ENTITY-CENTRIC ABSTRACTION AND MODELING FRAMEWORK FOR TRANSPORTATION ARCHITECTURES

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ABSTRACT

A comprehensive framework for representing transportation architectures is presented. After discussing a series of preceding perspectives and formulations, the intellectual underpinning of the novel framework using an entity-centric abstraction of transportation is described. The entities include endogenous and exogenous factors and functional expressions are offered that relate these and their evolution. The end result is a Transportation Architecture Field which permits analysis of future concepts under the holistic perspective. A simulation model which stems from the framework is presented and exercised producing results which quantify improvements in air transportation due to advanced aircraft technologies. Finally, a modeling hypothesis and its accompanying criteria are proposed to test further use of the framework for evaluating new transportation solutions.
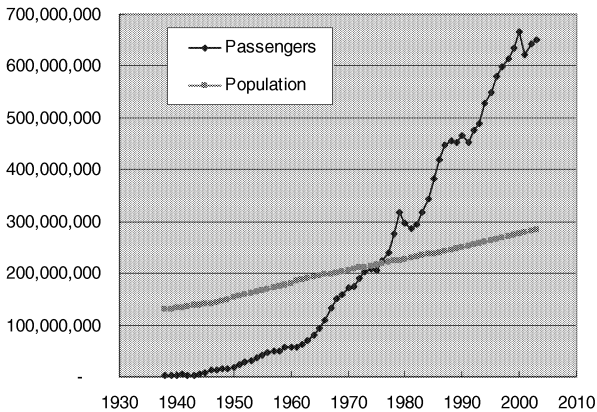
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INTRODUCTION

The U.S. transportation system witnessed unprecedented growth in the 20th century. In particular, since the 1960s, the modern aircraft—just like its predecessors, trains and automobiles in their times—has dramatically boosted mobility of the general public. As indicated in Figure 1, the air transportation system picked up momentum after Lindberg's transatlantic flight and yearly domestic enplanements have continued to outnumber the population since 1976, and the spread is expanding.

Figure 1. Yearly Domestic Enplanements and Population by Year

Note. **Source: US Census Bureau, Bureau of Transportation Statistics**

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With further enhancement in mobility, the public could spend less time on travel over a given distance, take longer trips in a given time, and/or travel in ways otherwise not currently possible or affordable. Such a positive scenario, however, is in jeopardy as the rate of expansion of mobility under the current transportation system is reaching a limit on the ground and especially in the air due to (partly unforeseen) growth in congestion, pollution and network delay (AIA, 2001). The aerospace community is undertaking various remedies in the face of this challenge including design of new commercial jets (e.g., Airbus A380 and Boeing 787), enhancement of capacity in both the airspace and terminal area, and development of environment-friendly technologies. Further, targeted research extends to general aviation, where some are experimenting with new types of aircraft and advanced operational structures (e.g., very light jets, on-demand regional air services, and even personal use air vehicles; Holmes, Durham, & Tarry, 2004). The premise motivating most of these initiatives is apparent: advanced technology spurs mobility enhancement. The temptation to look for innovation through technology alone, however, must be resisted. Systems thinking is required, as recognized in NASA's Aeronautics Blueprint: "The aviation system is a *system-of-systems*. . . . Furthermore, consideration must be given to the intermodal relationships within larger transportation systems (land and sea). These analyses require the construction of *complex, intricate and comprehensive system models*" (NASA, 2002).

If the system-of-systems premise is adopted, then the *design space* in which solutions may be found is much more open. Infusion of new technology into the existing infrastructure organization is but one possibility; a reorganization of how new, improved and existing systems interoperate is also an alternative. However, existing analysis methodologies and tools, developed for systems, can only bring us so far, and thus new approaches are required to fully examine new solution sets. Further, the system-of-systems perspective expands the problem boundary to fully include areas such as policy and economics—public and private interest groups must be examined together along with the networks that connect them. Altogether, creating complex, intricate and comprehensive models requires first a new holistic framework so that problems within systems domains can be properly formulated and then solved by designers of aircraft, airspace and so forth. At the same time, results that flow from the system-of-systems framework must be concrete and actionable, targeted at identifying the research and development necessary to realize the most attractive transportation futures.

In sum, the pursuit of a desired, future national transportation system and a full comprehension of the preferred paths to guide this pursuit together represent a tremendous challenge, one that surely requires the wisdom and innovation of many. The essential ingredients at the start, however, are clear: effective frames of reference, thought processes and problem formulations. It

is from this motivation that the present paper is written. The authors attempt to lay out a novel paradigm to address the challenge, starting from the idea that existing approaches are incomplete for the job is neither entirely new nor exclusive observations of the authors. Hence, the first part of this paper summarizes relevant research works indicative of the aerospace engineers' perspective, which then motivated the development of a broader intellectual construct. The second part formulates the transportation architecture and expresses the entities and their interaction dynamics in a generic, comprehensive manner. The final section presents initial results achieved through simulation and hypothesis of a more complete approach. The overall aim is to foster a generic, conceptual framework for the examination of air transportation architectures in the context of a larger National Transportation System (NTS), allowing problems to be recast so that today's designers can contemplate the future without preconceived boundaries.

BACKGROUND AND EXPLORATORY RESEARCH

Vehicle concept analysis

The design of advanced air vehicles was the initial research interest of the authors, especially focused on a new generation of small, general aviation craft after the inauguration of a focused project at NASA, the Personal Air Vehicle Exploration (PAVE) project (NASA, 2004). The major undertaking of the research was not to invent the latest in a line of futuristic airplanes or flying cars, as many enthusiasts have been attempting almost immediately since the beginning of flight (Bowers, 1990). Instead, the project focused on formation of complete baseline models for a family of air vehicles in order to calculate possible improvements of each through new technology infusion. Hence, six baseline Personal Air Vehicle (PAV) concepts were selected, ranging in configuration from an autogiro to a very light jet airplane, and their performance and economics were analyzed. The study process employed was composed of four major steps: (a) calibration of sizing codes for the baseline concept, (b) re-sizing of the baselines for the new PAV mission profiles, (c) update to state-of-the art models through technology infusion, and (d) a final sizing/performance study (Mavris & DeLaurentis, 2002). An example result from this process is shown in Figure 2, where the gross weight and direct operation cost metrics for baseline and state-of-art versions of a 1-to-8 seat autogiro are presented.

