FOUNDATION FOR STUDY OF FUTURE TRANSPORTATION SYSTEMS THROUGH AGENT-BASED SIMULATION

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Abstract

It is of paramount importance to quantitatively investigate potential future transportation systems on a national (or international) scale. An approach to addressing this formidable challenge is introduced, which foregoes the usual employment of reductionism in favor of a holistic perspective. An entity-centric abstraction framework is created and underpins the development of the Transportation Architecture Field (TAF) as a mental model of the National Transportation System (NTS). Four basic entity groups are identified: resources, stakeholders, drivers, and disruptors. The framework guides the construction of a virtual NTS couched in the form of an agent-based model, where nearly any conceivable combination of transportation resources, economies or policies is admissible. An aggregate calibration of the approach for the U.S. NTS is presented and perspective on research directions and collaboration are offered.

1. Introduction

There is a pressing need to quantitatively investigate potential future transportation systems on a national scale, i.e., the National Transportation System (NTS) to track the cascade of interrelated technological, infrastructure-related and societal perturbations throughout the entire system. Modeling and evaluating the behavior of the NTS is an overwhelmingly difficult task since it is a complex system, both in the colloquial and technical sense of the word. Complexity in the NTS stems primarily from three properties: the heterogeneity of constituent systems, the distributed nature of these systems [1], and the presence of deep uncertainty in exploring its future state [2]. In light of these general properties, the NTS may best be conceived as a *'living system'*—a collection of diverse things that evolve over time, organized at multiple levels, to achieve a range of (possibly) conflicting objectives, but never quite behaving as planned.

The traditional approach to modeling a large, complicated system is through the collection of many small-scale, hierarchically decomposed models into a unified whole. This approach is anchored in reductionism, the philosophical dogma that has dominated the modern sciences since Descartes [3]. Although the felicitous achievements over hundreds of years testify to its success, the reductionism strategy is not complete for the study of complex systems. It creates *'box-inside-a-box'* mentality and becomes simply impractical when a system is composed of unmanageable number of heterogeneous elements. This is, however, only a superficial reason. The fundamental shortcoming of reductionism comes from the fact that, as commonly noted, a whole is more than the sum of its parts. Holism, in contrast, takes the diametrically separated stance, which may facilitate one's intuitive understanding of a complex problem structure. Nevertheless, it does not necessarily generate useful results for the problem at hand. Holism alone would remain in a fuzzy realm and find no legitimate foundation without a substantial linkage to the tangible aspects of the problem.

The purpose of this paper is to introduce one approach for the ultimate goal of formulating the linkage. The foundational endeavor begins with abstracting the NTS with the belief that a holistic frame of reference is required to properly study such a multi-disciplinary, trans-domain system. The culmination of the effort turns up the Transportation Architecture Field (TAF) as a mental model of the NTS, in which the relationships between four basic entity groups are identified and articulated. This entity-centric abstraction framework guides the construction of a virtual NTS couched in the form of an agent-based model (ABM). The latter portion of the paper contains a brief description of how this ABM is created and what the model generates. Further, it is discussed how this generic approach can be extended beyond a national scope, calling for a worldwide collaboration among researchers to tackle transportation challenges that cross national boundaries.

2. Foundation

In this section, the 'foundation' that has resulted from abstracting transportation from the holistic perspective is briefly presented. The term foundation is chosen since the arrived-at abstraction and its embedded relationships form the basis for pursuit of modeling and simulation or, more aptly, the pursuit of answers to particular questions. A more detailed accounting of this foundation is already reported in Ref. [4]. A recent enhancement has resulted from a more operational point-of-view, recognizing that the foundation is entity-centric and time variant. These two traits are combined to form the TAF as the realization of the abstraction itself.

2.1 Entity-Centric Abstraction

The holistic perspective is essential to abstract the transportation system without prescribed boundaries. But what exactly is being abstracted? Here, embracement of the holistic perspective begins by adopting the assumption that (colloquially) *'everything is on the table'*. Two questions follow from this assumption: What is everything? What is the size of the table? If the questions were posed to a supreme transportation *architect*—a hypothetical individual who wishes to shape the transportation *architecture* under her/his design—she/he would surely realize that not only physical factors, such as vehicles and infrastructure, but also organizational elements, such as public interest groups and industrial firms, should reside inside of their problem boundary.

