An Integrated Economic, Land Use and Network Growth Model for Transportation Management and Policy Analysis in the Washington DC Area

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AN INTEGRATED ECONOMIC, LAND USE AND NETWORK GROWTH MODEL FOR TRANSPORTATION MANAGEMENT AND POLICY ANALYSIS IN THE WASHINGTON DC AREA

FINAL REPORT

Prepared for
Mid-Atlantic Universities Transportation Center

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16. Abstract

This paper demonstrates the feasibility of developing integrated urban systems model that considers transportation network investment and growth over time, which is a necessary tool for analysts to obtain accurate estimates of the total impact of transportation policies. Also, this paper presents a quantitative model that can forecast future networks under current and alternative transportation planning processes. The current transportation planning process is modeled based on empirical information collected from interviews with key transportation agencies and planning documents published by these agencies. The investment decision-making rules of and interaction/negotiations among state and local transportation authorities are explicitly considered in the proposed agent-based model. Results on a test network show the current transportation planning process can be improved in several different ways. Either a more centralized or more decentralized planning process can improve investment decision-making and enhance the performance of future transportation networks.

While it is certainly feasible to employ the proposed model to evaluate alternative planning processes out of intellectual interests, the most likely practical application of this type of models is probably the evaluation of the impact of a particular group of investment projects on future network performance. Another application is to forecast future networks for long-range transportation planning and policy scenario analysis. Currently, there is not a general method for generating future transportation networks 30 or 50 years from now, though this kind of planning horizon is often required for land use, greenhouse gas, and sustainability policy analysis. The model developed in this paper can fill this methodological gap.

Several aspects of the proposed model should and can be improved in future research. Model demonstration on a real-world network is clearly in order, and this work is underway for the statewide highway network in Maryland. The planning process model needs to be validated, possibly through comparisons between observed investment
decisions and model estimated investment decisions. The current transportation planning process in other regions may also be studied and modeled.

17. Key Words
Integrated urban systems model, transportation planning process

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LIST OF ACRONYMS

BRTB – Baltimore Regional Transportation Board
CLRP – Constrained Long-Range Plan
CIP – Capital Improvement Program
CNI – Capital Needs Inventory
CTP – Consolidated Transportation Program
DDOT – District Department of Transportation
DOT – Department of Transportation
EIS - Environmental Impact Statement
HNI – Highway Needs Inventory
ISTEA – Intermodal Surface Transportation Efficiency Act
MAA – Maryland Airport Administration
MARC – Maryland Rail Commuter Service
MAUTC – Mid-Atlantic Universities Transportation Center
MDOT – Maryland Department of Transportation
MdTA – Maryland Transportation Authority
MPA – Maryland Port Authority
MPO – Metropolitan Planning Organization
MTA – Maryland Transit Administration
MVA- Maryland Motovehicle Administration
MWAA – Metropolitan Washington Airport Authority
MWCOG – Metropolitan Washington Council of Governments
NEPA – National Environmental Policy Act
ODOT – Ohio Department of Transportation
RAC – Rider’s Advisory Committee
SHA – State Highway Administration
SIB – State Infrastructure Bank
STIP – Statewide Transportation Improvement Program
STP – Surface Transportation Program
TAB – Transportation Advisory Board
TAC – Technical Advisory Committee
TIP – Transportation Improvement Program
TSO - Transportation Secretary Office
TTF – Transportation Trust Fund
TPB – Transportation Planning Board
U.S. DOT – United States Department of Transportation
VDOT – Virginia Department of Transportation
1. INTRODUCTION

Urban systems are complex, open, integrated, and nonlinear systems, where economic, land use, transportation factors interact and produce a myriad of interesting and important system properties such as economic growth, equity, land development, congestion, and pollution. The interdependencies among these sub-systems that are critical for successful management and policy decision-making have motivated significant research efforts in developing integrated models of urban economic, land use and transportation systems. Monumental modeling contributions have been made by researchers from various disciplines including economics, regional sciences, urban planning, operations research, and transportation engineering. Most planning organizations in large urban areas now employ both land use and transportation models to guide land development and transportation investment decisions, and many have integrated land use-transportation model with feedback mechanisms for enhanced model consistency.

There are two unaddressed methodological issues in the field of integrated urban systems modeling and management. First, previous studies and applications assume away transportation investment and network changes over time. This limitation implies a fixed transportation network and ignores transportation revenue allocation, which can seriously bias transportation systems analysis when investments in transportation infrastructure (routine or stimulus investments) influence regional economy and employment, which is not considered in previous models. The need for incorporating transportation investment and network growth into integrated urban models is apparent for the analysis of traditional and innovative transportation management tools.

Second, urban system modelers often choose either equilibrium (i.e. solving a system of market-clearing equations) or evolutionary (e.g. micro-simulation) methods. Equilibrium analysis allows the modeled system to converge to a unique stable equilibrium, desirable for comparison purposes and mathematical rigor. Evolutionary analysis harnesses latest computational advances and tracks the wins or losses of individual agents, appealing for large-scale implementations and equity studies. While their complementarity is obvious, little effort has been devoted to integrating these two approaches at the theoretical, methodological, or application levels, probably because they emerged from drastically different disciplinary backgrounds and because there are concerns with regard to possible structural inconsistencies in a model that employs both approaches. Nevertheless, the potential reward of an integrated modeling approach that combines equilibrium and evolutionary paradigms deserves attention and analysis.

This research work presents an exploratory analysis of how the economic, land use and network growth for the Washington D.C. Area can be potentially integrated with transportation investment and network evolution analysis in urban systems modeling. In particular, the main interest is in incorporating transportation investment and network growth into integrated urban models for the analysis of traditional and innovative transportation management tools. This research includes discussion on possible integration of three interrelated component modules: regional economy and land use (RELU), travel demand (START), and transportation pricing and investment (MATS), which have already been developed and calibrated for the Washington DC area by the P.I. and the subcontractor separately in previous studies (Zhang (1), Zhang and Levinson (2), Safirova et al. (3), Safirova et al. (4). The main emphasis of this research is,
however, on the transportation pricing and investment module, as transportation supply modeling appears to be the least studied and explored area of integrated urban systems modeling, but which benefits the analysis of traditional and innovative transportation management tools. The following sections of this report present the discussion on the modules interrelation and integration and provide extensive description of the transportation pricing and finance module, especially developed within the framework of this research.
2. LITERATURE REVIEW

The growth of transportation networks is a complicated and multidimensional process that lasts decades. It is determined by investment decisions as, if no support is provided for a particular roadway, whether it is construction or maintenance, no growth effects would occur. Therefore, many researchers believe it is possible to predict and guide the process of network growth by influencing investment decision processes.

