integrated system, specifically examining different criteria for convergence, different methods of accommodating time of day and the influence of step size on the convergence are reported. Further, the integrated system developed is empirically applied to two sample networks selected from the Dallas Fort Worth network. Figure 10 presents the conceptual framework of the demand-supply integration proposed in Lin et al (2008).
Figure 9. Gliebe’s Dynamic Activity-Based Model System (Waddell et al, 2007)
Figure 10. Integrated Model of Bhat’s CEMDAP and Waller’s VISTA (Lin et al, 2008)
In the international arena, a noteworthy effort in the development of integrated demand-supply models is that of MATSim (MATSim Development Team, 2007). The Multi-Agent Transport Simulation (MATSim) model offers a mechanism for explicitly connecting activity schedules derived from an activity scheduler with dynamic network models. Activities are rescheduled iteratively depending on the feedback from the network. The process starts with a population synthesizer to generate individual agents whose activities and travel need to be simulated. Then, the process proceeds to a MATSim initialize where the initial activity-travel demands of agents are simulated. This includes the simulation of activity agendas, activity schedules, and location and mode choices. The entire agent database including socio-economic and activity-travel information is then fed into an Iterative Demand Optimization Process – Evolutionary Algorithm. In this algorithm, activity-travel schedules are routed using a dynamic Dykstra router and travel times are assigned to activity-travel schedules. The routes are then executed using a stochastic queue-based agent traffic simulation algorithm. Based on the results of the execution, scores are computed to characterize the learning process whereby travelers score their travel experience, learn from their experiences, and then readjust behavior in an attempt to improve their travel scores. This process continues iteratively until an optimal condition where individuals can no longer improve their scores is achieved.

Closer to home, the TRANSIMS (Transportation Analysis and Simulation System) constitutes another example of a model system where the demand and supply sides are simulated in an integrated framework with consistency and feedback across modeling modules (see TRANSIMS Overview available at http://transims-opensource.org/index.php?option=com_content&task=view&id=54&Itemid=91). The appealing facet of TRANSIMS is that it is capable of incorporating multimodal networks with explicit layers for highway, transit, and walk links. These layers can be interconnected to reflect travel across different modes of transportation. The process starts with a population synthesizer to generate a synthetic population of the region with socio-economic attributes. An activity generator then simulates activity-travel patterns for individuals using a regression tree algorithm. This includes the determination of activity type, possible locations, mode preferences, start and end times of the activity, participants, vehicle preference, and activity priority. The assignment of activities from survey households to synthetic households is done based on household demographic characteristics. The demographics of synthetic households must match the demographics of the survey households. A classification and regression tree algorithm (CART) is used to group the survey households having similar activity time patterns according to these demographic characteristics. The activity matching is done for each individual member of the synthetic household based on age, gender, and relation. Each activity in the list of activities assigned to each individual has an associated activity type (i.e. work, shopping, school, etc), duration, mode preference, beginning time, and ending time. The Route Planner module in TRANSIMS produces route plans for every individual according to the activity list generated by the Activity Generator. Moreover, the Route Planner selects the shortest-time path in the network for each individual trip. In addition to the activity list from the Activity Generator, the inputs to the Route Planner module include the TRANSIMS network (transit data and network data), the vehicle file, and the link travel times as feedback from the microsimulator. TRANSIMS creates a unique algorithm called a label-constrained, time-dependent shortest path which is a modification of Dijkstra's algorithm in order to select routes for each trip plan of an individual member of a synthetic household. Finally, the Traffic Microsimulator module in TRANSIMS executes travel plans and computes the overall intra- and intermodal transportation system dynamics. The Traffic Microsimulator is updated every second to ensure that dynamic vehicle behaviors are captured with enough fidelity to generate realistic overall traffic behavior. Each individual moves from one activity to another according to the plan obtained from the Route Planner, using combinations of modes such as walking, driving, or riding in a vehicle. All vehicle movements are simulated in detail to include driving on roads, stopping for signals, accelerating,
decelerating, changing lanes, stopping to pick up passengers, etc. Vehicles follow a set of rules that guarantee that no vehicle collisions will occur. This movement is accomplished by using a cellular automata principle. Each section of roadway is divided into cells where each cell either contains a vehicle or is empty. Simulation is carried out in discrete time steps. For each second, the vehicle decides whether to accelerate, brake, or change lanes in response to the nearby vehicles in the grid. The simulation guarantees that each vehicle makes decisions based on the state of every other vehicle in its surroundings at the same time.

The foregoing discussion is illustrative of the widespread interest in the development of integrated model systems for forecasting land use, travel demand, and network dynamics. The intent of this research project is to build upon these frameworks, utilize the knowledge and experience that has been gained, and develop an integrated urban model system that advances the cause of integrated modeling.

A CONCEPTUAL OVERVIEW OF THE PROPOSED MODEL SYSTEM

This section presents a simplistic representation of the conceptual overview of the proposed integrated model system. Many of the issues and challenges associated with the development of an integrated model system were articulated in the previous chapter of this report. It is inevitable that some of the issues will arise in the context of the development, implementation, and operationalization of the proposed model system, but the research team is confident that appropriate solutions can be formulated to address the issues and challenges in the context of Task 4 of the research project.

Figure 11 presents the conceptual overview of the model design for the implementation of the base year integrated model system. First, the algorithm starts with initial origin-destination trip tables. These trip tables may currently exist in the context of four-step travel demand models that agencies utilize for their transportation planning processes. These trip tables may also be synthesized using link traffic counts and there are sophisticated maximum likelihood and other techniques for synthesizing such origin-destination tables from observed traffic counts. The initial O-D trip tables are fed into the network simulation component of the dynamic traffic assignment model. Essentially, any dynamic traffic assignment model includes time-dependent networks, assignment, and simulation. The network simulation component of the dynamic traffic assignment model will simulate traffic movements in the network in accordance with the demand represented by the O-D tables. The resulting link volumes are checked against observed link counts to determine if the simulation is adequately representing true ground conditions. The original trip tables may have to be adjusted, using O-D table synthesis methods, in order to ensure that the network simulation results in link volumes that closely match ground counts. This initial process constitutes the first loop in the overall model system.