All of these factors "*on the table*" find a home under the *entity-centric abstraction framework*, unified through the concept of *entity*. Entity is analogous to object in the computer science domain. In objected-oriented programming, the internal view of any object uncovers states (or variables) and behaviors (or methods) as the defining elements. Similarly, an entity is composed of *attributes* and *functions*, which correspond to states and behaviors, respectively. Moreover, the entity can have *sentience* and *interfaces*. The role of these four key rudiments of the entity is to symbolize its being (attribute), doing (function), thinking (sentience), and linking to *'externalities'* (interface). Anchored in this conceptual foothold, the entity-centric abstraction is instantiated with particular entity characterizations.

2.2 Entity Categories

Two pairs of entity descriptors emerge from the abstraction process: *explicit-implicit* and *endogenous-exogenous*. Unlike under the reductionism mindset, the role of the descriptors is not to facilitate break-down of the entities into separate pieces. Instead, it is only to organize them by articulating their inherent natures. Four entity categories are generated based on the descriptors: *resources*, *stakeholders*, *drivers*, and *disruptors*. All these entities are inter-webbed by *networks* that define the linkages amongst themselves.

Vehicles and infrastructure are examples of *resources* that consumers physically experience (*explicit*) when traveling or sending shipments. Further, they are under partial or full control of the imagined architect, thus *endogenous*. But there are *'other-than-physical'* entities that desire to exert forces on the architecture for their own interests. This type of endogenous entity is called *stakeholder*, and in most circumstances their behaviors and decisions are not manifested in an explicit manner to the consumers (*implicit*). The stakeholders reside in both private and public sectors, ranging from the actual consumers of transportation services to the providers of those services. They have objectives representing their interests that dictate the manner in which they influence the transportation architecture, as shown in Table 1.

Table 1: Transportation Stakeholders

Stakeholder Group	**Primary Objectives**
Consumer	Max. travel utility
Communities/Society	Max. quality-of-life
Service Provider	Max. profit
Manufacturer	Max. profit
Insurers	Max. profit; Min. risk
Regulatory Agency	Max. public welfare
Infrastructure Providers	Max. capacity, public utility

While the stakeholders and resources are considered endogenous building blocks, the transportation environment contains *exogenous* entities that are outside of the architect's controllable domain. This entity class has been traditionally treated as given assumptions, circumstances, and constraints about the transportation environment (e.g., population, weather). *Driver* entities are largely concerned with economic, societal, and psychological circumstances that influence the stakeholder network by implicit means. On the other hand, *disruptor* entities explicitly affect the resource network and/or a portion of the driver entities by reducing the efficiency of the resource network, disabling particular nodes or links of the network.

2.3 Transportation Architecture Field

The specification of all entities, juxtaposed on the time-variant transportation environment, can be conceptually depicted in a pseudo 3-D space (Fig. 1). This space is called *Transportation Architecture Field* (TAF) where the entity descriptor axes generate four quadrants situating the corresponding entity group. Note that the arrows connect the adjacent quadrants only. The solid arrows indicate the direction of primary influence. For instance, adverse weather (disruptor) instantly affects the resource network; a good economy (driver) has a direct impact to the stakeholders that affect the resource network. In contrast, the dotted arrows indicate vague influence, probably with large latency. For instance, a secure, robust resource network may scale down the probability of disrupting incidents; an efficient resource network will positively influence the economy to an ambiguous extent.

The TAF is constructed through *'networking'* (organizing) the networks. The centrality of this arises from the recognition that the organization of things can be just as important as the nature of things to be organized. In particular, linking the resource and stakeholder network gives the TAF a *system-of-systems* character. The stakeholder network embodies decisions concerning the status of the NTS, while the resource network determines how the NTS is actually configured when accessed by consumers. The dual networks are co-mingled resulting in the *evolving* TAF.