Back to the 1950s through 1980s state and local transportation agencies in the country were involved with the construction of the US Interstate Highway System, and all the transportation infrastructure funding sources were concentrated on highway construction projects. In the mid 1980s, the focus shifted to the management investments, whether maintenance or operational, and till today these type of projects absorb most of the federal and state funds. Since then, many efforts have been put into the modeling and analysis of transportation network growth. Previous research has been done by scholars of different fields. Xie and Levinson (5) provided comprehensive review of the previous studies that followed five main streams. Earliest studies date back to the 1960s, when for the first time models of network growth were developed. At that time researchers relied on heuristic and intuitive decision rules for network growth due to computational simplicity and no specific traffic data requirements. In particular, Taaffe et al. (6) studied the economic, political and social forces behind infrastructure expansion in underdeveloped countries. Their study found that initial roads were developed to link economically developed regions and rural roads were built around these initial roads. Later on, in 1970s, transportation planners and economists took over the forecasting process and started to use traffic demand models to model the changes to networks. Their assumption was that network growth was the result of rational decisions by jurisdictions, property owners, and developers in response to market conditions and policy initiatives. Statistical analyses of transportation data became popular in the later years as new transportation data management tools supported the techniques.

In the last two decades the dynamic traffic assignment tools became highly popular for analyzing complex transportation systems. The concepts of preference or self-organization have been introduced to interpret network dynamics as a spontaneous process. In the first strand of research the focus was on describing network growth in stages, in the second - researchers constructed models that would replicate observed developed network patterns. However, these studies, originated by the interest to replicate the observation of network topologies, had to deal with simple networks using heuristic and intuitive rules for network growth and transformation due to the lack of understanding on the inherent mechanisms with regard to why and how transportation networks evolve. In recent years, solution algorithms to user equilibrium have been widely incorporated to solve the network design problems (NDP). Typically the NDP is formulated as a bi-level framework in which the lower-level represents the demand-performance equilibrium for given investment while the upper level represents the investment decision-making of the transport planner to maximize social welfare based on the unique equilibrium flow pattern obtained from the lower-level problem. If the NDP were how decisions are made, network changes would be due to planners’ rational behaviors to maximize the efficiency of a given network, measured according to some quantifiable objective, based on predicted traffic with budget and other constraints. Verhoef et al. (7) explored the interrelations between pricing,
capacity choice, and financing in a small network model; Zhang and Levinson (8) proposed an analytic model discussing properties of long-run network equilibrium with regard to price and capacity with different small network layouts and ownership regimes. Levinson et al. (9) focused on understanding the conditions under which new links could be constructed on a highway network as opposed to existing links being improved, and developed a model to predict the location of new highway construction based on the surrounding conditions of the new link, the estimated cost of construction, and a budget constraint. Levinson et al. (10) incorporated jurisdictional planning processes to forecast network growth. In their attempts to predict the Twin-Cities seven-county road network 30 years from now, they developed network forecasting models with stated decision rules, processes encoded in flowcharts and weights developed from official documents or by discussion with agency staff. Montes de Oca and Levinson (11) have shown that different levels of jurisdictions including the state (the Minnesota Department of Transportation), region (the Metropolitan Council), and seven counties developed respective stated decision making processes in which federal or local funding are allocated to road projects prioritized according to their funding needs based on measured pavement quality, level of service, safety, and other conditions.

When transportation scientists work on theories of transportation systems changes, policy analysis and network evolution characteristics and integrated transportation and land use modeling they may employ methods based on single-agent scenarios with system optimization tools; to a less extend – examine two or three agents in the context of toll road competition with game theoretical models. And agent-based simulation is just on the rise of popularity.

Agent-based modeling represents an analytic approach to explain the choices of multiple agents in conflict with each other with scope for cooperation, where the payoffs are interdependent. The application of agent theory usually requires acceptance of certain assumptions about the behavior of agents (in this case - jurisdictions) and their level of knowledge. When it is assumed that agents are instrumentally rational, a deterministic strategy may be used. Agent-based techniques come from computer science field and are useful for modeling behaviors of individual decision agents due to simplicity of the representation of agents and their interactions and appropriate for linking individual decision opinions between each other in order to predict transport network evolution. Agent-based modeling techniques have found many applications in transportation demand analysis. Microscopic traffic simulation can be viewed as an example of agent-based models. Vehicles are agents in a simulator and they interact between each other, while the road network characteristics remain static. Zhang and Levinson (12), for instance, have developed a prototype agent-based model for trip distribution and traffic assignment. In their work the agents have an ability to learn, store, and apply knowledge without an assumption of provided perfect information to the agents which makes agent-based simulation different and at the same time realistic in comparison with the traditional microsimulation. Also, in a later work Zhang and Levinson (13) examined the unique feature of the agent-based model and its modeling techniques for the prediction of important macroscopic travel patterns.
3. MODULES DESCRIPTION AND INTEGRATION

3.1 Introduction to the Modules

RELU: Regional Economy and Land Use model (RELU) is a spatially-disaggregated computable general equilibrium model of a regional economy that is grounded in microeconomic theory and can be used for comprehensive welfare analysis. RELU follows the structure of Anas-Xu (14), although several new features (presence of several agent types, explicit possibility of unemployment, modeling housing and building stocks, income and real estate taxes) position the model to tackle complex realistic problems. In its present calibration, the model features four groups of consumers/workers and four primary industries and construction/demolition industries, as well as decision-making by landlords and developers.

START: The START travel demand modeling suite was developed by MVA Consultancy and was recently calibrated for Washington DC (4). The Washington START model considers 40 travel zones, multiple modes (highway, rail, transit, HOV/HOT, park-and-ride), eight heterogeneous user types, and six trip purposes. Travel decisions are modeled as a nested logit tree. An iterative algorithm equilibrates travel demand and network supply.

