Grand Challenges in Modeling and Simulating Urban Transportation Systems

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Abstract

Congestion in surface transportation systems has reached unprecedented levels, and now costs tens of billions of dollars each year in productivity and extra fuel costs in the U.S. alone. Accidents kill tens of thousands of individuals each year, and pollution from vehicle emissions degrades the quality of life of every citizen. Given the cost and danger of experimenting with operational systems and limitations of purely analytic techniques, effective modeling and simulation (M&S) tools are essential to solving these problems. However, existing simulation tools are far from adequate, and typically focus on only a particular aspect of the problem. This paper surveys the use of M&S in modeling surface transportation systems. A grand challenge is proposed to realize robust, accurate models of transportation infrastructures and its users for large metropolitan areas over time scales ranging from minutes to years. M&S tools are needed to predict the impact of both planned and unplanned changes as well as the introduction of new technologies, to prioritize infrastructure investments, to manage the system under unexpected operating conditions and traffic loads, to develop emergency and security-related contingency plans, and to test the impacts of various governmental policies on regional economic viability. Meeting this challenge will require a holistic approach that includes accurate models of individual travelers and businesses, as well as the transportation infrastructure itself.

1 INTRODUCTION

Transportation systems have broad, far-reaching economic and social impacts in our modern society. Travel delays are a constant source of stress, frustration, and dissatisfaction to the traveling public every day. Traffic accidents account for more than 40,000 fatalities in six million crashes each year in the U.S. alone (ITS America 2001). Delays also increase operating costs in the movement of goods, leading to higher costs for consumers. Vehicle emissions are the leading cause of air pollution in the U.S., degrading the quality of life for drivers and non-drivers alike. These issues are increasing in importance on a global scale as developing countries expand their use of private vehicles, mimicking the behavior of industrialized nations.

It is well established that congestion on roads and highways is bad, and getting worse. A recent investigation by the Texas Transportation Institute (TTI) that studied 68 urban areas in the U.S. reports that the average annual delay per person has climbed from 11 hours in 1982 to 36 hours in 1999 (Schrank and Lomax 2001). The cost of these delays in the 68 areas that were investigated is estimated to be $78 billion per year, including 4.5 billion hours of delay, and 6.8 billion gallons of fuel. Another study projects that incident-related traffic congestion will result in $75 billion in lost productivity and 8.4 billion gallons of wasted fuel by 2005 (Booz Allen and Hamilton 1998). These figures do not include other negative consequences of traffic congestion such as increased pollution from vehicle emissions[1], higher vehicle incident (e.g., accident) rates, and increased operating costs for commercial and transit vehicle operations. Travel demand is expected to increase in the future, further aggravating this problem. For example, vehicle-miles traveled (VMT) are projected to increase by 50% to reach more than 4 trillion by 2020 (Department of Energy 2001).

Given the magnitude of the problem, even modest improvements in the performance of surface transportation systems can lead to sizable benefits. For example, only a few percent reduction in delay can result in billions of dollars saved each year.

2 NATIONAL CONTEXT

Development and exploitation of M&S techniques must operate in close conjunction with national efforts to improve surface transportation systems. A recent report by the Transportation Research Board

[1] Pollution from carbon monoxide and hydrocarbons usually increase with traffic congestion, although pollution from nitrous oxides may decrease due to reduced vehicle speeds.

outlines a strategic highway research program to address problems in the U.S. highway system (Committee on a Study for a Future Strategic Highway Research Program 2001). This report identifies four strategic research areas for highway research. These include (1) renewal of the deteriorating highway system, e.g., through the development of advanced construction techniques and materials, (2) improvement of highway safety through a better understanding of factors leading to crashes, and development of suitable countermeasures, (3) providing more reliable travel times by preventing and reducing the impact of nonrecurring incidents (e.g., crashes), and (4) providing highway capacity in a way that is consistent with economic, environmental, and social goals. The latter clearly calls for a systems-oriented approach to highway development that takes into consideration users and society as well as the transportation infrastructure.