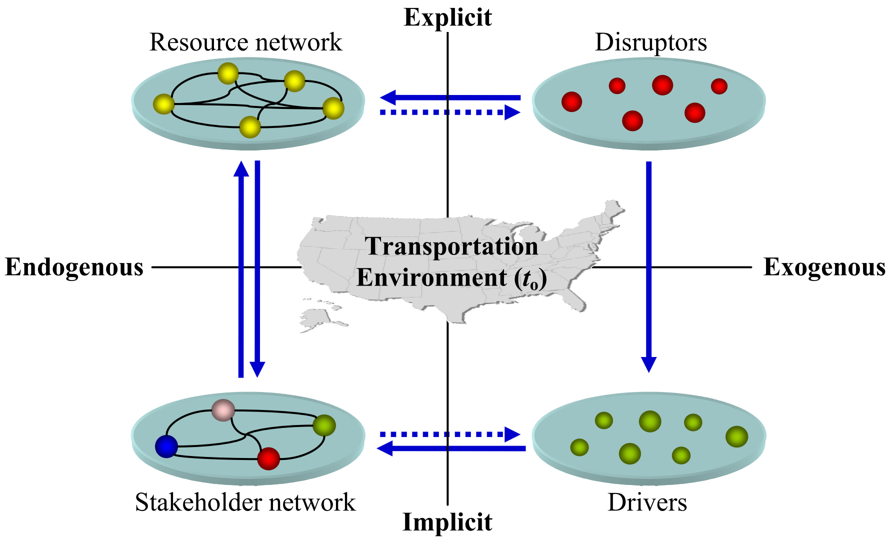

Fig. 1: A slice of the TAF at t_0 where time axis (not shown) is out of the plane of the figure.

3. Representation of Modeling Entities

The abstraction process revolves around the concept of an entity—a set of attributes, functions, interfaces and sentience with a flexible boundary. These four basic rudiments are the basis for representing the entities in the TAF.

3.1 Resource Network

Resource entities are vehicles, portals and enroute space—the tangible elements of the NTS. The resource network is a complicated web of these entities, providing means to transport people or products. A conceptual visualization of the resource network is given in Fig. 2 where three transportation modes are portrayed envisioning a unit travel mission profile. Two existing modes (airliner and car) are most important in terms of traffic volumes as the emphasis is on long-distance passenger trips. A *new mobility mode* is infused into this unit network as the focal point to explore future transportation architectures as shown.

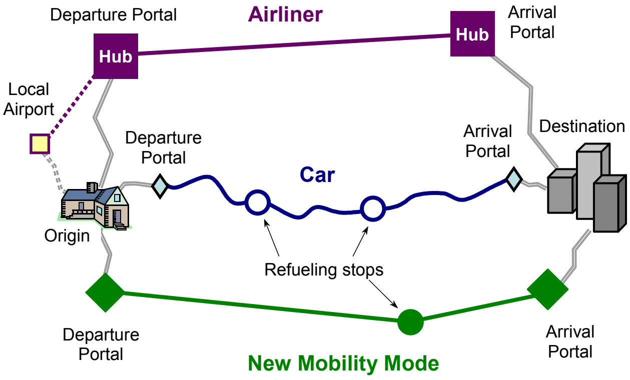

Fig. 2: Simplified Resource Network

A *vehicle* is a primary entity within the resource network. A motor vehicle is on-demand, cost-effective and suitable for daily, short-haul trips whereas commercial jet aircraft offers the most time-efficient method to traverse coast to coast. Despite their distinct characteristics, each vehicle can be regarded as an object that encapsulates its own functions and attributes including operational/economic characteristics. A brief synopsis of vehicles' attributes is given in Table 2. Other *'soft'* factors—including vehicle comfort, perceived prestige and safety, or security concerns—can be modeled and added with a certain ordinal scale.

Table 2: Attributes of Vehicle Resource Entity

Category	Attributes
Operational Performance	Cruise speed Maximum range License requirement Payload capacity Near all-weather operations
Economic Characteristics	Acquisition cost Direct operation cost Insurance/maintenance cost Price/fee schedule
Infrastructure Compatibility	Types of portal Types of enroute space Dual mode capability

Portals refer to the transition points between modes of transportation (except for the car mode). A portal can be characterized by the type of vehicle that it accommodates, location, maximum throughput per given time period, construction time/cost and required resources for operation. The operational scheme of portals varies. For example, airports operate under the centralized control system and on a scheduled basis whereas highway ramps accept on-demand traffic without a control tower. All of these features constitute a portal entity, defined by its own attributes, interfaces, and functions. Among the various attributes, the most important ones include time-related characteristics regarding transportation activities such as processing time for boarding a travel method, waiting times, and portal delay. These characteristics combine to take the majority of the non-moving portions of travel. Some representative attributes related to time are broken down in Table 3.

Table 3: Time Attributes of Portal Entity

Element	Description
Mode change	Required time to transfer from/to secondary mode
Wait-ahead	Required time for most scheduled services
Wait-in-line	Required time for processing ticketing, baggage claims and security check
Portal delay	Undesirable waiting time due to capacity limit, weather, etc.