MATS: The Transportation Pricing and Investment model was developed for Washington DC through a series of agency interviews in a previous UTC project led by the P.I. It is a quantitative model that replicates the pricing and investment decision-making processes of supply-side agents (e.g. state DOT, local government, transit agency, private road). It takes the output from regional economy, land use, and travel demand models to forecast future transportation revenue and revenue allocation to system preservation, safety improvement, and capital programming needs. Model output shows how facility conditions and capacities evolve over time, which in turn serves as input to economic, land use, and travel demand models.

RELU and START modules employ computable general equilibrium method, while MATS module utilizes evolutionary agent-based simulation techniques. What is common in these modules is that they explicitly model and track individual decision agents in the urban system.

3.2 Modules Integration

In RELU present calibration, the model features four groups of consumers/workers and four primary industries and construction/demolition industries, as well as decision-making by landlords and developers. Consumers in RELU are exogenously distributed into F skill groups. While they cannot change their skill group, each consumer within a skill group can make a series of choices. After deciding whether to work or to stay unemployed, consumers choose a triple \((i, j, k)\) corresponding to choices where to reside, work and what type of housing to choose. Unemployed consumers choose a pair \((i, k)\). Alternatively, the choice of unemployment can be associated with an artificial workplace zone \((j=0)\).

Conditional on discrete choices, consumers decide how much housing to rent, how much retail goods to purchase at each available retail location and how much labor to supply. For each type of consumer continuous-choice variables of the consumer conditional on chosen \((i, j, k)\) are housing size \((b)\) in the chosen type-\(k\) housing in zone \(i\), and the vector of quantities of retail
goods (Z) the consumer purchases from all the zones by traveling there from his place of residence at i. For employed consumers labor supply is implied by the choices of b and Z.

The utility maximization function given in RELU is of Cobb–Douglas form between housing and the subutility of all retail varieties. It is assumed here that the consumer views each location as offering a different retail variety. The consumer has an extreme taste for retail varieties and will travel to each retail location no matter how high the price of the goods offered there. Pricier locations are shopped less frequently and the full price of retail good entails travel time and cost.

As for budget constraints, the prices that are exogenously given to the consumer but are endogenous in equilibrium are the rent per unit of floor space of type k in zone i; the hourly wage rate paid to skill-f labor employed in a zone j>0, and the unit prices of retail goods sold in zone z (zone of retail industry). Values of rent and unit prices of retail goods are assigned by RELU in the first iteration, but are subject to change by investment module (MATS) in the following iteration. MATS agents (described later in the paper), after evaluating the performance of the whole network, can decide to invest into certain zones to improve accessibly to that zone which would increase the value of rent, or may decide to raise sales tax to generate more funds for transportation infrastructure.

In RELU H is the consumer’s total annual time endowment and d is the exogenous number of commutes (work days) in a year. The coefficient that measure the number of retail trips for purchasing one unit of retail good is Cijf. Gij is the expected travel time over all available travel modes of one round trip from i to j for any consumer and any purpose (work or nonwork), ignoring time-of-day variations in travel times. The corresponding monetary expected travel cost is gij. These travel times and costs are determined as expected values over travel modes such as highway, public transit and “other modes” and incorporate the efficient (cost minimizing) choice of routes by consumers who travel over a congested highway network. When the consumer makes his location decisions, he does not know which mode of travel, trip pattern and network routes he will choose on any given day or, equivalently, that over a year he will choose each available mode with some known probability. The expected travel times and monetary costs over all modes, trip patterns, and routes are taken as given conditional on each choice (i, j) in the first iteration in RELU, but are changed in START in the subsequent iterations during demand estimation. Also, when MATS agents invest into network configuration by increasing capacity or imposing tolls on some links to generate additional revenue, travel times and costs change as well. Travel cost gij in START is dependant on three performance measures defined by agents in MATS: predicted number of fatalities, volume-capacity ratio and zonal population distribution. The combination of these performance criteria for each link in the network identifies the order of link investments and therefore – capacity expansions. Capacity expansion on any single link affects travel times and costs for that link, thus influence generalized cost for the whole network. But these changes in travel costs and times happen only after first iteration execution, when RELU passes its values on to START, START estimates demands and only then MATS module is activated.

Value of time of consumers in RELU is included into the price of a retail good, hence it is assumed that value of time of unemployed is zero, and the final price of the retail good for them purchased in zone z includes only the goods sales price and monetary travel cost.
In order to derive the probability that a randomly selected consumer will choose a discrete state \((i, j, k)\) the generalized probit or nested logit models are used with assumption of alternative correlation structures among the utilities of the discrete alternatives. Once consumers choose among the discrete states \((i, j, k)\), including \(j = 0\), they must make mode choice decisions which is done in START.

As for producers, the inputs in RELU are business capital and groups of labor, buildings, and intermediate inputs from the other industries. Within each group, individual inputs, such as intermediate inputs originating from specific zones, are treated as closely related imperfect substitutes with a constant elasticity of substitution. Across business capital and input groups, the overall production function is Cobb–Douglas and constant returns to scale so that firm size and the number of firms in an industry will be indeterminate but industry output in each model zone will be determined. Each industry can potentially produce in every zone of the model and can import its inputs of any input group (except buildings) from all other zones.

Landlord behavior determines the short-run supply of floor space in buildings that will be kept vacant at market rents. For this purpose, residential and commercial buildings are combined into \(k=1, \ldots, \aleph\) types where \(\aleph = \aleph_1 + \aleph_2\). A landlord operates floor space in buildings by maximizing profit under perfect competition. The only decision a landlord takes in this model is whether to offer a unit amount of floor space for rent or withhold it from the rental market.

Developers in RELU buy the services of specialized industries that construct or demolish buildings. They are modeled as looking 1 year forward at a time. They are profit maximizing and competitive firms taking building asset prices, unit construction and demolition prices, and other costs as given. Developers determine how much of a given amount of land should remain vacant (and available for the future) or if a particular type of building should be built on it. In this way, developers determine structural density on individual lots and on the aggregate. Developers face construction and demolition prices, and unit per acre nonfinancial costs.