A second, related emphasis in surface transportation systems in recent years has been concerned with the exploitation of information technology such as new sensors, low cost computing, wireless communication, GPS, and the Internet to realize Intelligent Transportation Systems (ITS) (ITS America 2001). Now nearing the end of its first phase, ITS has already been deployed for many purposes such as tuning traffic signals and ramp meters to improve flow, electronic toll collection, dynamic highway message signing to provide drivers advance warning of congested conditions, and the realization of traffic management centers, among others. There are many opportunities to apply these technologies to further improve transportation system performance. Information systems can collect and disseminate information concerning the state of the transportation infrastructure on a much wider scale to enable automated selection of mode of transport (e.g., bus vs. automobile) and dynamic route selection for travelers. Advanced transportation management systems can exploit predictive capabilities (e.g., through fast simulations) to control traffic lights and freeway ramp meters to manage the flow of vehicles through the system. Automated crash detection and response systems can quickly detect incidents and apply corresponding actions, e.g., notification of emergency response teams and local hospitals. In-vehicle electronics can improve safety by avoiding crashes and improve the efficiency of vehicle operation. The 10-year ITS research program that is proposed aims to reduce the number of traffic fatalities by 15% overall by 2011 (saving 5,000 to 7,000 lives annually), save $20 billion in reduced delays, save one billion gallons of gasoline each year (with a proportional reduction in emissions), and provide reliable, accurate, up-to-date information concerning all travel choices available to users of the transportation system.

3 THE ROLE OF M&S

Modeling and simulation is essential to the development and assessment of future transportation systems, and can aid in its deployment. The uses of M&S for transportation systems today are many and varied. Numerous transportation planning and traffic engineering software packages have been developed. Here, we categorize simulators along two axes. The first characterizes the time scales over which the simulation operates, which is closely tied to its intended use. The second is concerned with the level of detail used by the model.

Regarding uses and time scales, simulations may be categorized as follows:

- *Long-range planning*. Simulations are often used for urban planning and to assess the impact of land use policies, community development (e.g., due to economic expansion), etc. Planning simulations can be used to evaluate the impact of changing demographics on transportation systems, e.g., the effects of an aging population. A principal use of these models is to estimate future traffic demands. An ambitious project with this purpose is TRANSIMS (Los Alamos National Laboratory 2001) that uses detailed models of individual traveler preferences and behavior to create models for traffic demand over different modes of transport (private vehicles, mass transit, etc.). These models are then used to drive simulations of regional traffic systems to assess system performance.
- *Design of transportation systems*. Simulation is used extensively to evaluate changes to transportation systems, e.g., addition or modification of roadways or the introduction of ITS. Typical objectives of these studies are to assess the impact of the proposed change on efficiency, safety, or pollution. The scope of these simulations ranges from modeling individual intersections to highways and freeway corridors and urban street networks to integrated networks containing multiple modes of transportation.
- *Traffic management*. Simulations can be used on-line as a tool to aid in the operation and management of transportation systems. The simulation is used as a tool to evaluate approaches such as signal control or freeway

ramp metering. Rhodes is an example of a hardware-in-the-loop simulation that couples a traffic simulations with traffic light control hardware (Head, Mirchandani et al. 1998)

A second characteristic that differentiates simulators is the level of detail captured by the model. Models are usually categorized as macroscopic, microscopic, and mesoscopic:

- *Macroscopic* models for traffic were first developed in the 1950's. They characterize traffic as an aggregate flow. Fluid flow equations are used to establish the relationship between flow rate, average velocity, and vehicle density. First order models assume a static relationship between speed and density. Second order models assume average speed is a function of time or space derivatives of density and speed. Third order models have also been proposed, however first or second order models are much more prevalent. Macroscopic models offer computational efficiency, but reduced fidelity because they cannot model the behavior of individual vehicles.

- In recent years improvements in computing speed have enabled the use of *microscopic* models that explicitly model the behavior of individual vehicles. Microscopic simulators typically include car following models to capture a driver's desire to maintain (at least) a specific spacing with the vehicle ahead of it. An alternate approach is to divide the roadway into discrete segments, and model individual vehicles as particles that hop from one segment to another, giving rise to cellular automata models. Microscopic models also often include gap acceptance models to characterize a driver's willingness to enter another stream of traffic or to change lanes. Many microscopic traffic simulators have been developed. A few examples include CORSIM (ITT Systems & Sciences Corporation 1998), PARAMICS (Cameron and Duncan 1996), MITSIM (Yang, Koutsopoulos et al. 2000), and VISSIM (Innovative Transportation Concepts 2001).