The *enroute space* infrastructure is composed of air routes, highways, rail roads, etc. Also, parts of the enroute space are support points en route (for rest and refueling) that have their own effects on block speed—the ratio of trip distance to combined travel time. The en-route space can be conceptualized through an entity representation as well. For example, a path-length parameter can be introduced to account for non-linear trajectory between points due to topographical or operational circumstances during a trip. The time-related interfaces can also be constructed to allow the inclusion of an array of delays possible in the course of traversing any physical portion of the NTS. Refueling time, climb profiles, intra-/inter-city traffic and other transient factors are some examples. Each enroute space has a particular degree of construction cost required, autonomy level, disruptor susceptibility and so forth. A portion of their characteristics is shown in Table 4.

Table 4: Enroute Space Entity

Rudiment	Items
Attributes	Types of portals and vehicles Path-length parameter Construction cost Operation cost & rule
Interfaces	Refueling/rest points Enroute delay effect (inter- and intra-city) Influence from weather effect Throughput of vehicles

3.2 Stakeholder Network

The entities in the resource network have a set of properties or attributes as they exist in the tangible form. In contrast, the organizational entities—the stakeholders—need a different treatment since representing their sentience as well as their interconnections is the key challenge. The use of agent-based modeling and simulation (ABM/S) is well-suited for manifesting the complicated behaviors of a collection of sentient entities.

ABM is a bottoms-up modeling technique that focuses on building an agency within the environment. It encodes attributes and behaviors at the individual component or microscopic level of the system. The system's macroscopic properties "emerge" because of these attributes, behaviors, and the interactions between them. Various definitions of the term agent can be found in the literature [6, 7]. Common keywords that relate many of the numerous definitions are "adaptive" and "autonomous". An agent is adaptive in the sense that it can use its experience to continually improve its ability to deal with shifting goals and motivations. It is an autonomous entity if it operates without external guidance and does not need to follow systematic instructions from the modeler who created it.

The stakeholders in the NTS are "agents", and can be modeled as such through the analysis of their goals and behaviors—i.e., manifesting sentience and functions. A consumer wants to maximize utility whereas an airline wants to maximize its profit. A series of actions should be chosen to fulfill this goal and the underlying mental activities that embody sentience can be implemented by a set of logical decision-making algorithms. In addition, probabilistic treatment can admit the possibility of *'irrational'* behaviors.

The mental model of each stakeholder entity can be analyzed and modeled independently. Then, a collection of these mental models can be organized by constructing a multi-agent architecture (MAS) as illustrated in Fig. 3.

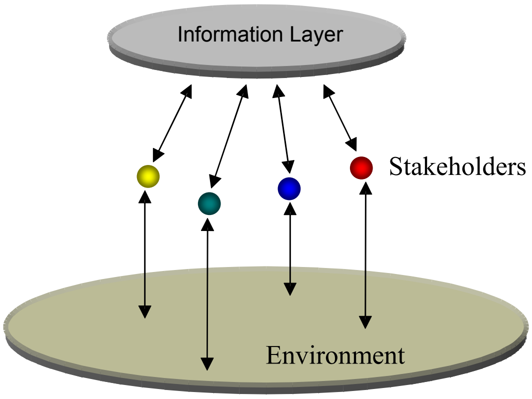

Fig. 3: Agent-Based Representation of the Stakeholder Network

The role of the information layer is to provide a route through which the stakeholders communicate and interact. In essence, the information layer encompasses the interfaces of stakeholder entities of interest. Then, in theory, the final form of the whole organization—i.e., the stakeholder network—emerges as simulation progresses. Benefiting from ABM's inherent flexibility in constructing the model, the modeling boundary of the stakeholders and their network can be easily extended with a varying degree of the fidelity, on a need basis within the problem scope of a modeler's interest.

3.3 Exogenous Entities

The previous discussion highlighted that entity attributes are the most salient rudiment for the resource network while the key issue for the stakeholder network concerns representation of sentience. The central challenge in representing exogenous entities is dealing with their influence on the environment—i.e., their interfaces.

3.3.1 Drivers

The driver entities are underlying sources of the stakeholders' behaviors from economic, societal, and psychological motivations. The economic drivers consist of various factors in a wide variety of forms. For example, in order to measure the nation's economic condition, the Gross Domestic Product (GDP) and the Consumer Price Index (CPI) may be used as the simplest top-level scalar metrics. Gasoline price is a simple scalar as well, but time- and location-specific variation should be considered to investigate microscopic behaviors of the stakeholders. In contrast, some factors exist with a disaggregate nature. Household income varies across individual households, so this entity must be treated in an array format. Besides purely economic concerns, demographic factors exert a significant force driving the overall demand profile of transportation activities: the locations where people live, the number of members per household, and age/sex/worker composition of population—all factors can be encapsulated in a multidimensional table.