There is a one-period lag required for any construction (demolition) to take place. Developers buy vacant land (or a building) in the beginning of the period, then act as a landlord to operate the asset for rental during the period and decide by the end of the period on whether and what kind of building to build (or whether to demolish an existing building). This decision depends on what value of the costs will be realized for a particular developer before the end of the year. Also, MATS agents impose additional costs for road improvements in the area surrounding developer’s land. These costs of road improvements/implementation should be accounted when calculating developers’ capital gains.

An output of the general equilibrium of RELU is the origin to destination matrix of all two-way daily person trips from any origin zone \(i\) to any destination \(j\) and back to origin \(i\), including commuting trips from residences at \(i\) to workplaces at \(j\) plus discretionary trips from residences in zone \(i\) to retail destinations in zone \(j\). These are found by summing over RELU functions evaluated at their equilibrium values. The trips of consumers computed in the demand module of RELU are loaded on to the supply network of START. The supply network uses the loads to compute costs of travel.
START characterizes speed flow*distance curves. The speed flow*distance curves for the arterial routes of the network are characterized using data from the transportation model of the Metropolitan Washington Council of Government (MWCOG). This highly disaggregated model establishes the relationship between capacity (flow*distance) and speed for the arterial roads of metropolitan Washington at different periods of the day. MWCOG data is aggregated to represent inbound, outbound, and circumferential links in a way consistent with the time periods and the zone delimitation adopted in Washington START. The speed flow*distance curves for the special links (freeways and HOV lanes) are characterized with the Van Aerde speed/density model, which is a single-regime model that simulates traffic for all ranges of speeds by the same equation and then are calibrated with SkyComp data and MWCOG data. The MWCOG model is used to provide a set of predetermined routes between each OD pair. These routes are taken as given in Washington START. They vary from one to nine, but almost half of the OD pairs have the maximum numbers of routes.

Transit service frequency in START is calibrated by using the National Transportation Database, WMATA 2002 Survey and budget documents and reported data for the VRE and MARC commuter rail services. Initial transit fares are based on WMATA fares in 2000 and published VRE and MARC fares. However, transit fares can be changed by MATS agents if transit revenues do not cover maintenance and capital expansion costs.

Monetary costs of driving in START, which includes fuel, fuel tax, vehicle depreciation, wear and tear, maintenance, and insurance, have been obtained from the Highway Capacity Manual 2000. They are converted in 1990 dollars. These costs are used to construct curves that establish the relationship between speed and costs of driving. The costs are first classified in three categories: fuel including taxes, running but nonfuel costs, and fixed costs. Once estimated in START, these costs of driving are evaluated in MATS. If agents “believe” generated highway revenues from existing gas tax rate are not substantial, they decide to raise gas tax by certain amount (calibrated in MATS); this change is reported to START, where travel costs and generalized costs are re-estimated. Running and fixed costs obtained from START are evaluated by MATS as well, since investment into links’ capacity directly affects travel times and costs of network consumers.

The travel times and costs of links in START correspond to link characteristics in MATS. The links in the network are organized in a priority queue, sorted by the performance measures of agents. MATS model takes the combination of factors - predicted number of fatalities, volume-capacity ratio and zonal population distribution - as the primarily identifier for the order of link expansion and, therefore, investments. Safety analysis is performed independently for arterial and freeway links. More detailed description of MATS model is given in the following section.

To summarize, the integration of the modules will work in the following way: first, RELU takes time costs and monetary costs of travel, disaggregated by skill level, trip purpose, and origin-destination pair, as given. The RELU simulation yields, in addition to other land-use and economic effects, trip demands at the same level of disaggregation as skill level, trip purpose and origin-destination pair. Then in START, those trip demands are disaggregated by mode, time of day period, and route, based on given by RELU calibrated distribution. In this way RELU provides START with an initial input of trip demands. Also, at this stage RELU-determined
wage rates are converted into a value of time for START. START minimizes travel costs at the level of the individual trip. When doing so, it iteratively redistributes trips among routes, time periods, and modes, and in each iteration computes generalized costs of travel. START terminates when the costs of travel converge to equilibrium values. At this point, the equilibrium generalized travel costs are aggregated over routes, time periods, and modes; the costs are split into time and money elements and passed as a new set of transportation costs along with other demand forecasting results to MATS. An investment agent-based module MATS starts to operate and causes annual investment changes, based on the agents’ endogenous performance measures (correlated to demand distribution within the network), producing an updated network of capacity expanded and/or deteriorated links. At this iteration investment related supply changes correspond only to agents’ revenues generated from network users through START’s demand estimation at first iteration. When MATS has updated network, START module re-estimates travel demand and calculates new transportation costs.

Meanwhile, if agents in MATS are not satisfied by revenue amount collected through START estimated demand distribution, new revenue generation polices, such as accessibility improvements through developers and additional taxation policies for consumers are passed from MATS to RELU module. With the new transportation costs from START and new policies obtained from MATS, RELU finds new equilibrium land-use and economic values, including new travel demands, wages and policies. START processes these new travel demands and wages as described above and runs again, then passes its values to MATS, and so on.
4. MATS MODEL DESCRIPTION

The most appropriate modeling technique that captures investment process as well as interaction of the agencies when they deal with resource sharing and coordination is agent-based modeling approach. When transportation scientists work on theories of transportation systems changes, policy analysis and network evolution characteristics, most often they employ methods based on single-agent scenarios with system optimization tools, to a lesser extent – examine two or three agents in the context of competition with game theoretical models, and agent-based simulation is just on the rise of popularity. Agent-based techniques provide a strong foundation for modeling the interaction between agencies when they decide on pricing and investments of roadways within their jurisdictional boundaries. Agent-based modeling represents an analytic approach to explain the choices of multiple agents in conflict with each other with scope for cooperation, where the payoffs are interdependent. The application of agent theory usually requires acceptance of certain assumptions about the behavior of agents (in this case - jurisdictions) and their level of knowledge. Specific real-world investment policies are certainly the vital inputs for modeled decisions that can be constrained by the cost of the link improvements, limited budgets and policy initiatives.