Upon the completion of the initial network simulation with adjusted trip tables to replicate ground counts, the origin-destination travel times resulting from the network simulation are obtained. These travel times constitute an accurate representation of travel times in the network, considering that they are based on link volumes that closely match ground counts. The travel times are fed into the activity-based microsimulation model system. The activity-based microsimulation model system simulates individual activity-travel patterns for a synthetic population of individuals for the base year. The activity-travel patterns (plans) are provided to the dynamic traffic assignment model. The dynamic traffic assignment model assigns the trips onto time-dependent shortest paths (TDSP) in accordance with the origin-destination travel times that were used to generate the activity-travel patterns in the first place. Therefore, there is an arrow from the origin-destination travel times box to the time-
dependent shortest path assignment box, and there is an arrow from the activity-travel simulator to the time-dependent shortest path assignment box as well.

![Flowchart of Proposed Integrated Model System (iMUBETA): Base Year Operation]

There are a few components of the model that are not depicted in the flow chart in the interest of brevity and clarity. Census data is used to synthesize a population for the base year. The synthetic population is then allocated to individual parcels and building units using the land use microsimulation model system. The residential and workplace location choice models in the land use microsimulation model system provide long term location choices for individuals and households. All of the individual socio-economic characteristics and household and workplace location attributes are inputs to the activity-travel simulator. In the base year, much of the population synthesis and the land use microsimulation constitute exogenous entities that provide inputs to the model system.

Upon the completion of the time-dependent shortest path assignment, the movements of assigned trips are simulated in the network simulation component of the dynamic traffic assignment model. As mentioned earlier in the report, the dynamic traffic assignment model is capable of tracking individual vehicles through their routes, while using macroscopic traffic flow characteristics to represent speed-flow-time relationships. The network simulation results in a new set of origin-destination travel times that are once again fed to the activity-based microsimulation model system. Activity-travel patterns of...
individuals are adjusted in accordance with the new travel time information and these amended patterns, together with new origin-destination travel times, form the basis of an updated time-dependent shortest path assignment. The assignment results are used to simulate network conditions yet again and a new set of origin-destination travel times are obtained. The process is repeated until the origin-destination travel times (and therefore, simulated link volumes) do not change from one iteration to the next. Appropriate convergence criteria must be applied to determine an acceptable stopping point for this iterative process. This constitutes the second loop of the base year integrated model system.

When the process stops, the origin-destination travel times (and any other accessibility measures of interest) are fed into the land use microsimulation model system for the next time step (usually taken as one year in the land use modeling context). In a future year, the application of the model system is a little different from that in the base year. The conceptualization of the process for a future year is shown in Figure 12.

In the future year operationalization of the integrated model system, the land use microsimulation model system uses the accessibility measures from the previous year or time-step to simulate land transactions and markets. New areas may get developed, new office buildings may be built, and so on. As a result of these land use changes, individuals may relocate or change job locations, and businesses may relocate as well. Based on the new development pattern, a new synthetic population is generated. When a full-fledged population evolution model is in place, the synthetic population from the base year can simply be evolved over time to obtain the synthetic population for the future year, while controlling
for marginal totals that are generated by the land use microsimulation model and other exogenous regional macroeconomic models.

Once the land use model is complete and a new synthetic population is generated, the activity-travel simulation process can take place for the horizon year. The activity-travel simulator takes information from the land use model and the population synthesizer, combines it with network level of service measures from the previous year, and generates activity-travel patterns for all individuals along the continuous time axis. However, there is a unique angle here that is being explored and proposed by the research team. For many individuals in the population, there is simply no change that takes place from one year to the next. Everybody in the household ages by one year, but otherwise the household is intact with exactly the same home, work, and school arrangements and socio-economic structure. In that case, it is largely unlikely that activity-travel patterns will change in any substantive way for these households. So, it is sufficient then to simulate activity-travel patterns for those households and individuals who have actually experienced a transition other than aging by one year. For example, a residential relocation, a job relocation, a life changing event, a change in socio-economic status or structure, reaching a threshold age (such as retirement age, movement from one level of schooling to another), a vehicle transaction, and/or worsening congestion may all contribute to changes in activity-travel patterns. The research team would like to define a set of criteria that would warrant a complete simulation of activity-travel patterns for households and individuals, and a set of criteria that would not warrant such a complete simulation effort. For households that experience no change, the previous year’s activity-travel patterns can be adapted, perhaps with some random minor perturbations to account for random variations that may take place from one year to the next. This formulation would greatly speed up the simulation process and substantially reduce computational burden and model run times.

The remainder of the process mimics that seen in the base year model design. The activity-travel simulator generates activity-travel patterns that are fed into the time-dependent shortest path assignment algorithm of the dynamic traffic assignment model. The assigned trips are simulated through the network using mesoscopic traffic simulation techniques and new origin-destination travel times are obtained. These new travel times are fed back into the activity-travel model to adjust activity-travel patterns. The adjusted activity-travel patterns and new set of origin-destination travel times are fed into the time-dependent shortest path assignment routine once again. The assigned trips are simulated through the network and new link volumes and travel times are obtained for the next iteration. When origin-destination travel times and link volumes no longer change from one iteration to the next, the process stops as per a user-defined convergence criterion. The feedback processes depicted in the proposed model design are similar to the convergent feedback processes proposed by Boyce and Bar-Gera (2006), and methods of successive averaging (direct averages or weighted averages) will be deployed to enhance the efficiency of the convergence process. The new link travel times and accessibility measures are fed to the land use microsimulation model of the future year and the process continues for as many horizon years as desired by the analyst.