On the other side of the driver entity group, cultural and psychological elements offer a unique challenge. A working model showing quantitative and meaningful effects of these elements rarely exists, but the basic methodology of representing these entities is not so complicated. The strength of their attributes can be mapped by ordinal scales, and the modeler needs to define the relationship between the scale and each stakeholder's interface under the proper assumption. While this work might be arbitrary, it is significant that modeling of *'less-quantifiable'* factors can be accomplished by perturbing the strength of the relationships, which may end up with a routine calibration process. Survey studies and subsequent analysis would be easily accommodated through this avenue if such results become available.

3.3.2 Disruptors

The primary influence of the disruptors is related to the efficiency of the resource network. These undesirable entities can be considered as an instance of discrete events, although their cascading consequences are likely to resonate over time. By and large, these events can be reduced to a few elements: location, strength, duration, and locality (coverage). All these elements are associated with uncontrollable nature for which probabilistic treatment can account. The Monte Carlo Simulation can be employed to invoke disruptor entities in the transportation environment, supported by calibration from empirical data.

In actual simulations, each disrupting event will have varying degree of effect and influence to a particular portion of the resource network. For example, automotive travel is generally resistant to inclement conditions, while air travel is sensitive to short-term changes in weather. This whole mechanism can be completed with incorporating thresholds within the interface of the resource entities.

The influence of the disruptor entities is two-pronged as one recalls Fig. 1. Some events directly affect the psychological driver, which is especially evident when the extent of harmful effect is far-reaching. Representing this mechanism follows in the same fashion as in the above case. If the psychological driver is modeled with the scales that directly affect the stakeholders' behaviors, the inclusion of thresholds in the driver interface can properly model the relationship between the disruptor and the driver, eventually towards alternating the stakeholders' behaviors.

4. Creation of the Virtual World

Formulating a virtual version of the NTS is the final destination in creating a computational model, where all entities are interconnected to have concrete, physical, real meanings. This integration initiates a state in the TAF and subsequent states emerge from entity interactions, resulting in a *virtual world* being observed.

4.1 Integration and Simulation with Locales

The concept of *locale* is introduced as a basic building block of final integration. A locale is an abstract representation of a unit geographic environment that encapsulates its own transportation resources and stakeholders, economic and societal circumstances, and disruptors as portrayed in Fig. 4. It can represent a state, a county or an area with the same zip code depending on required level of model granularity. The overall model fidelity depends on how accurately locales are modeled, so sufficient detail is desired but balanced against the need for computational feasibility.

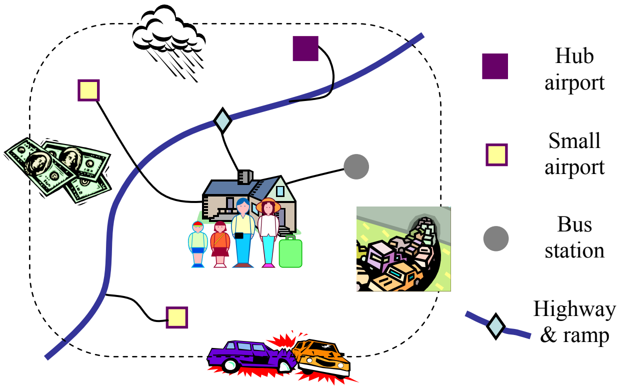

Fig. 4: Abstraction of Unit Locale

The construction of a particular locale is very similar to the process of creating an object from a class in object-oriented programming. First, four entity groups should be defined as global components. In doing so, these global components should be tied with the real world for a particular time period of interest. As discussed, they can be any objects: simple scalars, matrices, probability distributions or a real and/or logic functions. A unit locale is a composite instance built from the global components, and thus inherits most of their original properties.

The transportation environment is a set of N interlocking locales with appropriate topological information and many heterogeneous objects that the stakeholders can interact with directly: vehicles, portals, events of delay, and so forth. Care should be taken since, for each locale, some properties should be tailored to reflect specific conditions for its respective modeling target. The overall resource and stakeholder networks are synthesized upon completing the creation of locales. As simulations progress, the collective behavior over the entire system can be fed back into the global components. This information then affects and changes the global components themselves, which in turn updates the locales where new sets of local agents are populated. Just like the real NTS, the whole model possesses its own collective sentience. This completes the conceptual mechanism of the virtual NTS, or the simulated TAF as portrayed in Fig 5.