In order to convert qualitative information of decision-making to quantitative structured model, the agent-based approach requires the development of several component modules, such as historical demand model with socioeconomic and demographic information, links maintenance and expansion costs module, decision-making module and investment module. However, different from existing network growth models that assume exogenous network investment decisions, agent-based model can consider transportation network growth as endogenous and supply-side driven. When running agent-based model of investment decisions on a network the travel demand model can predict link-level flows according to the network, socioeconomic and demographic characteristics. Based on the demand forecasting results, links calculate revenues and costs. Agents (i.e. agencies) execute their priorities and after that the investment module of decision-making starts to operate and causes annual supply changes producing an updated network with new link capacities and network performance measures. Following each round of investment decisions, the transportation network may grow with expanded capacity or degenerate when not properly maintained, leading to supply-side changes. In every iteration supply changes correspond to agent’s budgets which are decided annually. The following agents with the corresponding decision rules have been used in our model.

An agent-based model is developed to simulate the investment decisions of and interactions among various state and local government agencies in the transportation planning process. Then this model is integrated with Land Use and Travel Demand modules, describes earlier. Agents in the model are described in the following subsections. While transit agencies are interviewed in the empirical study, the model currently only considers highway investment. We expect to expand the model to consider multimodal transportation investment in the future.

4.1 Multimodal MDOT Agent

The Maryland Department of Transportation (MDOT) is one of the State’s largest agencies “committed to delivering a balanced and sustainable multimodal transportation system” for
Maryland’s residents and businesses. (15) MDOT handles partnerships across modes and with partner agencies to support statewide plans. MDOT retains responsibility for decisions on capital investments as well as operating and planning activities that reach across all modes of transportation and is responsible for distributing the state’s transportation budget between the modes. At the same time the Transportation Secretary’s Office (TSO) establishes transportation policy in the State. (16) MDOT represents the MDOT Agent in our model. MDOT Agent tries to achieve the most efficient use of the existing transportation system: maintenance and preservation are prioritized over other needs to extend the useful life of facilities and equipment in existing budget shortfalls. MDOT has a unified pot of money - Transportation Trust Fund (TTF) - that provides flexibility to fund high-priority projects across the state regardless of transportation modes. Nowadays, system preservation accounts for 42% of MDOT Agent’s expenditures. (16) It means that only about 39% of the MDOT’s budget goes to capital programming (keeping in mind that about 19% of the budget usually goes to debt payments and to local governments and the state general fund). In the future, system preservation may require even greater portion of the budget if new sources of funding are not being identified for both maintenance and capital expansion needs. However, U.S. Department of Transportation will be awarding grants under the Interim Transportation Investments Generating Economic Recovery (TIGER) Guidelines for the projects meeting certain criteria. (17) These grants will be helpful in achieving a better state of the transportation system in Maryland. To qualify for the TIGER grants the projects should demonstrate significant long-term benefits (state of good repair, livability, sustainability, safety) and lead to creating new jobs and economic development in the Region. These criteria help to assume that the percentage of budget allocated to Maryland’s system preservation and capital expansion activities will remain on about the same level as nowadays, as the TIGER program favors both types of expenditures. Also, this grant program will continue supporting the current transportation policy practices in Maryland, keeping safety, congestion mitigation and accessibility improvements as top priorities in project selection process. Of the 42% MDOT Agent allocates to system preservation where the Maryland SHA gets 14% and 52% goes to transit needs of Maryland Transit Administration (MTA) and WMATA. (15)

MDOT Agent’s capital expenditures which, as was mentioned earlier, account for 39% of total expenditures, are also distributed among different state modes, where the SHA receives the biggest chunk - about 52% (according to current transportation program), and 33% goes to meet WMATA and MTA needs. (See Figure 2 for schematic representation of MDOT’s budget allocations) Once funding is distributed to the mode administrations, then the process of budget allocation to different improvement activities and projects begins. Each mode administration, in particular the SHA, MTA and WMATA, has their own investment processes based on the policy priorities of the MDOT. These processes are explained in the subsequent sections.

4.2 State and Local Agents in Charge of Highway Investment Decision-Making

When the SHA, which represents State Agent in the model, receives funding from the MDOT for maintenance and preservation needs, it decides on its own how to use that money. The State Agent first ensures that the roads belonging to state system are properly maintained. Only after investing into structural deficiencies, State Agent can put money into capacity expansion activities. Usually State Agent relies on its Highway Needs Inventory that includes the list of all
structural deficiencies in the system. As it is almost impossible to fund all of those deficiencies due to budget shortfalls, the projects from the Inventory are mostly selected based on 2 measures: road/pavement roughness and age of bridges in the system. It is important to mention here, that from the interview with the SHA staff it was found out that bridges usually require twice as much funding as pavements do. This leads to an assumption that two thirds of available operational funding is spent on bridges, and one third – on pavements. Road roughness quality is measured using the International Roughness Index (IRI). It is a measurement of the “bumpiness” of the road. Low values (0-94) indicate a very smooth riding quality, while higher values (above 220) indicate a rougher riding road. The range of IRI for each category of roads is based on limits set by the Federal Highway Administration. Assuming the State Agent inspects IRI on all state links, the first candidates for funding would be links with the highest IRI. The State Agent tries to maintain about 84% of pavements in the system in “acceptable” condition. As for bridges, the more time has past since its last maintenance, the higher the possibility the bridge requires improvement works. Therefore, bridge projects from the Inventory are assumed to be selected for funding based on their maintenance schedule. At the same time, all the bridges (about 2500 bridges) in the system should be in safe conditions. It is also worth mentioning here that while pavement and bridge maintenance consumes the majority of State’s system preservation budget, there are 24 special smaller funding categories dedicated to specific needs including drainage, traffic signs, and community improvement. As we do not know the percentage of funding going to these “small” needs, we assume that money for these activities comes from State Agent’s own budget. For capital projects State Agent is required to work in coordination with state counties and MPOs (they represent Local agents in the model). Local agents are responsible for generating their own revenues through various local taxes and fees and are required to perform regular evaluation of the roads within their jurisdictional boundaries. Some of the roads in local jurisdictions may qualify for State agent’s funding, which is determined through the policy and technical prioritization process.

Each local jurisdiction (e.g. counties and cities; referred to as Local Agents in the model) may propose a project for state funding for a variety of reasons, such as being very important for local needs as well as state development, but still it can not be guaranteed to be sponsored due to the State agent’s policy considerations, limited financial resources and technical evaluation. In reality, some projects move forward when the SHA selects them as preferred alternatives in studies, in other cases - projects are delayed or dropped because funding is unavailable, because other “more important” projects emerge, or simply because there is controversy from policy point of view whether the State benefits from a particular project or not. Sometimes locally proposed transportation improvements are listed for years in local or state plans before any action is taken to get them funded. This is largely due to the lack of financial resources and the “black box” of political decisions that produce unpredictable decisions on funding.