POPULATION SYNTHESIS

Activity-based microsimulation model systems and land use microsimulation model systems require a disaggregate population for the urban area under consideration so that long term location choices, medium term vehicle ownership choices, and shorter-term activity-travel choices can be simulated at the level of the individual decision-making unit, whether it be a household or a person. Population synthesizers have been developed in the context of microsimulation approaches to activity-travel
demand modeling, starting with that developed by Beckman et al (1996) for TRANSIMS. These synthetic population generators typically use census-based marginal distributions on household attributes to generate joint distributions on variables of interest using standard iterative proportional fitting (IPF) procedures. Households are then randomly drawn from an available sample in accordance with the joint distribution such that household-level attributes are matched perfectly. However, these traditional procedures do not control for person-level attributes and joint distributions of personal characteristics. As a result, while household attribute distributions (joint distributions) are matched perfectly in the resulting synthetic population, the person attribute distributions are not necessarily matched very well. When population synthesis is done for small geographies such as census blocks or block groups, the mismatch in person attribute distributions can be considerable.

In an effort to improve upon previous population synthesizers, the research team has developed a new population synthesizer called HIPGen, the Heuristic Iterative Population Generator. This synthetic population generator generates synthetic populations whereby both household-level and person-level characteristics of interest can be matched in a computationally efficient manner. The algorithm involves iteratively adjusting and reallocating weights among households of a certain type (cell in the joint distribution) until both household and person-level attributes are matched. In addition, the population synthesis procedure embedded in HIPGen is capable of correcting for zero-cell and zero-marginal problems that are encountered when population synthesis is done for small geographies. The census public use microdata sample (PUMS) serves as the disaggregate data set from which households can be drawn according to the weights computed through HIPGen. Figure 13 offers a concise overview of the overall procedure for population synthesis in HIPGen.

The synthetic population generator interfaces with the land use microsimulation model system in two ways. First, information from the land use microsimulation model is used to obtain population control totals that can be used to start the iterative proportional fitting algorithm and generate joint distributions of attributes of interest. Once the synthetic population is obtained, then the land use microsimulation model implements location choice models to assign households to residential building units and workers to job locations. Thus, the synthetic population generator and the land use microsimulation model system go hand-in-hand and the research team is currently engaged in an effort to integrate HIPGen in an urban land use microsimulation model system. In addition, the synthetic population serves as an input to the activity-travel microsimulator so that activity-travel patterns can be simulated for each individual along the continuous time axis. The current version of HIPGen has been found to be extremely computationally efficient with a synthetic population of more than three million individuals residing in more than 2000 block groups being synthesized in about four hours using a high-end personal computer with a quad-core processor.

The research team recognizes that the ideal model design calls for the development and integration of population evolution models whereby a synthetic population from one year can be aged and evolved over time through the life course. The current version of HIPGen requires users to obtain population control totals for each horizon year and synthesize the population to match those control totals. In many instances, such control totals may not be available, and even if they are available, it would be desirable to use such control totals to validate the population evolution models which can explicitly account for life course events and structural dynamic changes in population characteristics (aging of the population, labor force participation and drop-out, child-bearing, household formation and dissolution, and so on).
Figure 13. Heuristic Iterative Population Generator (HIPGen)

**Step 1: Estimate Household and Person Type Constraints**
- Household and person sample data
- Household and person level marginal distributions
- Adjust priors to account for zero-cell problem
- Adjust marginals to account for the zero-marginal problem
- Run Iterative Proportional Fitting (IPF) to estimate household and person-type constraints

**Step 2: Estimate Household Weights**
- Household and person sample data
- Household and person-type constraints from Step 1
- Run an Iterative Proportional Updating Algorithm to estimate sample household weights that satisfy both household and person-type constraints

**Step 3: Generate the Synthetic Population**
- Household and person sample data
- Household weights from Step 2
- Adjust the household type joint distributions to get the frequency of different household types in the synthetic population
- Estimate household selection probability distributions using the estimated weights
- Create synthetic population by randomly selecting sample households based on selection probabilities for each Household type
- Repeat the last procedure to obtain a desirable Synthetic Population so that the person joint distribution is closely matched
The research team is now working intensively on the development of a set of population evolution models based on recent research efforts reported in the literature. Sundararajan and Goulias (2003) report on a demographic microsimulation system called DEMOS that builds on some of the earlier work by the first author on the development of a demographic forecasting tool called MIDAS (Goulias, 1991). DEMOS is a longitudinal simulation model that evolves persons during the simulation. An individual is simulated through the entire simulation period in annual increments before proceeding to the next individual in the population. This method of demographic simulation is reported to be more computationally efficient and less intensive in terms of data read/write activities.

Figure 14 shows the flowchart describing the functioning of DEMOS. After reading input data regarding an individual and progressing the individual through the first year, the household attributes are determined first. Then, person attributes are simulated, the use of information and communication technologies is simulated, and finally a set of activity-travel models are deployed to simulate activity-travel patterns. If a child is born during the simulation, the child’s behavior is simulated after that of the mother. Similarly, if an additional member is added due to marriage, then the new person is simulated based on data about the member in the original database. A user can specify the number of years and the number of simulations or replications for each person to be simulated.