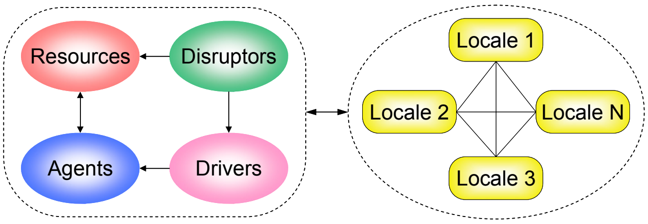

Fig. 5: Simulation of the TAF

The organization of this *'simulation universe'* offers the simplicity while allowing a remarkable amount of information to be processed. A wide variety of interactions and elements within the transportation environment at a host of different levels can be treated with enhanced flexibility and traceability. This feature will offer the manageable complexity of implementing a better simulation granularity and fidelity, or even a *'new universe'* in response to a need for examining a totally different situation.

4.2 Implementation and Test

The scope of the modeling exercise is quite large: long-distance, passenger transportation activities are examined, considering intercity trips of 100 or more miles in the entire continental United States over a single calendar year. Some specific parameters and equations used for the model can be found in Ref. [11]; the complete set of modeling specifications are being prepared for publication.

4.2.1 Brief Model Description

Before constructing a working model, a database review was done. The U.S. government has always been interested in the trends and characteristics of the NTS. The most important database used was the 1995 American Travel Survey (ATS) [7], a study by the Bureau of Transportation Statistics that interviewed approximately 80,000 households nationwide. Other databases include the 1995 Nationwide Personal Transportation Survey (NPTS), an important database that treats daily travel in the U.S. [8]; TranStats, an extensive intermodal transportation database [9]; the 2000 U.S. Census and several other sources. One disadvantage of using several disparate sources is that not all of the data agree on certain characteristics. Thus, care must be taken with the construction of models, but it is inevitable that a certain amount of uncertainty exists in the data and thus the model.

Four vehicle groups were considered in constructing the resource network. The primary groups consist of personal cars (including light trucks and SUVs: code CAR) and commercial airlines (both business and coach class: code AIR), which make up the vast majority of all household travels (about 96%). The general aviation (GA) aircraft, split into a piston single-class aircraft (code GAP) and a business jet-class aircraft (code GAJ), makes up the final standard groups. Although only a small portion of the total NTS traffic (less than 1%), general aviation is critical for explorations of future aerospace technologies, as it is widely considered a leading indicator of an on-demand, point-to-point, and distributed air transportation system. Other transportation modes, such as trains, buses and ships, were omitted from this study.

Any stakeholder in the NTS, in theory, can be treated as an agent. As an aggregated group, travelers are the chief players in the NTS. Other agent types, despite being less numerous, have far more complicated behavior patterns that are beyond the scope of the present model. The actual behaviors of the traveling public are extremely diverse in reality, even though every individual agent assumes the same behavioral rules for each traveler and each trip has distinct features. The primary attributes of a traveler include household income, vehicle ownership, location (whether a traveler lives in a big city or a rural area), and a list of trips over a period of time. Each trip has its own attributes as well: personal/business travel motivation (the potential ability to have the trip expensed), trip distance, location of destination, and number of travel party. The implemented behavior of traveler agents is to choose the best alternatives for a trip, which is mathematically treated through a multinomial conditional logit model.

All entities are situated in a set of locales where the agents and the relevant structures are populated during the simulation runs. The model uses four locales as a physical space of large metropolitan areas (L), medium-sized cities (M), small-sized cities (S), and non-metropolitan or rural areas (N). The agents are dispersed within these spaces as they are dispersed in reality, using the databases to follow population trends and movements within the time period of the experiment. An extensive database analysis was carried out to differentiate each locale's characteristics. The synopsis of this outcome is summarized in Tables 4 and 5. Four distinct locales have respective portal accessibility and the amount of delay. Also, the origin-destination matrix reveals the travel demand profile in terms of spatial distribution.

Table 5: Portal Accessibility

Access distance to	L	M	S	N
Hub airport (mi)	2-40	2-60	50-100	100-200
Small airport (mi)	2-10	2-12	2-30	4-75
Freeway ramp (mi)	1-5	1-5	1-10	1-40

Table 6: Origin-Destination Matrix

O D	L	M	S	N
L	9.16%	7.77%	4.03%	12.17%
M	5.94%	3.96%	2.46%	7.91%
S	2.73%	2.52%	1.17%	4.62%
N	7.49%	7.61%	4.64%	15.83%

4.2.2 Calibration of the Simulation Model

To implement the virtual TAF, a simulation code, named ***Mi***, has been developed. It is a simple object-oriented program in Java^{TM}. The simulation speed is quite fast—on the order of one minute for one million agents.