- *Mesoscopic* models lie between macroscopic and microscopic models. They typically model clusters or platoons of vehicles, and focus on modeling the interactions between clusters. Examples of mesoscopic models include CORFLO/NETFLO 1 (Taori and Rathi 1996), DYNASMART, DYNEMO (Fellendorf, Schwerdtfeger et al. 1996), and INTEGRATION (Prevedouros and Wang 1999).

4 M&S GRAND CHALLENGE

Effective modeling of transportation systems requires consideration of many complex processes with subtle, but important, interactions. For example, for many years a common solution to solving traffic congestion was to build more roads. New roads led to reduced congestion in the short term. However, attracted by short commute times, new housing developments sprang up near the new roads. Travelers became more willing to drive further to work, or to make that extra trip to the store or restaurant, further increasing demands on the traffic infrastructure. Mass transit fell into decline because it becomes less effective as population densities decrease and travel by private automobile becomes faster and more convenient. This in turn forced cutbacks in service and/or higher prices, making public transportation even less attractive, perhaps to the point where it is only used by those in low income brackets who had no other alternative. After a few years, the roadways again become congested. Further expansion by building additional roads leads to another round of population growth, expansion, and economic development. Geographic barriers may eventually constrain development, driving up home prices, increasing densities, and increasing costs of new roads. These factors contribute to making transit more attractive.

This cycle has been repeated time and time again in many cities around the world, leading to urban sprawl and little tangible improvement in the transportation infrastructure. A good discussion of some of these effects is presented in (Sterman 2000).

Modeling and simulation of transportation systems in a major metropolitan areas calls for a holistic approach that can encompass the many and varied factors affecting system dynamics. As such we pose the following grand challenge problem: *Develop simulation tools that can accurately forecast the behavior of large, complex, multi-modal transportation systems and their interaction with people and society spanning broad spatial and temporal scales.*

There are several key elements to this challenge problem:

- *Large and complex*: Techniques must be scalable to enable simulation of major metropolitan areas such as New York or Atlanta. The tools must enable one to understand and quantitatively evaluate complex interactions within the transportation infrastructure and between the infrastructure and its users (both persons and goods).

- *Multi-modal*: Interactions between different modes of transport (private vehicles, buses, rail, air) are of particular importance, not only because they often utilize the same infrastructures, but because the demand for different modes are inter-related.
- *Interaction with people and society:* The tools must model not only the transportation infrastructure itself, but it must also model/simulate traveler behaviors, focusing on interaction between the two across short and long time scales. Personal behavior and use patterns are greatly impacted by the perceived effectiveness of the transportation infrastructure.
- *Varying spatial and temporal scales:* Tools are need to make predictions on the order of minutes to hours ahead for on-line traffic management (e.g., incident response, emergency evacuations), and years ahead to project long range effects of population growth, migration, etc. Spatial scales may range from modeling in-vehicle devices to main arteries to major metropolitan areas to (in the case of air and freight) national levels.

5 KEY ISSUES

The focus of our grand challenge is on the unscheduled transportation system, representing the movement of individuals within a given space and time. A transportation system is described as “unscheduled” when the individual chooses the trip departure time and/or mode of travel subject to their own needs and constraints.

Our grand challenge focuses on an entire regional transportation system including both households and companies. Households generate trips according to a need to complete household activities, and companies generate trips based on a need to acquire and deliver goods and services. See Ettema and Timmermans (1997) for an overview of activity-based approaches to travel analysis.

5.1 Problem Characteristics

A regional transportation system supports the economic viability of a community by promoting the safe and cost efficient movement of people and goods. The following bullets provide some examples of the different temporal and spatial characteristics of these systems.