In Figure 15, the order in which life course events are simulated in DEMOS is depicted. The process starts with a check on “death” to see if the person is to be retained in the population. Following death, based on gender, the individual is exposed to a “birth” event to see if a new person enters the simulation. The next event is that of a child leaving the home, which is applied to individuals 25 years of age or less. Based on marital status, an individual is then exposed to marriage or divorce. In all cases, household attributes for other members of the household are adjusted to maintain internal consistency. A series of other household attributes and personal attributes are then simulated using probabilistic models of such items as labor force participation, driver’s license holding, and occupation type. Observed distributions in the population and transition matrices are used to carry out the simulation for these attributes.
Figure 14. Flowchart of DEMOS Simulation (Sundararajan and Goulias, 2003)
More recently, Bhat and his colleagues (Eluru et al, 2008) have developed a comprehensive framework for population evolution in the context of a comprehensive microsimulation modeling enterprise for urban systems. The population evolution model structures and paradigms outlined in the Bhat approach appear to be an appropriate point of departure for developing a population evolution model in the context of this project. Figure 16 presents the overall analysis framework for the population evolution model proposed by Bhat. The model system includes a migration model system to account for households moving in and out of the region. Then, there are three components in the socio-economic evolution system, one for individual level evolution and choices, one for household formation and dissolution, and one for household-level long term choices.
Individual level evolution and choice models facilitate the simulation of individual-level evolution processes including demographics related to aging, deaths, and births, personal mobility-related choices of obtaining a driver’s license, and school and employment participation choices. Figure 17 depicts the range of models and phenomena accounted for by this submodel system.
Figure 17. Individual-level Evolution and Choice Models in CEMSELTS (Eluru et al, 2008)

The Household Formation and Dissolution model system accounts for evolutionary processes that may occur at the household level. The marriage/cohabitation models describe the decision of single adults to marry or enter a cohabiting arrangement and consequently form a new household. The second set of models involves representing the marriage/partnership dissolution process, typically through a divorce or separation event. A move-in model accounts for persons moving into a household while a move-out model accounts for persons leaving the household. Those leaving the household may form their own
new household, join another existing household, or simply move out of the region. Figure 18 depicts the household formation/dissolution model system.

**Figure 18. Household Formation/Dissolution Models in CEMSELTS (Eluru et al, 2008)**

Bhat’s model of population evolution then proceeds to a set of household long term choice models including residential relocation decisions (move, housing type, housing location), automobile ownership and transaction decisions (number, type of each vehicle in household in terms of body type/size and age, decision to purchase/acquire/trade or replace), and information and communication technology ownership decisions (telecommunications devices, internet access, computers). Finally, the model also includes a bicycle ownership model. All of these models (choice processes) are embedded within the land use microsimulation model system or the activity-based microsimulation model system proposed in this project. It is possible that these submodels can be isolated into their own entity to mimic the structure proposed in Bhat’s model. However, as these models are likely to be well integrated in the respective microsimulation model systems already in place, it is not necessary to do so. For example, longer term residential and employment location choices are modeled in the proposed system within
the land use microsimulation model system. The auto and bicycle ownership choices are modeled as a precursor to the activity-based microsimulation model system, with appropriate feedbacks. At this time, the research team has not yet made a decision regarding the reflection of information and communication technology choices in the model system. A decision will be made on this aspect depending on data availability and model logic.

**LAND USE MICROSIMULATION**

The design and implementation of the land use microsimulation model system is based on extensive experience that Prof. Waddell of the research team has amassed over the past decade (Waddell et al, 2003). The original vision of an integrated microsimulation model system that captures the entire range of choices of households and businesses stemmed from some of his early work in this arena and is presented in a concise form in Figure 19.

![Figure 19. Vision for Modeling the Urban Choice Continuum](image)

Consistent with the two basic philosophies that guide this project, i.e., microsimulation and behavioral representation, the land use microsimulation model system proposed for implementation in this project mimics market transactions and agent based interactions in a robust integrated urban systems model. In many ways, it is truly representative of the urban systems simulator originally envisioned by Kitamura et al (1996). More importantly, the disaggregate nature of the model allows one to account for self-selection in household and employment location choices, where households and individuals choose to locate in areas that suit their mobility and lifestyle preferences (Pinjari et al, 2007). The overall structure and framework of the model system is shown in Figure 20.
Figure 20. Structure and Logic Flow of Land Use Microsimulation Model System (Waddell et al, 2008)

The model is designed to mimic the behavior of households as they purchase or rent housing stock, transition from one state to another, relocate, and choose job locations. Similarly, businesses also make location choices according to market forces and conditions. Real estate developers and the development community make decisions about where to develop new land and price the land and new building stock that is built. Thus, the land use microsimulation model system is a market-based behavioral model system representing the behaviors, interactions, and transactions among various agents. The boxes in the flowchart that are not shaded constitute integral components of the land use microsimulation model system.
A multitude of factors are considered in modeling location demand components of the land use microsimulation model system. For example, factors that affect household demand for housing types and locations may include (Waddell et al, 2008):

- Housing type: single family, residential with 2-4 units, or multi-family
- Accessibility to total employment
- Accessibility to retail employment
- Net density in units per acre of a particular housing type in a zone
- Number of housing units of a particular housing type in a zone
- Average age of the buildings of a type in a zone
- Percent of households in a zone in the lowest income group
- Percent of households in a zone in the second lowest income group
- Percent of households in a zone in the highest income group
- Percent of households in a zone that have one or more children
- Percent of developed land in the zone that is in industrial use
- Percent of developed land in a zone that is in residential use
- Travel time to the central business district (CBD), in minutes

Similarly, factors that impact business demand for building types and locations may include:

- Building type: Industrial, Warehouse, Retail, Office, or Special Purpose
- Accessibility to total population, total employment, and high-income households
- Basic employment in a zone per square mile
- Retail employment in a zone per square mile
- Service employment in a zone per square mile
- Accessibility to basic, retail, and service employment
- Total square feet of commercial space of a particular type
- Building age
- Net density of the building type in a zone
- Percent of developed land in a zone in industrial use
- Percent of developed land in a zone in retail use
- Travel time to the CBD, in minutes
- Presence of a highway in a zone