Figure 2. [Top] Six Baseline Concepts Studied (clockwise from upper-left). Cartercopter Gyroplane, Lancair Columbia 400, Groen Bros. Hawk 4 Autogiro, Robinson R-44, Eclipse 400 VLJ, and Boeing Dual-mode Rotorcraft Concept. [Bottom] Payload and Technology Sensitivities for an Autogiro Concept Aircraft
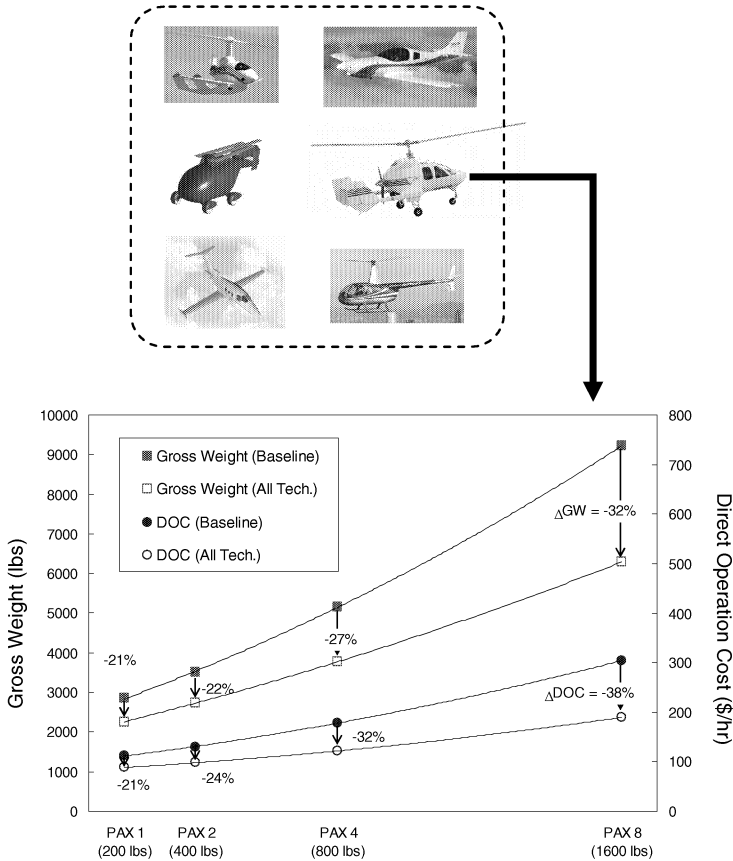
While the capability envelope for each advanced technology configuration was established from the studies, what remained elusive was how to rank relative merit across all baseline platforms. For consideration of alternatives within a configuration class, the traditional approach in concept evaluation defines a scalar metric which measures the quality of each alternative, m_{perf}. When multiple objectives are involved (vector $\overline{m}_{perf}$), and a design tradeoff is required, Multi-Attribute Decision Making techniques are employed in the evaluation process to investigate a set of candidate designs. The result is a functional relation between the performance metrics and the

set of vehicle configuration, $\overline{x}_{veh}$ (e.g., aspect ratio, wing area, thrust-to-weight ratio) and technology, $\overline{x}_{tech}$ (e.g., advanced flow control, thrust-vectoring) design variables, Equation 1.

$$\overline{m}_{perf} = f(\overline{x}_{veh}, \overline{x}_{tech}) \tag{1}$$

These scoring approaches generally require the use of physics-based codes to evaluate the function, which implies that the evaluation process can be performed within a specific vehicle platform, not across a wide variety of different platforms, let alone revolutionary concept vehicles. Even if there exists a universal physics-based code that can simultaneously evaluate a wide variety of PAV concepts, a designer would still face the *incommensurability* issue—a certain metric is only meaningful within the same family of vehicles. For example, time-in-hover capability has no meaning for a fixed-wing vehicle.

**Transition from vehicle to mobility**

Redress of the incommensurability issue was found in the concept of mobility as metric. Indeed mobility, defined as the ability to travel from *doorstep-to-destination* (D-D), captures the inherent intent in the pursuit of superior aircraft while also explicitly representing the reality of the traveler in his/her trip. A recent study by the Volpe Center on comparative travel times across a range of commercial air trip types demonstrated the importance of understanding reality in a D-D mobility context. The data displayed in Figure 3 is for connecting service in the 500-999 mile range and shows that about half of the time spent on such trips occurs *outside* of the aircraft.