- Over longer periods of time, households choose their origins (e.g., the locations of their homes) subject to home availability, their budgets and individual tastes, proximity to work, and other household constraints (quality of schools, etc.)
- Over longer periods of time, companies choose to locate their businesses based on perceived market demands for the goods or services by individuals within a region, availability of raw materials, and capacity of the local and regional transportation infrastructure.
- On any given day, trips are generated by an individual's need or desire to travel. At a basic level, this may derive from an individual's position within a household. These trips may vary by time-of-day, day-of-week, day-of-year, or day-of-lifetime. Trips may be for any purpose including work, shop, recreational, etc.
- On any given day, trips are generated by a company's need to acquire or deliver goods and services. These needs may follow normal business cycles, and may be influenced externally by economic conditions or governmental policies.
- On any given day, the individual (whether associated with a household or company) chooses whether or not to make a trip, the trip destination, departure time, mode or modes of travel (e.g., drive alone, car pool, walk-transit, etc.), specific trip route, and travel speed profile.
- During any given trip, individuals make decisions about the vehicle spacing, and lane. Based on observed roadway conditions or other external information (e.g., via radio or cell phone), they may adjust their travel en-route.
- Individual trips may be assigned to interconnected modal sub networks (e.g., highway, rail, bus, walk) each with their own dynamic characteristics (e.g., capacity, service times.)
- Capacities and service times may vary based on the number individuals currently traveling on the sub network, system control policies (e.g., traffic signals, ramp meters, toll way prices) and other external influences (e.g., weather, traffic accidents, infrastructure construction.)

5.2 Challenges of Scale and Complexity

Modeling of regional transportation systems offers significant challenges in both scale and complexity.

- Scale: Consider the number of households and companies within any major metropolitan region in the United States. For example, in the Atlanta metro area there are 3.5 million people, 2.0 million workers, 1.5 million households, and about 1.0 million work trips per day. Further, consider the uniqueness of each of these households and businesses, and variation in the number and types of trips generated by these households on any given day. Next consider the day-to-day variation (or lack of variation) in these trips across weeks, months, and years.

- Complexity: Consider the different travel options available to travelers. These options may include alternate modes (e.g., walk, drive, bike, transit), alternate routes, and alternate departure times. Further consider that different individuals do not necessarily chose the "best" alternative. Individuals may chose based on incomplete knowledge, constrained budgets, or simply by habit. Given the same conditions, there is no guarantee that individuals will choose the same alternative.

Simulations tracking the decisions and locations of individuals must manage millions of individual entities interacting with each other and with the infrastructure, over both space and time.

New techniques for managing these interactions within a computational framework will be necessary. Possible solutions may originate from existing areas of parallel processing and multi-resolution modeling.

5.3 Multi-Modal Transport Challenges

One possible solution framework can separate the different modal systems (e.g., walk, automobile, bicycle, bus, rail, etc.) This will allow sub-models and simulations of the various modes to evolve and mature at different paces.

We can identify and distinguish smaller, scheduled transportation systems within the larger, unscheduled system. For example, buses and heavy rail operate on fixed schedules along fixed routes, and these schedules will constrain the unscheduled travelers if these modes of travel are to be used. Delivery and pick-up services follow prescribed routes and time schedules.

A well-defined and documented framework and architecture, defining transitions and transfers between these various sub-models is necessary.

Interface, interoperability, and synchronization standards, defining the transfer of individuals from one sub-model to another, will be required, as will be techniques for efficiently managing the multitude of transfers required during any given time interval.

5.4 Challenges in Human Behavioral Modeling

At the core, this effort will challenge us to develop better models of human behavior and decision-making. Each day, individuals are making a multitude of decisions, each with implications and impacts that may stretch over varying amounts of time. For example:

- Sub-second to minute scale: vehicle following (acceleration or deceleration), lane change behavior (much work here already), en-route destination changes, etc.
- Daily decisions: Is this trip necessary? Can I combine trips to create a chain? Which destination (e.g., go to local store or a distant mall?), which route? which mode (e.g., private vehicle vs. public transit)?
- Weekly, monthly, and seasonal decisions: pick-up and delivery schedules, routing habits, household and business needs (that drive the demand for travel.)
- Annual and longer term decisions: household, company, and facility location; car and fleet ownership

Decisions are driven by many factors, such as perceived performance of transportation modes, out of pocket costs, economic conditions (state of economy, housing prices, tax policies, etc.), availability of facilities (e.g., housing markets, land use policies, quality of schools, tax incentives), and other external influences (e.g., weather, etc.) We often assert that transportation, land-use, environmental impacts, and economic growth are interrelated, but our understanding of these relationships is tenuous, at best.

These challenges offer many opportunities for interdisciplinary collaboration including economics, psychology, and systems engineering.