Factors considered in the land development and redevelopment components of the model system may be categorized under several classes. They may be described as follows:

- Expected Revenue
  - Current market price for type of development at zonal location
  - Quantity and type of development feasible under development rules
- Expected Costs for New Development
  - Land cost
  - Hard construction costs (replacement cost of structure)
  - Soft construction costs (development impact fees, infrastructure costs, taxes, or subsidies)
- Density of Development
  - Regulatory constraints (land use plan, urban growth boundary, environmental constraints)
  - Land value
  - Land use
- Filter for Considering Developed Parcels for Redevelopment
  - Improvement to land value ratio of parcel
- Additional Costs for Redevelopment
  - Current building improvements
  - Demolition costs

The inclusion of these factors offers a range of capabilities and policy sensitivity in the land use microsimulation model system. The research team will explore ways to further enhance the behavioral representation of the model components. For example, it is plausible that households choose residential locations based on quality of school districts and crime statistics. If it is possible to obtain such data at the level of spatial resolution required for land use microsimulation modeling, these factors may also be included in the model specifications. It should be noted that these statistics are not necessarily required at the individual parcel-level; rather it is sufficient to have such data for aggregate geographical units such as tracts, zones, block groups, or zip codes. People often look at these statistics at a more aggregate level and therefore the mismatch in spatial representation is not likely to be an issue in considering these factors in household residential location choices.

Each of the boxes represented in the flow chart includes a series of submodels. It is rather cumbersome to represent and identify all submodels within a conceptual flowchart. Suffice to say that a series of submodels are estimated to address each of the behavioral phenomena identified in the conceptual design. For example, the following land development submodels are included in the system:

- Real estate price model
- Expected sale price model
- Development proposal choice model
- Building construction model

Household location model component includes the following submodels (which are explicitly identified in the framework):

- Household transition model
- Household relocation model
- Household location choice model

Similarly, employment location model component includes the following submodels:

- Employment transition model
- Employment relocation model
- Employment location choice model

Finally workplace location model component includes the following submodels:
- Economic transition model
- Home-based job choice model
- Workplace location choice model
- Job change model

The structure of a typical model component showing the submodels that would be included and the flow of information across modeling modules is shown as an illustrative example in Figure 21. Similar model structures exist for other modeling components of the land use microsimulation model system.

![Figure 21. The Structure of a Typical Location Model](image)

It is noteworthy that several aspects of population evolution that were described as part of the population synthesis process are already captured by modules of the land use microsimulation model system. These aspects of population evolution may be eliminated from the population synthesis and evolutionary process model that was described in the previous section. However, it is critical to ensure that there is tight integration across the population evolutionary processes handled in the population synthesizer and those handled in the land use microsimulation model system. As the research team moves forward with the design and development of the population evolution model system, a tight integration between the model components of the population evolution model and the land use microsimulation model will be ensured.
ACTIVITY-TRAVEL MICROSIMULATION

The activity-travel microsimulation model system design is derived from activity-based model development efforts that Dr. Pendyala, the principal investigator of the project, has been involved in over the past 15 years (Pendyala et al, 1998; Pendyala et al, 2005). The activity-based microsimulation model system is capable of simulating activity-travel patterns of individuals along the continuous time axis with one minute serving as the level of time resolution. Activity-based microsimulation model systems should be capable of representing time-space interactions and prism constraints that affect and govern daily activity-travel patterns (Kitamura et al, 2000). History dependency in activity engagement should be reflected through the incorporation of lagged dependent variables that reflect the history of activity engagement until the current time step under consideration (Kasturirangan et al, 2002). Thus, if an individual has already engaged in shopping activity earlier in the day, then the likelihood of pursuing another shopping activity later in the day drops. Similarly, the activity duration dedicated to a shopping activity would be lower as well, due to satiation effects. Incorporation of interactions among household members is now gaining increasing attention in the context of activity-based model systems. Household interactions result in joint activity engagement (coupling constraints), activity-task allocation among household members, and vehicle allocation among household members. Thus, there are several aspects of behavior – most notably the incorporation of time-space interactions and time use allocation behavior with continuous representation of time – that distinguish activity-based model systems from tour-based model systems that are seeing implementation in practice at this time.

Figure 22 presents a concise overview of the proposed model structure for the activity-based microsimulation model system that the principal investigator has formulated and refined over the years. In this model system, census socio-economic data and information from a household travel survey are combined with initial network level-of-service measures to synthesize a population in the household attributes generation system. Not only does the household attributes generation system include a population synthesizer, but it also includes model components capable of simulating an activity-travel skeleton of fixed or mandatory activities for each individual in the same household. This system also embeds a household and work place location choice model so that the spatial aspects of the activity-travel skeleton can be defined. A time-space prism constraints model formulated using the stochastic frontier modeling methodology defines closed and open periods for each individual. Individuals are able to engage in activities and travel during the open periods and must remain at the fixed activities during the closed periods. The system then proceeds to the prism constrained activity-travel simulator. This simulator constitutes the heart of the activity-based model system. Within each open period, the activity-based model system simulates activity engagement, activity durations, destination and mode choices including mode transitions within and between trip chains, and activity scheduling and rescheduling in response to congestion on the network. The prism constrained activity-travel simulator does so while respecting the time-space prism constraints modeled in the household attributes generation system. The activity-travel plans or records produced for each person constitutes a list that can be dynamically assigned using dynamic traffic assignment models, or aggregated to origin-destination flows by time of day block to perform static or dynamic traffic assignment. The origin-destination travel times from the dynamic traffic simulator are fed back into the household attributes generation system and prism-constrained activity travel simulator until convergence criteria are met.
Figure 22. Framework for Activity-Based Microsimulation Model System
Figure 23 presents an overview of the structure of the prism constrained activity travel simulator at the heart of the activity-based model system.