Figure 3. Distribution of total time (337 minutes) for Air Trips
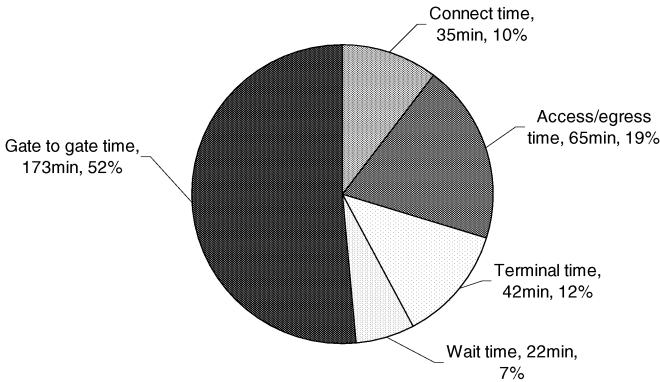
Thus, the study of advanced air vehicles in this context had its emphasis on reducing D-D trip time, not simply gate-to-gate and spawned the Benefit Exploration Tool (BET) considering an origin-destination trip network with portals. The tool enables a user to construct any multimodal transportation means through synthesis of a set of vehicle metrics, $\overline{m}_{perf}$ (e.g., speed and refueling range), and infrastructure characteristics (e.g., portal wait/transition time, *TWAIT*, and access distance). It then compares D-D time on a user-selected mission range. The BET interface is shown in Figure 4, where the panel on the top is used to change trip options while the slider bar below the bar chart modifies the mission range (and the D-D time comparison bar chart is updated in real time).

Figure 4. D-D Travel Time Visualization using BET
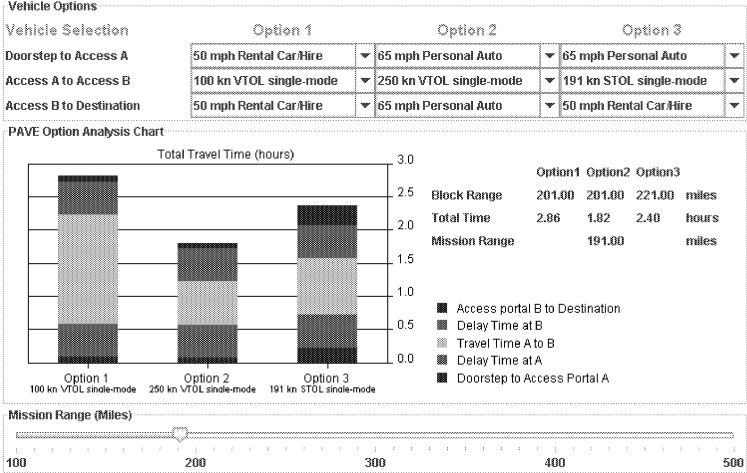

The BET laid the foundation for the study of mission (trip) parameters and vehicle performance metrics simultaneously, encapsulated in the Benefits Visualization Tool. This tool also emphasizes D-D time within a PAV concept investigation process with the addition of a net-present value (NPV) analysis, based on the premise that travel time saving over time is converted to monetary profit to a specific user. This user is designated as λ, and the set of trips he/she takes is θ of which element is μ. Summarizing, the set of user mobility metrics $\overline{m}_{mob}$ (e.g., average travel time) result from a function (g) of trips taken and the mode performance over those trips, Equation 2,

$$\overline{m}_{mob} = \sum_{\mu \in \theta(\lambda)} g(\mu) \circ f(\overline{x}) = \sum_{\mu \in \theta(\lambda)} g(\mu, \overline{m}_{perf}) \qquad (2)$$

where $\overline{x} = [\overline{x}_{veh}, \overline{x}_{tech}]^{t}$. Hence the amount of the hypothetical benefit from a prescribed PAV utilization pattern can be quickly computed and visualized. For this purpose, a trade-space analysis was developed, underpinned by the *Unified Trade-off Environment* (Mavris & DeLaurentis, 2000), through specialized *solution space* diagrams as illustrated in Figure 5. In this example, one element of $\overline{m}_{mob}$, the NPV after a certain time period, is examined. The detailed process was demonstrated by DeLaurentis, Kang & Lim (2004).

Figure 5. Mobility Solution Space Diagram. Constraint Boundary is Line of Constant NPV=0 after 5 years. A Shift of the Design Point X to Feasibility is Accomplished by a Small Increase in Cruise Velocity (*V*) and Modest Decreases in *TWAIT* and *DOC*. The BVT Illuminates the Fact that Increasing *V* Alone Cannot Achieve the Goal.
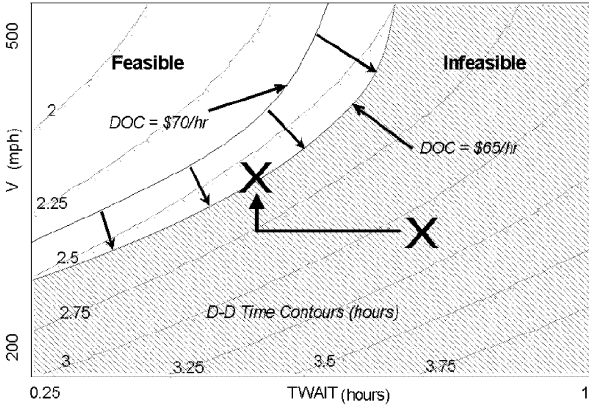
This line of research under the mobility theme resolved the incommensurability issue with some limitations: that is, a particular user and utilization pattern must be specified. Recognizing that utility differs among consumers, there is a need to characterize personal mobility solutions in the context of mode choice and the value of time. This focus has been addressed in the literature several times, dating to the early 1970s (Drake, Kenyon & Galloway, 1969; NASA, 1971; Winich, 1983). For example, Drake, Kenyon and Galloway (1969) focused on mapping preferred modes on the utility space defined by value of time and distance. More recently, Downen & Hansman (2003) performed a web-based survey of active general aviation (GA) pilots and then developed a mode choice model.