Calibration of the model was rather simple, although time-consuming. The basic agent decision-making algorithm responded quite well with no interference, and it is only in the tweaking of internal parameters that any significant time was spent after the initial development of the model. Cases were run repeatedly on the order of one to ten million agents to fine-tune the model to closely match the 1995 ATS data. The most important response monitored during the calibration was overall market shares of the four transportation modes, shown in Table 6.

Table 7: Overall Modal Share Result

	CAR	AIR	GAP	GAJ
1995 ATS Data	75.88%	23.48%	0.64%*	
Present Model	75.92%	23.44%	0.42%	0.22%

*No further breakdown available in the ATS database.

This modal split is satisfactory, but the simulation results should also correspond to the real behaviors of the traveling public, which necessitates closer investigation from different angles. Accurate matches are shown for the chosen mode with respect to the travel motivations, as revealed in Fig. 6.

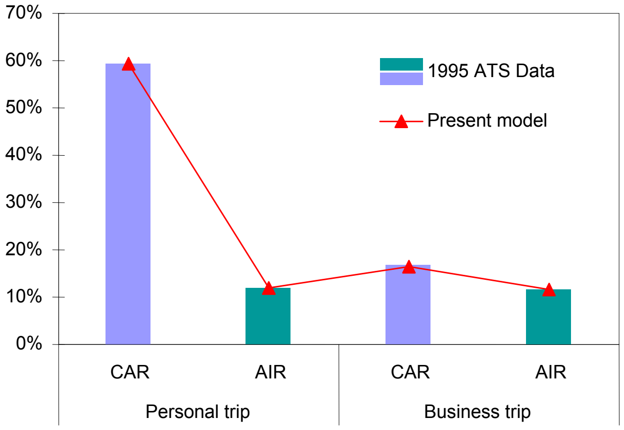

Fig. 6: Trip Purpose and Modal Split

Also, a short-distance traveler is likely to use an automobile, so the market share of CAR should shrink as travel distance increases, and vice versa for AIR. These trends from the 1995 ATS data and the calibration result are plotted together in Fig. 7 and Fig. 8, respectively.

Considering the level of abstraction inherent and the absence of *model-artifacts* in the model, the results were remarkably good. The created virtual world has become very similar to the NTS in many respects. Small mismatches were the inevitable price stemming from simplifying the real world, which could be diminished by increasing the model granularity.

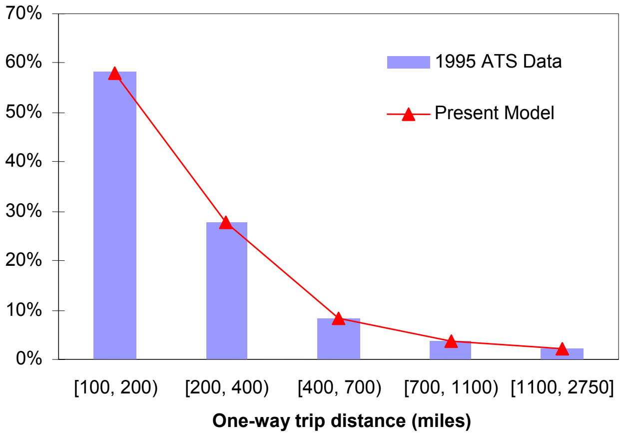

Fig. 7: Distance Bracket Distribution for CAR

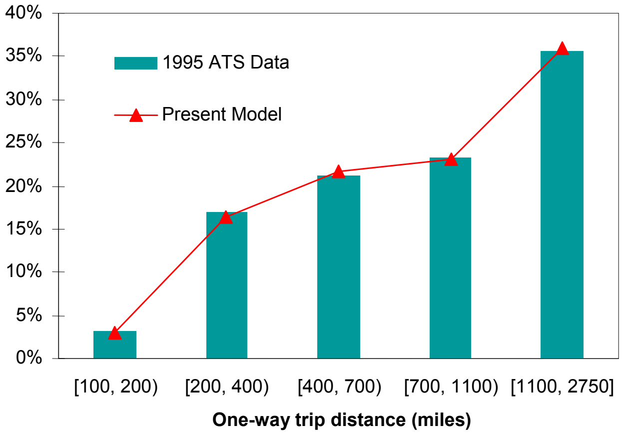

Fig. 8: Distance Bracket Distribution for AIR

5. Summary and Perspectives

A foundation for a means to consider a wide range of future transportation systems has been presented. A broad description of the major parts of the foundation comprised abstraction, modeling, and implementation. Relevant references have been cited for more detailed treatment of each. Overall, the foundation and the agent-based simulation studies briefly described in this paper appeared to the authors to have two noteworthy implications.