In the prism-constrained activity-travel simulator, one starts at the beginning of an open period. In this open period (which constitutes a time-space prism bounded by constrained or closed periods), one examines whether there is time to pursue an activity. If no time is available in the prism, then the individual must proceed to the next fixed location or activity. The mode choice model is run, while respecting modal constraints and schedules, any existing activity duration is adjusted to fill up the prism, and the open period ends. If, however, time is available to pursue an additional activity, then an activity type choice model is run to determine which activity will be pursued. History dependence variables are included in the model specification to reflect satiation effects. A combined destination-mode choice model is run to determine the location that the individual will pursue the activity and how the individual will get there. The range of destinations that can be visited by walk will be very different than those that can be visited by transit and likewise with respect to the automobile. The hazard-based activity duration model is run to determine the amount of time that the individual will pursue the activity. Then, a split population survival model is run to determine if the individual wishes to engage in more activities or prolong the current activity. If the individual does not wish to engage in more activities within the open period, then the mode choice is adjusted (to ensure modal consistency and constraints are respected), activity duration is adjusted and the open period ends. If an individual chooses to participate in additional activity, then the process starts again with a check of time available in the open period.
this way, activities are simulated in the time-space domain with explicit recognition for history dependency, time use allocation behavior, time-space prism constraint effects, and modal consistency. Trip chains are automatically generated as a result of this activity-travel simulation process, which is fundamentally different from the tour-based modeling approach where primary and secondary tours are set up in the beginning.

Figure 24 shows how a daily schedule may appear in the context of daily time-space prisms. This figure may apply to a worker who has regular work schedules. It can be seen that the prism constrained activity travel simulator includes several consistency checks and rules throughout its procedures. In this regard, the activity-travel microsimulation model system proposed here is a hybrid set of rule-based heuristics and analytical econometric modeling systems (Arentze et al, 2001).

![Figure 24. Representation of Time-Space Prisms in Daily Activity Schedule](image)

There are several additional noteworthy considerations in the context of the development and formulation of the activity-based microsimulation model system. Many of the features and functions of the household attributes generation system are now subsumed by the new population synthesizer/evolution model and the land use microsimulation model system. The new population synthesizer (HIPGen) and its successor population evolution model take care of synthesizing the population and its attributes. The land use microsimulation model system takes care of household and employment location choices. Thus, these functions no longer need to be embedded within the activity-travel microsimulation model system. In the final model implementation, all of these overlaps across model systems need to be reconciled and fully integrated in a seamless manner to ensure consistency, and avoid redundancy that can lead to unnecessary computational burden and internal conflicts.
The issue of feedback is one that the activity-based microsimulation modeling team has grappled with for quite some time. The original design, as depicted in Figure 22, called for a routine feedback process wherein origin-destination travel times from the dynamic traffic assignment model were fed back to the activity-travel simulator to adjust activity schedules, destination and mode choices, and activity durations. This process would be repeated until the travel times between two successive iterations showed no appreciable difference as per a user-defined convergence criterion. This process appears to work well and the proposed model design for this project is consistent with this paradigm for feedback.

However, the activity modeling team has worked recently on methods that take an approach more similar to that seen in TRANSIMS. Taking a leaf out of the TRANSIMS approach to activity-travel routing and microsimulation, the original design was modified to couple the activity-based travel demand model system with a dynamic event-based network simulator (Kitamura et al, 2008). In this approach, each trip coming out of the prism constrained activity travel simulator constitutes an event. All of the events are simply listed in chronological order to represent the diurnal generation of travel in a region. Each event is then routed on the network as per the current network conditions. As trips get loaded, congestion may develop, shortest paths are dynamically updated, and trips get re-routed enroute as the paths change. This approach has shown great promise and appears to be a strategy that is worth considering in the ultimate development of the integrated model system in this project. Figure 25 depicts the event-based approach to travel routing and microsimulation that has recently been experimented by the team.

![Figure 25. Activity-Based Microsimulation in an Event-Based Traffic Simulation Context](image-url)
In this approach, an individual decides to engage in an activity. This decision is passed on to an event manager. The event manager processes this information to make sure that the event can take place and passes it back to the decision processor. The next series of decisions (such as destination and mode) are determined to complete the definition of the event. The event is then passed by the event manager to the traffic simulator which routes the trip as a travel event. As soon as the travel is completed, the event manager holds the agent on the waiting list and then passes the agent back to the decision processor. The decision processor determines the activity duration and at the completion of that activity, the process starts again with an individual deciding whether to engage in another activity. This process proceeds along the time axis. As trip events get executed on the network, travel times and paths get constantly updated and subsequent events get routed as per the conditions on the network at each instant in time along the trip. Thus, enroute re-routing can take place, and subsequent activity engagement patterns in the day can be adjusted depending on arrival times at activity locations. It is possible that trip events get loaded simultaneously, for example when trips have exactly the same departure time down to the minute. What is needed is an excellent vehicle or event tracking system, a purpose that is well served by the event manager. As trips get routed on the network, the event manager monitors the progression of the trip or event and informs the event of an update in the shortest path. This process can be executed once to complete the simulation without the necessity of a feedback process or loop. This is because network conditions get updated and travel plans get executed and re-scheduled on the fly throughout the day as the diurnal variation of the network plays itself out. The research team will carefully consider alternative design options in the final design and implementation of the integrated model system where the activity-based microsimulation model is seamlessly interfaced with the dynamic traffic assignment model system.