Figure 6. Market Space Plot for Choice Transportation Modes

(a) Drake et al. (1969)

(b) Downen and Hansman (2003)
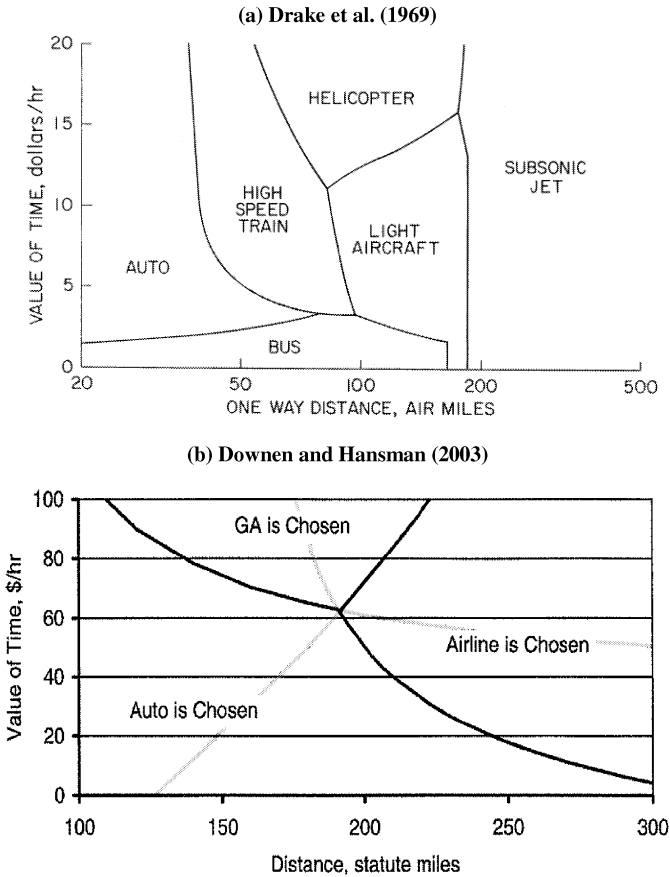
Mathematically, the models underlying the results in Figure 6 are expansions of Equation 2, introducing the parameter Ω and function $h(\Omega)$ to represent performance of other-than-air mode. Also, we can now express mobility summed over a class of users, their trips, and modes used, Equation 3.

$$\overline{M}_{mob} = \sum_{\lambda} \sum_{\mu \in \theta(\lambda)} h(\Omega) \circ g(\mu) \circ f(\overline{x}) \qquad (3)$$

Stakeholder dynamics as mobility drivers

While the mobility-focused research includes the travelers explicitly into the concept evaluation loop, it is only the tip of the iceberg. In fact, there is a

multitude of players involved, individuals and organizations that have a stake in what transpires. Further, they generate a dynamic behavior: as travelers' preference changes over time, the response of service providers shifts, and subsequent actions of vehicle manufacturers occur to meet new needs of service providers, etc.

Several threads of work that explore these stakeholder dynamics in air transportation have been ongoing. For example, Bhadra et al. have developed a means to estimate future air transportation timetables, which represent in an aggregate way future traveler demand based on historical trends as well as supplied assumptions (Bhadra, Gentry, Hogan & Wells, 2005). Additionally, other researchers at MITRE have investigated service provider stakeholder's dynamic through an agent-based simulation called Jet:Wise (Niedringhaus, 2004). Taking airline companies and leisure passengers as agents, the model attempts to explore the evolution of the airline industry within the National Airspace System (NAS). In each cycle of simulation, airline agents make successive decisions to achieve their respective goals. The work by Hansman (2005) generated conceptual ideas for a model of dynamic behavior in air transportation based on careful analysis of the historical data and a particular examination of information technology across all organizations in the system. Likewise, Kang, Lim, DeLaurentis & Mavris (2003) considered dynamic interaction between manufacturers and research agencies in the new mobility resource development cycle and attempts to identify promising operational policies. This Systems Dynamics (Sterman, 2003) approach was an initial foray into the world of feedback dynamics known to exist in real transportation markets and a first step in search for a synthetic view. All together, though, each of these experiences in the realm of stakeholder dynamics are not yet enough to obtain meaningful results within the system-of-systems space, specifically geared towards the overall D-D mobility issue. Further development and investigation is necessary.

In summary of this section, beginning from the traditional starting point of vehicle design, a set of improved perspectives (and tools) for exploring new transportation solutions has evolved. Yet, the comprehensive model for the problem as it is, a system-of-systems, remains illusive. Pieces of the puzzle are at hand, but the complete puzzle as a whole is not apparent nor is the dynamics which define its evolution. More specifically, the analysis and design tools do not represent all of the design degrees of freedom, including physical resources, organizational entities, and the inter- and intra-connected networks that tie them together. The remainder of this paper describes the new advancement in response to this intellectual need, through abstraction and hypothesis of a solution methodology. The start is the formulation of a generic transportation architecture.

## GENERIC TRANSPORTATION ARCHITECTURE AND ITS ABSTRACTION

An architect is concerned with overall patterns of form and function and therefore must think using a holistic perspective. We embrace the holistic perspective by adopting the *everything-on-the-table* thinking about the future evolution of transportation. However, the immediate question is raised: What is everything? To answer, an examination of what constitutes the NTS, generally, is the first step. Subsequently, the concept of *Transportation Architecture* can be articulated and then analyzed properly.

Constitution of the NTS

Transportation resources

As mentioned, the usual focus for improvements in the NTS has historically been on vehicles and their infrastructure, and later their operation in the NAS. These are called transportation resources altogether. Transportation resources in the NTS comprise many heterogeneous types of vehicles and corresponding infrastructure. Traditionally, resources within a general category have been treated in their own realm. However, improvement in mobility will demand an integration of these now distinct dimensions. Consequently, a view that encompasses all resources in the NTS together is useful, as shown in Figure 7 where a hypothetical new mobility resource is positioned without linking to any existing system toward the center of the figure. Exploring a new mobility resource in this larger context can reveal its competitive advantage relative to existing resources.