First, the approach successfully foregoes the usual employment of a reductionism perspective. The abstraction framework effectively guides modeling in such a way that nearly any conceivable combination of transportation resources, economies or policies is quantitatively admissible. Future scenarios, based on vehicle technologies [10], system-level changes, economic disruptions [11] or any number of other important system changes, could be evaluated against baseline values to showcase the effects of these changes. The complexity of such an undertaking again can be partially mitigated by the primary innovation of the foundation: proper couching in the abstraction framework leading naturally to the modeling interfaces required. The simplicity revealed by abstraction (at the price of model details) can answer certain questions that perhaps could never be approached if high levels of detail were demanded. Furthermore, this simulation framework can seamlessly integrate diverse groups of users; policymakers, designers, urban planners and others involved in various aspects of the NTS can share a *computational laboratory* that promotes systems thinking and a unifying context.

Second, while demonstrated by calibration to the U.S. NTS, this generic approach holds promise as a framework for tackling challenges as broad as global transportation. The concept of locales can be extended beyond the national level to study multi-national, trans-continental or even inter-continental scenarios. In such cases, the role of the stakeholder and exogenous entities are absolutely critical, and thus are accounted in the presented approach. It seems intuitive that any future, transformed global transportation system will face barriers of policy, procedure, and economics of even greater difficulty than purely technological ones. Therefore, a framework that supports the inclusion of stakeholders and exogenous factors by providing modeling interfaces and a clear rationale for their role in the *'network of networks'* seems capable of providing valuable guidance to members of national and international transportation planning organizations. Just as aircraft designers over the past decades have experienced the paradigm shift from performance to affordability in finding better, robust designs [12], so too may today's engineers and policy makers benefit from a holistic perspective in collaboratively working towards a more efficacious future state of global transportation. The challenge is enormous, the collaborations are essential, and so we must get started together.

References

[1] Carson J and Doyle J. Complexity and Robustness, *Proceedings of the National Academy of Sciences*, Vol. 99 (Suppl. 1), pp. 2538-2545, 2002.

[2] Lempert R, Popper S and Bankes S. *Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis*, RAND Corporation, 2003.

[3] Grosholz E. *Cartesian Method and the Problem of Reduction*, Oxford Univ. Press, New York, 1991.

[4] DeLaurentis D, Lewe J and Schrage D. Abstraction and Modeling Hypothesis for Future Transportation Architectures, *AIAA International Air and Space Symposium and Exposition: The Next 100 Years*, Dayton, OH, 2003.

[5] Woodridge M and Jennings N. Intelligent Agents: Theory and Practice, *The Knowledge Engineering Review*, Vol. 10, No. 2, pp. 115-152, 1995.

[6] Holland J. *Hidden Order: How Adaptation Builds Complexity*, Addison-Wisely, Reading, MA, 1995.

[7] 'The 1995 American Travel Survey: Micro data File,' Data CD-ROM, Bureau of Transportation Statistics, 1999.

[8] '1995 National Personal Travel Survey,' Federal Highway Administration [online database], http://www-cta.ornl.gov/npts/1995/doc/index.shtml [accessed 6 May 2002].

[9] 'TranStats,' Bureau of Transportation Statistics [online database], http://itdb.bts.gov/homepage.asp [accessed 18 Aug. 2003].

[10] Lewe J, Kang T et al. An Agent-Based Simulation Tool for NASA's SATS Program, 2nd Place Entry in NASA/FAA 2002 University Competition, May 2002.

[11] Lewe J, Upton E et al. An Agent-Based Framework for Evaluating Future Transportation Architectures, *AIAA 3rd Aviation Technology, Integration & Operations (ATIO) Forum*, Denver, CO, 2003.

[12] Mavris D, Bandte O and DeLaurentis D. Robust Design Simulation: A Probabilistic Approach to Multidisciplinary Design, *Journal of Aircraft*, Vol. 36, No. 1, pp. 298-307,1999.