DYNAMIC MULTIMODAL NETWORK TRAFFIC ASSIGNMENT AND SIMULATION

Advances in computing technologies and algorithmic developments have both contributed immensely to recent developments in vehicular traffic simulation and dynamic traffic assignment (DTA). Simulation-based dynamic traffic assignment (SBDTA) systems are aimed at estimating and predicting urban transportation system traffic conditions for a target horizon period by embedding vehicle traffic simulation within the overall solution algorithm. The SBDTA system can then be applied to either predicting short-term traffic conditions or establishing fixed-point network equilibrium conditions for longer-term transportation planning purposes.

The network to which the SBDTA is applied may contain hundreds of thousands of nodes and links and involve time periods ranging from hours to days. This creates tremendous computational (memory and performance) requirements. Many SBDTA models are not spatially or temporally scalable, meaning that the temporal or spatial scale of the modeled network is limited by the computer on which the model is executed. One common strategy to enhance computational efficiency in the context of microsimulation model systems is parallel computing. Parallel computing allows for computational efficiency through three basic mechanisms: concurrency, memory, and scalability. Computer Clustered Multiprocessing (CCM) architectures offer great scalability, allowing a cluster to be scaled up to thousands of computer nodes.

From the standpoint of simulating vehicular traffic on a roadway network, one intuitive and advantageous strategy would be to decompose the network of interest into subnetworks and distribute the computations associated with each subnet onto different computer nodes in the cluster. Subnetwork-independent computations are handled by individual computer nodes (e.g., simulation of vehicles moving on links in respective subnets) and subnetwork-dependent computations (e.g., vehicles
traversing from one subnetwork to another) are handled by inter-computer-node communications through message passing interface (MPI) protocols.

There have been several advances in the parallelization of traffic microsimulation models. For example, the Transportation Analysis and Simulation Systems (TRANSIMS) utilizes spatial partitioning, or domain decomposition, to execute the cellular automata (CA) traffic simulation model. The shortest path and assignment algorithms, however, were not implemented in the domain decomposition mode, limiting the scalability of the model system.

One of the principal investigators on this project, Dr. Yi-Chang Chiu, has pioneered the development of spatially and temporally scalable dynamic traffic assignment models (Chiu et al, 2008; Chiu and Villalabos, 2008). The model systems developed by Dr. Chiu involve a multi-resolution assignment and loading of transportation activities. The proposed system is such that it is a fully integrated cluster computing simulation and traffic assignment system which applies parallel computing capabilities not only to the network partitioning scheme for network simulation, but also to the shortest path and assignment procedures to create a truly scalable system. The system's spatial scalability makes it possible to implement the model system for large scale model networks and megapolitan regions. In addition to spatial scalability, the model system is designed to function as a temporally multi-resolution model. Subnetworks with different temporal granularity requirements may be designated with different simulation intervals. Finally, the system utilizes state-of-the-art Anisotropic Mesoscopic Simulation (AMS) traffic flow modeling theory which departs from typical mesoscopic models which employ link-based speed calculations. The proposed model design allows for accurate interrupted and uninterrupted traffic flow representation, point queues, and moving queues, all modeled in a computationally efficient manner. Further, since the basic data structure of the model is based on a database, a feature that will be built into the model system includes the capability for the model to interact in real time with the database and respond to user commands for use in signal control modeling, lane capacity reductions, as well as real-time traffic assignment modifications.

The proposed model design for the dynamic traffic assignment and simulation model system is shown in Figure 26. The system is modular in nature and includes three major components – the person-mode-specific demand generation interface module, the hierarchical time-dependent shortest path and traffic assignment algorithm module, and the spatially and temporally scalable anisotropic mesoscopic simulation model. The person travel agendas are obtained from an activity-based travel microsimulation model such as that described in the previous section. This module is not an integral part of the dynamic traffic assignment model per se, but provides a specification of the type of information that is needed to facilitate the execution of dynamic traffic assignment and simulation.

The shortest path algorithm is a well studied problem, but a complexity introduced by the proposed system is its distributed nature in order to run on a parallel computing system. By partitioning the network into multiple subnetworks, the shortest path algorithm must be once again revisited. Most research has focused solely on parallelizing the shortest path algorithm and utilizing the network as a whole. For the proposed model system, however, spatial scalability is of utmost importance, and therefore parallelizing the shortest path algorithm is not sufficient.
In the computer sciences and web-based traveler information system arenas, hybrids of static hierarchical shortest path algorithms have been utilized to create high-speed algorithms for vehicle navigation systems and web-based mapping systems. The innovation within the proposed system involves taking the hierarchical shortest path algorithm and formulating it as a time-dependent formulation.

Figure 27 depicts an example base network which will be utilized to simply demonstrate the concept of the hierarchical time-dependent shortest path (HTDSP) algorithm. The sample base network has been segmented into three partitions and the boundary nodes are 4, 5, 6 and 7. The time dependent shortest path follows the one-all shortest path method. For every node in each partition, a shortest path is found to all other nodes within that partition. Therefore, a shortest path will be known for each node to its respective boundary node (within each partition), otherwise termed Level 2 TDSP networks. The idea of the hierarchical shortest path is to create a second network that maps the boundary nodes of each partition to one other (Level 1 TDSP). In order to determine the global shortest path, the Level 1 TDSP network is utilized by evaluating the link costs (the minimum Level 2 path cost traversing the respective network) as the path traverses from partition to partition. The travel time from within partition
boundary node to boundary node is already known; therefore, a global shortest path can be determined. Since the numbers of boundary connections are small, the solution to this TDSP problem is relatively fast.