Figure 7. NTS Resource Hierarchy
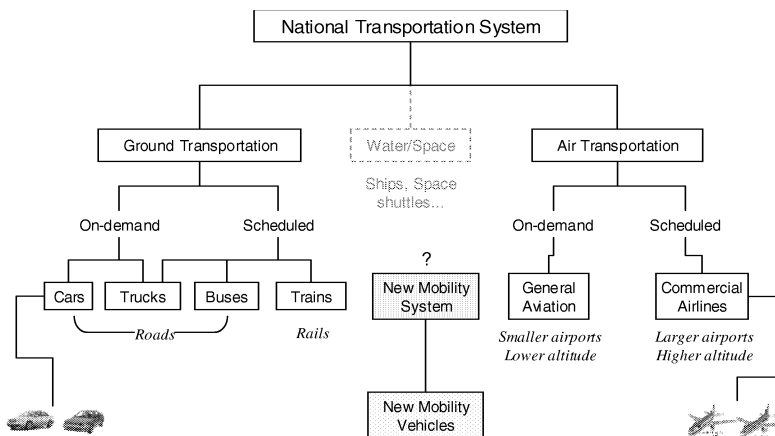
Transportation stakeholders

The mobility perspective included the travelers, or the transportation consumers, in the research scope and the dynamic organizations thrust sought to extend this further. Though the travelers and vehicle operators are not shown in Figure 7 (they are not resources, but users of resources), they are important nonetheless. Any individual or organizational entity has its own will, a sentience, which guides actions that affect the NTS. These entities are called the transportation stakeholders. The relevant stakeholders are identified in Table 1, representing both private and public sectors, ranging from the actual consumers of transportation services to those involved in technology *research and development*.

Table 1. Transportation Stakeholders

Stakeholders		Descriptions	Objectives
Public	Consumers	Individual travelers or shippers (for commercial goods) that are the end user for the transportation system.	max. utility as fcn (time, cost, safety, comfort)
	Society	Represents the aggregated interests of citizens, from research agencies, to communities, to the national level.	min. noise, emission max. quality of life
Industry	Service Providers	Own/operate resources and sell transportation services to consumers.	max. profit, market share
	Manufacturers	Design/produce/sell transportation resources to service providers and/or consumers.	max. profit, market share
	Insurance Companies	Provide protections against mishap operation of transportation resources by collecting insurance fee.	max. profit, market share
Government (Policy-makers)	Regulatory Agencies	Impose rules on the system that restrict stakeholder activity and resource characteristics.	max. safety, security
	Infrastructure Providers	Plan and approve employment and enhancement of infrastructure resources.	max. capacity, min. delay
Indirect Stakeholders	Media	Report information, forecast and plan from/to the public.	Varied, but vague
	Research Agencies	Develop and provide transportation related technologies.	Provide firm foundation for transportation development

Each stakeholder has objectives that dictate the manner in which they influence the transportation architecture. Indirect stakeholders influence the

NTS by their outputs or goals being accepted or filtered by other direct stakeholders. An intangible network that defines the connection between stakeholders can be imagined. This connectedness comes in two forms. First, one particular stakeholder may interact with another directly. Second, if a stakeholder influences a particular resource, after permeating through the resource network, the state of the transportation architecture will be modified.

Besides stakeholders and resources, many other influences that are traditionally treated merely as given assumptions, circumstances and constraints can be juxtaposed within the transportation environment. These are introduced next.

Transportation drivers

In a market-driven world, most transportation phenomena are governed by many economic factors. Household income and gasoline/ticket prices drive consumer behavior while demographic-related issues (e.g., population shifts, urbanization) and commodity prices influence businesses. Further, transportation activities are motivated by cultural and psychological reasons. Some trips are made as a lifestyle choice and are influenced by specific cultural events: summer vacation, Thanksgiving, etc. Psychological factors are also important. The surge in air travel after Lindbergh's successful transatlantic crossing is a prime example. These factors are called drivers (Table 2) and are largely concerned with economic, societal and psychological circumstances that influence the stakeholder network. With perturbation in any of the drivers, each stakeholder seeks to adapt to the changed circumstances, which brings fundamental reconfiguration of the transportation architecture.

Table 2. Transportation Drivers

Effect	Examples
Determining overall demand profile for transportation activities	• Economic factors. GDP, household income, fuel price • Societal factors. demographic characteristics, urbanization trend • Psychological factors. culture, perception of safe/secure system

Transportation disruptors

There is a range of discrete events that also impact transportation. Weather influences the resource network on a real-time basis: visibility problems, icing, and thunderstorms are primary issues that degrade punctuality and safety. Natural disasters also have their place in the

transportation environment. These natural events affect the local environment, and the influence may cascade into the remainder of the national system. In contrast, there exist artificial events under two categories. The first group influences the resource network directly (e.g., traffic accident, mishap operation). The second category of events affects psychological concerns, an element of the driver group. The drop in air travel after the 9/11 attacks on the U.S. in 2001 is a primary example. Taken together, those disruptors (Table 3) affect the resource network and/or a portion of the drivers. They reduce the efficiency of the resource network, disable particular nodes and links of the network, and may even bring the entire system down.

Table 3. Transportation Disruptors

Effect	Examples
Causing delay and/or cancellation of transportation activities	● Natural disruptors. weather related events that affect operational condition of resources ● Artificial disruptors. accident, terrorism, pollution

Disruptors and drivers are related with an analogy of the electrical circuit. Drivers are akin to electrical current sources which generate electrical current (transportation activity) and disrupters are akin to impedances which change the magnitude and phase of the current. These two groups together determine circumstances and constraints for all transportation activities. Drivers and disruptors are significant parts of the NTS, they are difficult to describe and are often too transient to predict, and thus they are frequently poorly represented in air transportation analysis.