In the model the State Agent considers 2 factors when selecting capital projects for funding (whether they are state or local): policy factor and technical evaluation. For each factor a project gets a score. For policy factor a score can be as high as 60 points, and for technical evaluation – a maximum of 40 points. A score for policy factor depends on who is promoting a project: the State Agent or a Local Agent. If State Agent proposes a project, than that project always gets 60 points for policy factor. If a Local Agent – then a score will depend on how important a project is for local needs (policy score given by a Local Agent), its score obtained from State Agent
technical evaluation and the amount of contribution a Local Agent is willing to pay if the State agent fails to identify enough resources for that project.

The State agent’s technical evaluation is based on three performance measures, which are safety, congestion and accessibility improvements. A project can get up to 15 points for safety performance, 15 points – for congestion and 10 points – for the need of accessibility improvements in particular zone. Capital projects submitted by Local Agents and projects in the State agent inventory undergo the same technical evaluation. Technical evaluation of projects’ safety performance and point assignment are performed in the following manner: first, the accident rates for each link in the system are calculated, and then the rates of all the links are compared between each other and scaled in descending order. That said, after comparing various accident prediction models used in the literature and application of those models to the data, the Poison models for arterial and freeway links from the study done by Chen et al. (18) are used in this research for safety evaluation (local links are treated as arterials and freeways are treated as state links in this model). Local links in the network are ranked based on the following estimated Poisson model for arterial links (18):

\[
Y = 4.61215 - 0.085300X_1 + 0.327695X_2 + 0.027944X_3; \quad (4.1)
\]

Where:
- \(Y\) - Accident rate in peak or off-peak hours;
- \(X_1\) - Annual average volume per hour during peak and off-peak periods;
- \(X_2\) - Median type (divided or not);
- \(X_3\) - Intersection density (defined as the ratio of number of intersections to Link length).

State agent links are ranked based on the following estimated Poisson model (15):

\[
Y = 5.81252 + 0.1140E-03X_1 - 1.358E-02X_2 + 0.142474X_3 - 0.064002X_4; \quad (4.2)
\]

Where:
- \(Y\) - Accident rate during peak or off-peak hours,
- \(X_1\) - Volume per lane;
- \(X_2\) - Median width;
- \(X_3\) - Auxiliary lane ratio (the total length of auxiliary lanes on a link to the length of the link);
- \(X_4\) - Number of through lanes.

Evaluation of projects’ congestion performance and point assignment are performed as follows: first, the volume/capacity ratios for all the links in the system are calculated, and then those links are scaled in descending order based on determined ratios. For the purposes of this study the traditional determination of capacity is used:

\[
X_i = V_i/C_i; \quad (4.3)
\]

Where:
- \(V_i\) – volume on a link i,
Ci – capacity on a link i.

Accessibility is usually referenced as the measure by which travel costs are determined (e.g. the impedance function from gravity models applied to the travel time between two zones) and, also a spatial element reflecting the distribution of the activities in a region. In this model two standard measures of job and residential accessibility are adopted to convert travel time changes into accessibility shifts as was done in the P.I’s previous studies. Accessibility changes due to changing travel costs between origins and destinations, jobs and houses located in a specific zone may become more (or less) accessible relative to other zones in the region, which leads to increased (or decreased) level of future jobs and houses in that zone. The models for residential and employment distributions are adopted from Zhang (19) and as follows:

The population of the zone i after accessibility changes:

\[
P_i^2 = \frac{P \cdot P_i^1 \exp[b(A_{i,E}^2 - A_{i,E}^1)]}{\sum_i P_i^1 \exp[b(A_{i,E}^2 - A_{i,E}^1)]}
\]

(4.4)

Where:
P - Total study area population,
\(P_i^1\) - Initial population of the zone i,
b – Calibrated sensitivity coefficient of accessibility measure,
\(A_{i,E}^1\) – Initial accessibility to work of zone i,
\(A_{i,E}^2\) – New accessibility to work of zone i.

Employment in the zone i after accessibility changes:

\[
E_i^2 = \frac{E \cdot E_i^1 \exp(A_{i,P}^2 / A_{i,P}^1)^b}{\sum_i E_i^1 \exp(A_{i,P}^2 / A_{i,P}^1)^b}
\]

(4.5)

Where:
E – The fixed total study area employment,
\(E_i^1\) - Initial employment of the zone i,
\(A_{i,P}^1\) – Initial accessibility to house of zone i,
\(A_{i,P}^2\) – New accessibility to house of zone i.

In the model population and employment growth are evaluated for each zone, and then zones are scaled in descending order based on their future estimated populations and employments. The links connected to zones with highest growth are prioritized for funding.

Whenever the SHA performs investment procedures based on the above described measures, which in their own turn depend on the performance of each individual link, the transportation network grows and expands in places where links score the highest for policy and technical factors. Policy factor has higher weight than technical evaluation (60 points versus 40 points), which explains why in some cases there no action is taken for technically “needed” projects. A link with the highest combined policy and technical score is funded first, then next “in line” link is funded, and so on. The investment process continues till the point when the budget is exhausted. In case, if there is still money left after previous links’ investments, but that amount is
not sufficient to fund the next link “in line”, then that link is dismissed by its successor link and the cost of improvement for successor link is compared against available funding. If the cost is matched, then the link is financed, otherwise – a new link down the scale is selected.

From interview observations, it can be stated that the performance measures of the Local Agents are the same with the State, but the point distributions are different as they are determined through the processes of Local Agents’ budget allocations. When selecting state links that might qualify for the State funding, Local agents perform not only the technical evaluation, but also the policy evaluation. And again, policy factor has higher weight than technical factor (60 points versus 40 points). Local agent’s policy evaluation is also some kind of “black box” of decisions, which means that this process is very subjective. Projects from which a Local Agent benefits the most are given the highest scores, but it is difficult to predict which project a Local Agent will consider beneficial and which – not. However, each Local Agent can not submit unlimited number of projects with high scores and neglect projects with low policy scores. To remind, the final decision on funding is after the SHA, and Local Agent’s low policy score may turn out to be high score when the SHA re-evaluates locally proposed projects. Therefore, to closely reflect reality, in our model we assume that every Local Agent submits 5 projects with policy score 60, 4 projects with policy score 40 and 3 projects with policy score 20. When performing technical evaluation, a Local Agent considers the same three measures as the State agent does, but the point assignment is different. The total number of scores a particular project can get for overall performance is 40.