![Diagram of network connections](image)

**Figure 27. (a) Base Network, (b) Level 2 Partitioned Network, (c) Level 1 Boundary Network for Hierarchical Time-Dependent Shortest-Path Algorithm**

A new mesoscopic modeling concept that departs from the typical link-based queue-server model, called the Anisotropic Mesoscopic Simulation (AMS) model has been gaining increasing attention. The AMS model is built upon an intuitive concept that, at any time, a vehicle’s prevailing speed is affected only by vehicles in front/ahead of it, including those in the (immediate) adjacent lanes. In other words, for any vehicle \(i\), only those leading vehicles (in the same lane or in the adjacent lanes) present in vehicle \(i\)'s immediate downstream and within a certain distance are considered to be influential to vehicle \(i\)'s speed response. This is similar in concept to stimulus-response type car-following models with the difference that the stimulus of a vehicle’s speed response is represented in a macroscopic form. As shown in Figure 28, for the modeling purpose, the Speed Influencing Region for vehicle \(i\) (SIR\(_i\)) is defined as vehicle \(i\)'s immediate downstream roadway section in which the stimulus is significant enough to influence vehicle \(i\)'s speed response. The prevailing speed of vehicle \(i\) is determined by using a macroscopic speed-density relationship based on the density in SIR\(_i\). Every vehicle retains its own speed according to traffic conditions in front/ahead. The analytical and numerical properties of AMS has been studied previously and it has been found that AMS exhibits important fundamental traffic flow properties in characteristics, shockwaves and merging flows.
Figure 28. A Conceptual Representation of the Anisotropic Mesoscopic Simulation Model
The research team is currently experimenting with prototype implementation of the proposed temporally and spatially scalable dynamic traffic assignment and simulation model system using the Puget Sound region network. Initial results are promising and show that the model system is capable of simulating traffic dynamics on large networks within very reasonable computational times. However, the initial experimentation did not include full traffic control details, typically desired for traffic simulation. The research team is currently debating the extent to which such details can be incorporated in this study within the scope and resources available.

The research team is also making headway on the conceptualization of a methodology for including transit in a multimodal network assignment framework. As shown in Figure 29, the development focuses on innovative modeling concepts and approaches, which are motivated by the following critical and unique research considerations:

- The person-level travel decisions are modeled in an integrated framework whereby mode choice, departure time choice, location choice, and route choice decisions are evaluated in a coherent framework consistent with the household activity agendas.

- Dynamic models of traffic and transit assignment explicitly consider person-level travel and activity agendas. This directly aids in the development of multi-modal traffic assignment methods that incorporate heterogeneity due to individual socio-demographic attributes.

- The feedback of an individual’s travel experience (e.g., through network congestion or pricing) will affect an individual’s travel agenda, considering their time-space prism constraints and value of time. The dynamic, multi-modal travel conditions explicitly affect household members’ travel agendas. Such feedbacks will be studied from day-to-day learning as well as within-day adjustment standpoints. The day-to-day learning process seeks to understand the eventual state of the entire system at both microscopic individual and macroscopic levels, which would be relevant for policy related questions. The within-day adjustment process entails the sequence of decisions that arise when a disturbance in the transportation system prevents a trip maker from being able to execute the original travel agenda, modeling how such adjustment decisions are made, and capturing how such adjustments lead to deviations in macroscopic system performance.
Figure 29. Conceptual Framework for a Multimodal Dynamic Traffic Assignment Process

CLOSING SUMMARY AND NEXT STEPS

In closing, the research team has spent considerable time and effort in identifying issues and challenges in the development of integrated model systems and the development of a grand design for an integrated model system in which many of the issues and challenges can be addressed without undue complexity. There are several issues that remain to be resolved and conceptual ideas that need to be implemented and operationalized.

In summary, the model design proposed by the team is as shown in Figure 30. In this figure, the process starts in a base year with an initial set of origin-destination trip tables. A base year calibration procedure ensures that the dynamic traffic assignment model is providing link travel times consistent
with those seen in the real-world. Once this bootstrap calibration procedure is completed, the origin-destination travel times are fed into the base year modeling process. The activity-based travel microsimulation model system utilizes the origin-destination travel times to simulate activities and trips for each person in a base year synthetic population along the continuous time axis. The base year synthetic population is generated using a new heuristic algorithm that controls for and matches both household- and person-level attribute distributions in the synthetic population. These trips are assigned and simulated using the dynamic traffic assignment model and the new origin-destination travel times that result from the simulation are fed back into the activity-travel simulation model. Activity schedules are adjusted, destination-mode choices are adjusted, and new activity-travel patterns are assigned by the dynamic traffic assignment model. This process is continued until convergence is achieved and a new set of equilibrated origin-destination travel times are obtained.

The base year origin-destination travel times are fed into the land use microsimulation model system for a future year to determine land use development patterns, household and business location choices, and other real-estate market phenomena (prices, for example). The synthetic population is aged and evolved from one year to the next to reflect the population dynamics through lifecourse events and a new set of urban conditions is produced. The activity-travel simulation process, the dynamic traffic assignment and simulation process, and the feedback process between them until convergence is achieved are all similar to those executed in the base year. The entire process is then repeated for another horizon year.

The research team is now defining databases that would comprise the integrated model system. This involves the identification and detailed specification of input, intermediate, and output databases that are necessary and desirable for the efficient operation of the integrated model system. Many data items are common across model entities and care is being taken to ensure that parsimony and consistency in data definitions are maintained. The research team is also identifying solutions to any outstanding issues that need to resolved and finalizing operational methodologies that would ensure behavioral and computational consistency across model systems (for example, treatment of transit). The research team will be spending considerable effort in enhancing the project website in the next few weeks so that the website starts serving as a major resource for the professional community interested in integrated modeling of the urban built environment, travel, and activities.
Tasks 1 & 2: Identification of Issues and Conceptual Model Design

Figure 30. Overall Conceptual Design of Proposed Model System
REFERENCES


*Tasks 1 & 2: Identification of Issues and Conceptual Model Design*