The union of all ingredients described in this section comprises the Transportation Architecture, and we now use this term to avoid confusion associated with NTS which is usually used to refer the transportation resources (only) in many occurrences. Identification of the generic types of systems involved in the transportation architecture point to, but do not establish, the desired framework for effective analysis. First, there must be some organizing formalism that includes all design degrees of freedom, including physical resources, organizational entities, and the inter- and intra-connected networks that tie them together. This formalism is presented next in more depth through abstraction and hypothesized use of a modeling approach.

Entity-centric abstraction
The traditional approach to modeling a large, complicated system is to assemble many small-scale, hierarchically decomposed sub-system models.

This approach is anchored in reductionism that has dominated the modern sciences. While a multitude of achievements over hundreds of years testify to its success, the reductionism strategy is not complete for the study of system-of-systems. It creates box-inside-a-box mentality and becomes simply impractical when an unmanageable number of heterogeneous elements are involved. This leads to engaging the power of abstraction for it requires a rigorous mental activity that enables attainment of the holistic perspective. The essence of abstraction is the notion of both classifying things (creating sets) and representing organization (forming networks) using articulate lexicon for the purpose of examination at the holistic level. Proper abstraction aims for generic, universal, uniform semantics, and its ultimate goal is generation of functional expressions which allow practitioners and theorists of this field to navigate, communicate, model and design collaboratively as well as produce a useful product to the decision makers.

Concept: Entity and entity descriptor

Under the entity-centric abstraction framework, all of those factors on the table find themselves a home, unified through the concept of entity. In the modeling and simulation field, the term entity generally refers to a structural component of a discrete event simulation that has attributes and that causes changes in the state of the simulation (Ingalls, 2002). Also, entity is analogous to object in the computer science domain as defined as a concept or thing with crisp boundaries and meaning for the problem at hand (Rumbaugh, Blaha, Lorensen, Eddy, & Premerlani, 1991). 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.

Therefore, an entity can be thought of as an extended form of object, though not necessarily having the crisp boundaries for the purpose of obtaining inherent flexibility. For example, a car is modeled as an entity that has attributes, functions and interface, without sentience. Attributes of a car contain certain characteristics that are unique to (or that defines) the car: make, model, vehicle identification number, gas mileage, etc. However, speed and position at a particular time belong to the interface since the values of those variables result from interaction with other entities: road conditions, other cars, the driver, etc. The entity-centric abstraction captures any instance among everything, and upon completion of identifying things of interest, modelers simply include the corresponding entity or entity groups.

In the prior section, four groups of entity were established: Resource, Stakeholder, Driver, and Disruptor. Based on observation of these entity groups, a certain generality can be extracted, which will be relevant in modeling. In doing so, we imagine a supreme transportation architect—a hypothetical individual (or group) who wishes to shape the transportation architecture under her/his design. There are things under partial or full control of the imagined transportation architects and there are things that beyond their control. For example, resources are obviously controllable; the architect can design and operate them. Stakeholders are not fully controllable but the architect can influence stakeholders in a direct or indirect way. On the contrary, there are things within which have no control variables even for the mighty architect. For instance, weather has unidirectional influence on resources; the nation's wealth has wide-reaching effects on transportation but take imperceptible feedbacks from the transportation architect, if any. To capture these mutually exclusive categories, the terms *endogenous* and *exogenous* are applied to the four entity groups.

In a similar vein, we can imagine a user of the architecture experiencing a transportation activity. When a user (consumer) travels or send a shipment, there are tangible things that are directly encountered (e.g., vehicles and weather). But there are also other things that have indirect influences: operator's policy, economy, etc. Their existence can be inferred but they are not tangible. To capture these mutually exclusive categories, the terms *explicit* and *implicit* are applied to the four entity groups.

There are, then, four logically deduced entity descriptors. The nature of an entity's influence on the architecture can be either explicit or implicit and its source of influence can be either endogenous or exogenous. In contrast to the reductionism mindset, the role of the descriptors is not to facilitate break-down of the entities into smaller pieces. Instead, it only intends to organize them by articulating their generic, endowed natures. The descriptors are complete since they can notionally embrace everything on the table in its entirety. They also naturally embrace these externalities in conjunction with those internal factors in an attempt to describe the whole.

Synthesis: Transportation architecture field

The specification of all entities, juxtaposed on the time-variant transportation environment, is depicted in a pseudo 3-D space format (Figure 8). This space is called the *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 which then affect the resource network. In contrast, the dotted arrows indicate weak 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.

Figure 8. A Conceptual Snapshot of the Transportation Architecture Field (TAF) with Respect to Given Time *t* = *t*ₒ Where Time Axis (Not Shown) is Out of the Plane of the Figure
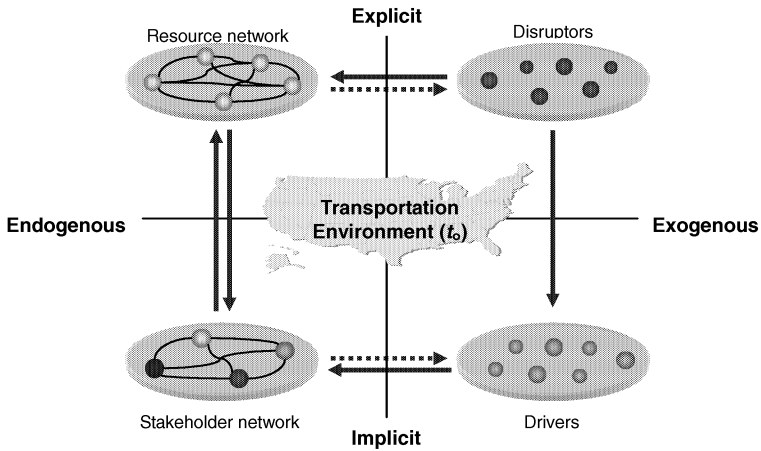
The TAF is constructed through networking (organizing) the networks, under the recognition that the organization of things can be just as important as the nature of things to be organized. In particular, linking the resource and stakeholder network gives the transportation architecture a system-of-systems character. The stakeholder network embodies independent decisions concerning the status of the transportation architecture, while the resource network determines how the transportation architecture is actually configured when accessed by consumers. These multiple networks organized in different layers are co-mingled and evolve over time, resulting in the evolving TAF. The type, structure and attributes of the networks can be treated as the architecture design parameters to the extent that such freedom is consistent with reality.