Link scores obtained from Local agents’ technical evaluation are summed with the corresponding policy scores given by each Local Agent. After that Local agents submit a list of qualified links. To remind, each agent can submit 12 projects (5 projects with policy score 60, 4 – projects with policy score 40, and 3 – with score 20). Combined with the technical score, these 12 projects will need to have the following number of scores:

- 5 projects with scores greater than 80, where 60 points would come from policy factor,
- 4 projects with scores 61 – 80, where 40 points would come from policy score,
- 3 projects – with scores 41 – 60, where 20 points would be from Local Agent’s policy evaluation.

4.3 State–Local Agency Interactions in the Highway Transportation Planning Process

Multi-agent planning is when multiple agents coordinate their activities. It involves: 1) agents’ planning for a common goal – the future state of the transportation network, 2) the State agent’s coordinating and compiling the plans of others into the general merged plan, and 3) a Local agent refining its own plan while negotiating priorities or resources with the SHA agent in the general merged plan. The general idea of multi-agent planning is to combine a planning method for each agent with an auction for delegating investment priorities in the shared transportation system.

In this research model the agents are making their investment plans independently of what the other agent is planning but they have to coordinate their efforts in creating one merged plan.
based on those independent plans. The performance measures valued by each individual agent determine which links in the network qualify for funding and therefore are included into their plans.

In the multi-agent planning process the agents’ primarily characteristics are:

1. Each agent does not have the accurate abilities to solve the whole problem, i.e. each agent cannot determine all the links in the system that require investment.
2. Data about links is not centralized, so it must be shared by all agents.
3. Each agent has its own ranking system for determining candidates for investment.
4. All agents in the system are designed to be self-interested and myopic. That is, in making a decision, such as selecting a particular link into a plan, the agents are only concerned with their own needs. Agents have no way to estimate other agent’s needs but have an idea of what would benefit to the global welfare of the system. The main goal of the Local agent is to prioritize links based on performance measures, and the main goal of the State agent is to reevaluate that prioritization and assign funding.

The links in the system are organized in a priority queue, sorted by the performance measures of Local agents, and then the links are sorted again by the State agent. In detail, the negotiation process between agents can be described as follows:

1. First, each agent, whether State or Local, ensures that all the links in the system are properly maintained. Each agent uses its own budget for maintenance needs.
2. After maintenance, each agent selects candidate projects for capital expansion. Each Local agent observes all the links under his supervision, ranks links based on performance measures as was described earlier and submits links to the State agent for further consideration. State Agent performs technical evaluation for his own links as well.
4. The State agent evaluates the condition of Local links again but based on his own performance measures. During this process, links can get higher scores than was assigned to them earlier, or can get much lower scores even if a link was originally claimed to be “high priority”. Therefore, some of a Local agent’s links get funded and some of them not. If a particular link is not funded, it is sent back to a Local agent. In this case, a Local agent funds this link if it was high priority and budget still allows after maintaining links within local system. Otherwise, this link may be left for next year investment process.

It is important to note, that all the agents are subjectively rational when making decisions. And in many cases they make preferences based on their policy considerations, rather than technical assessment.

4.4 MATS Testing Results

Although the proposed model structure can evaluate most investment scenarios in real world networks, this paper considers a hypothetical city with grid network for ease of interpretation, and focuses on the comparison between current investment regime and alternative centralized state regime, where all roads are controlled by state government, and decentralized local regime,
where each local jurisdiction controls investments into its own roads. The hypothetical city network consists of 10 by 10 grid road way links of 2-mile in length and an initial capacity of 775.5 vehicles/hour on each link. In the city a uniform initial land use pattern is assumed, and each node has 100 residents and 100 jobs. Each network link is assigned to either the State Agent or one of the five Local Agents. Based on the existing planning process, the State Agent controls all major state highways, represented by two north-south corridors, two west-east corridors, and a beltway system in the stylized network. All other links are assigned to the five Local Agents with one local agent in the city center and each of the four other local agents occupying one of the four corner areas in this stylized network.

When the agent-based simulation is executed, the travel demand model first predicts link-level flows. Based on the demand forecasts, revenues available to state and local agents are computed respectively based on the existing revenue policies (i.e. fuel tax, registration fees, and some general funds). After that the investment model, developed in Section 4, operates and forecasts investment decisions based on the current planning processes adopted by state and local agents. After each round of investment decisions, the network is updated with improved capacities for links selected for investment. Network performance measures are also computed for each investment cycle (one cycle per year), including total travel time, total distance traveled, average speed, total revenue collected, user benefits/consumer surplus, and net total social benefits. A time horizon of 50 years was chosen for the simulation experiments to observe the effects of current and alternative investment processes on future network performance.

Three transportation planning and investment processes are considered:

1. **Base Case**: This scenario represents the existing transportation planning and investment process in the DC-Baltimore Area as described in Section 3 and modeled in Section 4;
2. **State Control Case**: The State agent has centralized control over all links in the system and makes decisions for the entire budgeting and investment process. And
3. **Local Control Case**: State agent has no influence in the transportation planning process at all. Each of the five local Agent monitors and budgets the links within its jurisdictional boundaries.

Figure 7a illustrates the transportation network changes and capacity increases over a 50-year period when transportation investment decisions are made according to the current planning process in the DC-Baltimore region wherein state and local agencies share power and engage in negotiations. This planning process has resulted in a hierarchical network with two major north-south freeways, two major west-east freeways, and a beltway system also with higher capacities. This network topology is consistent with that in many U.S. urban areas.

Figure 7b presents the transportation network changes under complete State Control where the state agent makes all investment decisions only based on technical considerations such as safety, congestion and accessibility. Overall, the future network under State Control is similar to that under the current planning process, which is consistent with our empirical observations that state DOT and State Highway Administration are the dominate decision makers in the current planning process and controls most of the resources. Further examination reveals that under complete State Control, there are fewer investment projects on the periphery of the network.
compared to the existing planning process. Clearly, state agent invests in peripheral roads under the existing planning process only because these projects are high-priority projects for the individual local agents (the state-local negotiation procedure is at work).