5.5 Challenges in Management and Control

Opportunities for management and control of the existing infrastructure can be implemented at various points within the system. Local control policies can be implemented at the intersection level (e.g., how much green to show to each intersection movement, how many vehicles per hour to allow at a specific ramp meter.) Subsystem control policies can be implemented to increase or decrease transit service times, or to vary pick-up and delivery routes and times. Various pricing strategies can be used to control the number of vehicles traveling along a toll-way any given time. As new communication technologies come on-line, opportunities for provision of real-time information including the prescription of trip departure and routes.

Long-term governmental policies (e.g., land-use, environmental, tax incentives) can be applied to affect facility location (e.g., households or businesses), enhance the infrastructure (whether, when, and where to build new roads). Availability of resources availability of land, water, power, and other raw materials may act to constrain growth.

6 END PRODUCTS AND IMPACT

Our goal is to develop an overall framework and suite of tools that can foster, support and promote the investigation of relationships between transportation, land use, the environment, and regional economic viability.

Ultimately, these tools will help decision makers and system managers make better decisions. Decision-makers include travelers concerned with saving time and out-of-pocket costs; businesses concerned with minimizing transportation costs and improving on-time reliability of service; transportation managers concerned with reducing system congestion; and government policy makers desiring a better understanding of the impacts of their policies on the long-term economic viability and quality of life for their region.

Regional, unscheduled transportation systems offer one example of a family of large-scale systems that are strongly influenced by quasi-random events. Weather, traffic accidents, equipment failures, varying availability and accuracy of information (both pre-trip and en-route), and individual preferences are all examples of these external influences that can impact overall system performance.

Insights gained from exploration of our grand challenge can be transferred to other large-scale systems problems including environment, climate, and economic systems.

7 REFERENCES

Booz Allen and Hamilton (1998). Incident Management: Detection, Verification, and Traffic Management, Filed Operational Test Cross-Cutting Study.

Cameron, G. D. B. and G. I. D. Duncan (1996). "PARAMICS, Parallel Microscopic Simulation of Road Traffic." Journal of Supercomputing **10**(1): 25-53.

Committee on a Study for a Future Strategic Highway Research Program (2001). Strategic Highway Research: Saving Lives, Reducing Congestion, Improving Quality of Life, Transportation Research Board and the National Research Council.

Department of Energy (2001). http://www.eia.doe.gov/oiaf/aeo/aeotab_7.htm.

Etteman, D.F., and H.J.P. Timmermans (1997) Activity Based Approaches to Travel Analysis, Elsevier Science, Tarrytown, New York .

Fellendorf, M., T. Schwerdtfeger, et al. (1996). "DYNEMO, A Mesoscopic Traffic Flow Model to Analyze ATT Measures." Transportation Planning Methods.

Head, K. L., P. B. Mirchandani, et al. (1998). The RHODES Prototype: A Description and Some Results. Proceedings of the 77th Transportation Research Board Annual Meeting. Washington D. C., (Paper No. 981399).

Innovative Transportation Concepts, I. (2001). VISSIM Simulation Tool, http://www.itc-world.com/VISSIMinfo.htm.

ITS America (2001). Ten-Year National Program Plan and Research Agenda for Intelligent Transportation Systems in the United States, The Intelligent Transportation Society of America and the United States Department of Transportation.

ITT Systems & Sciences Corporation (1998). CORSIM User's Manual, Version 1.04, Federal Highway Administration, U.S. Department of Transportation.

Los Alamos National Laboratory (2001). TRANSIMS, http://transims.tsasa.lanl.gov/.

Prevedouros, P. D. and Y. Wang (1999). "Simulation of Large G=Freeway and Arterial Network with CORSIM, INTEGRATION, and WATSIM." Transportation Research Record(1678): 197-207.

Schrank, D. and T. Lomax (2001). The 2001 Urban Mobility Report, Texas Transportation Institute, The Texas A&M University.

Sterman, J. D. (2000). Business Dynamics, System Thinking and Modeling for a Complex World. Boston, MA, Irwin McGraw-Hill.

Taori, S. and A. Rathi (1996). "Comparison of NETSIM, NETFLO I, and NETFLO II Traffic Simulation Models for Fixed-Time Signal Control." Transportation Research Record(1566): 20-30.

Yang, Q., H. N. Koutsopoulos, et al. (2000). "Simulation Laboratory for Evaluating Dynamic Traffic Management Systems." Transportation Research Record(1710): 122-130.