The TAF is summarized by representing the interactions mathematically through integration, over a time period of τ, of the influence of design and/or state variables in each network $(\overline{X}_R, \overline{X}_S)$, metrics of the other network, disruptors $\overline{\delta}(t)$, and drivers $\overline{\gamma}(t)$. An example variable in the resource network is the service connectivity between two airports while an example in the stakeholder network is the pricing of such connectivity in relation to competitors. Metrics for the resource network are given in Equation 4 while

those for the stakeholder network are given in Equation 5, with a note that the weak feedback from stakeholders to drivers is ignored for now.

$$\overline{M}_{RN} = \int_{\tau} \phi(\overline{X}_R, \overline{M}_{SN}, \overline{\delta}(t))\ dt \tag{4}$$

$$\overline{M}_{SN} = \int_{\tau} \varphi(\overline{X}_S, \overline{M}_{RN}, \overline{\gamma}(t))\ dt \tag{5}$$

$$TAF(\tau) = F(\overline{M}_{RN}, \overline{M}_{SN}) \tag{6}$$

While the equations can be written in compact notation, these integrals are clearly coupled and unsolvable analytically; they represent complex behavior and must be approximately evaluated through simulation, for which a first attempt is to be described in the next section. Despite the best intentions, however, it is the authors' view that the entire transportation universe can never be modeled completely. Yet, the continued effort to fully integrate all entities is meaningful from a pedagogical point of view. Under these circumstances, the best practices appear to be the considered construction of interfaces to link diverse domains, the inclusion of uncertainty to account for incomplete information across interfaces, and the implementation of programming flexibility to accommodate changes that arise. Just as the transportation architecture is a living system, so must be the methodology that models it.

INITIAL SIMULATION MODEL AND MODELING HYPOTHESIS

Brief description of the model

The time and space boundary of the present modeling exercise is quite large: the entire continental United States over a single year. Long distance, passenger transportation activities are examined, considering intercity trips of 100 or more miles. Before constructing a working model, a database review was done. The most important database identified and used was the 1995 American Travel Survey, built by the Bureau of Transportation Statistics through interviews of approximately 80,000 randomly selected household nationwide (BTS 1999). Based on the ATS and other transportation data, instantiation of resource and stakeholder models proceeded.

Transportation resources

Transportation resources are made up of vehicles, portals, and enroute spaces. Each element of the resource is created from class/template as illustrated in Tables 4 and 5.

Table 4. 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

Table 5. 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.

Instantiation of resources created from the templates are integrated in a generic trip route—an origin-destination network as shown in Figure 9. Note that one can infuse a new mobility resource as the generic focal point for exploration of mobility-related questions.

Figure 9. Generic Origin-Destination Trip
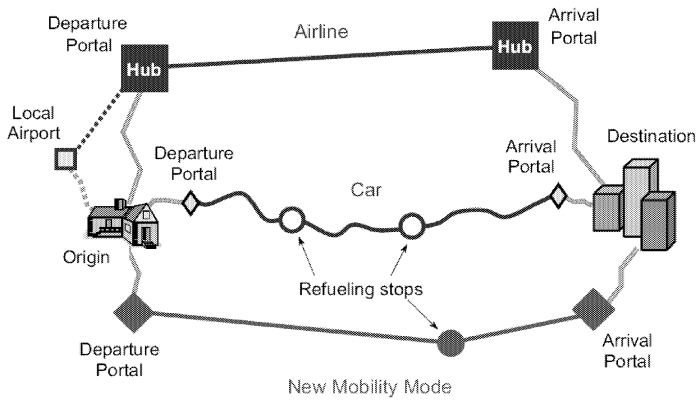
Four transportation modes were considered for the study. The primary groups consisted of personal cars (code CAR) and commercial airlines (code AIR), which make up the vast majority of household travels (about 96%) according to the ATS data. The GA aircraft, split into a piston single-class aircraft (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 since the area of concern of this work is primarily the interface between cars, commercial airlines, and general aviation.

Transportation stakeholders

The use of agent-based modeling (ABM) is well suited for manifesting the behavior of a collection of sentient entities—the stakeholders. The idea behind ABM is that the global behavior of a complex system derives from the low-level interactions among its constituent elements. Upon construction of a virtual world on the computer, the user invokes the simulation and observes the result: That is, let them play and watch. Agent-based simulations (ABM/S) can reveal both qualitative and quantitative properties of the real system, so ABM/S can be deemed as computational laboratories to perform experiments to test nearly any kind of imaginable hypotheses (Dibble, 2001).

Any stakeholder in Table 1 can, in theory, be treated as an agent. The most practical way to begin the modeling process, however, is having a

manageable number of agent groups. As an aggregated group, travelers are the chief and most active players among the stakeholders. Other agent types, despite being less numerous, have more complicated behavior patterns that are beyond the scope of the present work. The primary attributes of a traveler include household income, vehicle ownership, location (whether a traveler lives in a big city or 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, number of travel party and location of destination. There exist somewhat soft attributes for a traveler and a trip such as whether a particular traveler feels uncomfortable to fly in a small plane and the amount of urgency associated with the traveler—defined here as on-demand travel, the desire for travel without the time necessary to get the lower, advanced-purchase prices. 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 (Train, 2003).