Figure 7c plots the transportation network changes under decentralized Local Control. Recall that in this case the state agent has no power at all and each local agent controls the resource from its own jurisdiction and makes investment decisions solely based on the interests of its own jurisdiction. Unsurprisingly, the resulting future network is much less hierarchical and capacities are much more evenly distributed in all areas of the region. Local agents apparently have no incentives to building major high-capacity freeways that primarily serve through traffic. Under this type of decentralized local control, the future network most likely consists of many major arterial roads with moderately high capacity. It should be pointed out that this network topology under Local Control has a lot more redundancy (i.e. good alternative routes) than that under the current planning process or under State Control, and therefore should be more resilient to traffic accidents, disasters, and targeted attacks.

Numerical results summarizing the performance the future networks are provided in Table 1. Compared to the two alternative planning processes, the current transportation planning process will produce a future network that is inferior by all performance measures: higher total vehicle hours traveled, lower vehicle kilometers traveled, lower average speed, lower total revenue, lower user benefits, and lower net social benefits. These finding based on the stylized grid network suggests reform of the current transportation investment process. Before any actual recommendations are made, analysis on a real-world network should be conducted. We are currently testing the effectiveness of several alternative planning and investment processes on the Maryland statewide highway network. It is to our surprise that the Local Control scenario is shown to be the most effective based on user benefits and net social benefits. This implies that the current investment strategy by state agencies that focuses on expanding the capacity of the most congested bottlenecks may not be a very good long-term policy. It is probably more effective to address the congestion problem on a particular road by expanding the capacity of its parallel roads, which in the long run produces a transportation network with a more balanced capacity distribution, not a very hierarchical one.

5. CONCLUSIONS

This paper demonstrates the feasibility of developing integrated urban systems model that considers transportation network investment and growth over time, which is a necessary tool for analysts to obtain accurate estimates of the total impact of transportation policies. Also, this paper presents a quantitative model that can forecast future networks under current and alternative transportation planning processes. The current transportation planning process is modeled based on empirical information collected from interviews with key transportation agencies and planning documents published by these agencies. The investment decision-making rules of and interaction/negotiations among state and local transportation authorities are explicitly considered in the proposed agent-based model. Results on a test network show the current transportation planning process can be improved in several different ways. Either a more...
centralized or more decentralized planning process can improve investment decision-making and enhance the performance of future transportation networks.

While it is certainly feasible to employ the proposed model to evaluate alternative planning processes out of intellectual interests, the most likely practical application of this type of models is probably the evaluation of the impact of a particular group of investment projects on future network performance. Another application is to forecast future networks for long-range transportation planning and policy scenario analysis. Currently, there is not a general method for generating future transportation networks 30 or 50 years from now, though this kind of planning horizon is often required for land use, green house gas, and sustainability policy analysis. The model developed in this paper can fill this methodological gap.

Several aspects of the proposed model should and can be improved in future research. Model demonstration on a real-world network is clearly in order, and this work is underway for the statewide highway network in Maryland. The planning process model needs to be validated, possibly through comparisons between observed investment decisions and model estimated investment decisions. The current transportation planning process in other regions may also be studied and modeled.
REFERENCES


10. Levinson, D., Xie, F. and de Oca, N. M. (2007) Forecasting and evaluating network growth, Accepted for publication.


Table 1: Future Network Performance under Alternative Transportation Planning Processes

<table>
<thead>
<tr>
<th>Performance Measures</th>
<th>Base Case</th>
<th>State Control Case</th>
<th>Local Control Case</th>
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</thead>
<tbody>
<tr>
<td>VHT (Million hours/year)</td>
<td>0.322</td>
<td>0.316</td>
<td>0.310</td>
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<tr>
<td>VKT (Million km/year)</td>
<td>12.7</td>
<td>13.2</td>
<td>13.0</td>
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<tr>
<td>Average Speed (km/hour)</td>
<td>39.2</td>
<td>41.8</td>
<td>42</td>
</tr>
<tr>
<td>Revenue ($Million/year)</td>
<td>46.5</td>
<td>48.5</td>
<td>47.7</td>
</tr>
<tr>
<td>User Benefits/Consumer Surplus ($Million/year)</td>
<td>201.7</td>
<td>274.7</td>
<td>293.8</td>
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<tr>
<td>Net Social Benefit ($Million/year)</td>
<td>248.2</td>
<td>323.2</td>
<td>341.5</td>
</tr>
</tbody>
</table>
Figure 1: Integrated Economic, Land Use and Network Growth Model Schema
Figure 2: MDOT Agent Budget Allocation between Highways and Transit
SHA’s Portion – 14% of TTF

SHA Budget Allocation for Maintenance and Preservation

Pavement Maintenance – 1/3 of Maintenance Budget

- Pavements’ selection based on IRI
- Determine IRI for all pavements in the system
- Select pavement with highest IRI
- Fund
- Check funding availability
- End of process

Bridge Maintenance – 2/3 of Maintenance Budget

- Bridges’ selection based on their age
- Determine age for all bridges in the system
- Select bridge based on its age
- Fund
- Check funding availability
- End of process

Other Modes

Figure 3: State Agent (SHA) Maintenance Budget Allocation
Figure 4: Summary of the State Agent (SHA) Investment Processes
Well-documented technical decisions

Policy decisions

Subjective Evaluation

Local Agent State Links Investment Process

Policy Evaluation
Maximum 60 points

Select 5 projects with policy score 60

Select 4 projects with policy score 40

Select 3 projects with policy score 20

Subjective Evaluation

Technical Evaluation
Maximum 40 points

Safety

Congestion

Econ. Development

Calculate score for each link

Combine score

Select

5 "high priority" projects – with score 81 - 100

4 "medium priority" projects – with score 61 - 80

3 "low priority" projects – with score 41 - 60

Submit

The State Agent Investment Process

Figure 5: Local Agent (Counties) Project Prioritization for State Agent Funding
Figure 6: The Complete Existing Highway Investment Decision-Making Process with State and Local Agents
Figure 7: Future Networks under Alternative Transportation Planning Processes