Transportation environment

All model components are placed in a set of locales—abstracted collections of people, transportation resources and other socioeconomic factors. It is in these locales that travelers and the relevant structures are populated and created during the simulation runs. The model used 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). Travelers were dispersed within these spaces as they were dispersed in reality, using the databases to follow population trends and movements within the time period of the experiment. The synopsis of locale description is summarized in Table 6. The origin-destination matrix reveals the travel demand profile in terms of spatial distribution. Also, four distinct locales have different portal accessibility and the amount of delay.

Table 6. Locale Characteristics

(a)   Origin-destination matrix

Orig. \ Dest.	(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%

(b) Portal accessibility				
Access Distance	(L)	(M)	(S)	(N)
to Hub airport (mi)	2–40	2–60	50–100	100–200
to Small airport (mi)	2–10	2–12	2–30	4–75
to Freeway ramp (mi)	1–5	1–5	1–10	1–40

Simulation studies

A simulation code, named **Mi**, has been developed which is implemented in Java. Initially, the code was calibrated to year 1995.

Calibration Results (code BSLN)

Calibration of the code was straightforward, though time-consuming. The basic agent decision-making algorithm responded quite well with no interference. 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 7.
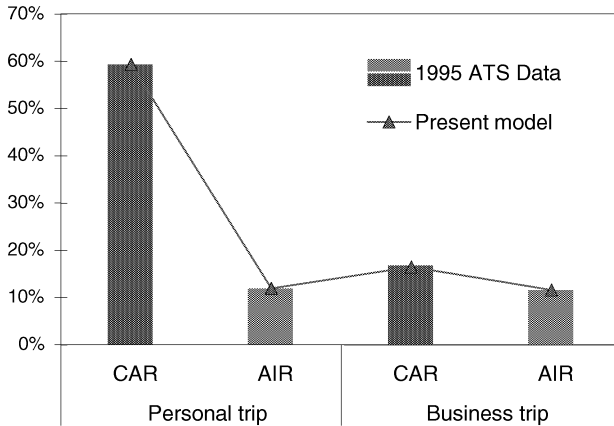
Table 7. Overall Mode Share Result

|	CAR	AIR	GAP	GAJ
ATS1995	75.88%	23.48%	0.64%*	
BSLN	75.92%	23.44%	0.42%	0.22%

Note. No further breakdown available in the ATS database.

This modal split result should also correspond to the differentiated behaviors of the traveling public, which necessitated closer investigation from different angles. Acceptable results are also shown for the chosen mode with respect to the travel motivations, as revealed in Figure 10(a). A long-distance traveler is likely to use a commercial airline, so the market share of commercial airlines (AIR) should grow as travel distance increases. This trend from the 1995 ATS data and the calibration result are plotted together in Figure 10(b).

Figure 10. Model Calibration Result
(a) Trip Purpose and Modal Split

(b) Market Share Analysis Result for Airline
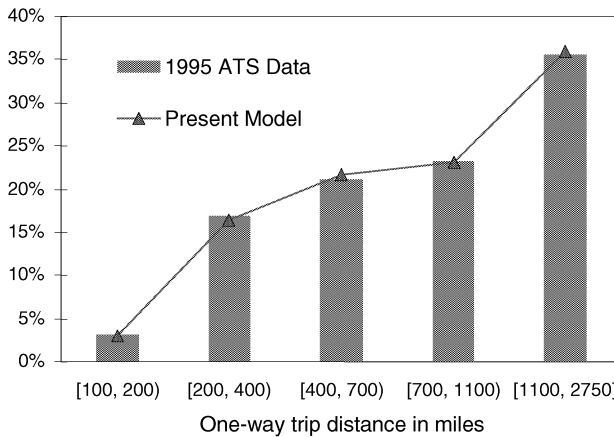
Overall, considering the level of abstraction inherent in the model, the results were remarkably satisfactory. Small mismatches were the inevitable price stemming from simplifying the real world, and they could be diminished by increasing the model granularity. Recalling the key assumptions of the previously discussed models in the second section of this paper (λ includes income only, μ includes distance only, and these two are static or fixed), the initial simulation model presented overcomes these limitations. For example, compared to Figure 6 models, it consists of

parameters such as distance, purpose, size of trip party, etc. Further, big advantage is that λ and μ were calibrated based on actual data. So, the model is a better approximation of the real TAF, and then we can run some scenario simulation and watch the results.

PAV simulation (code PAV)

This simulation scenario consists of the replacement of the existing GAP with a new mobility vehicle based on NASA's Rural/Regional Next Generation concept. The image of the advanced general aviation aircraft is portrayed below, with its target performance characteristics.

Figure 11. NASA's Low-cost, Tail-fan Concept GAP

Cruise Speed: 200 mph
Range: 500 miles
Passenger Seats: 5
Acquisition Price: $75,000
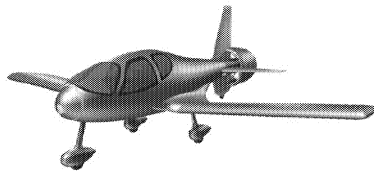
The preparation of simulating this scenario can be done with straightforward alteration of design requirements of the GAP. To be more specific, an investigator simply needs to change the values in the input area of the program. The corresponding field values are Speed (from 180 to 200 mph), Refuel Range (1200 to 500 mi), Seats (from 4 to 5) and Cost Index (from 100 to 90). The simulation infusing this future GAP revealed that it would attract about 2.4 times as many travelers as the previous GAP. This was due primarily to the design's low projected costs and the faster cruise speed. Other transportation modes were not affected much, and the result is shown in Table 8. The numbers in the round brackets indicate the net relative changes or the sensitivities of the market shares in comparison to Scenario BSLN.

Table 8. Overall Mode Shares of Scenario PAV

	CAR	AIR	GAP	GAJ
PAV	75.49%	23.30 %	1.01%	0.20%
	(-0.56%)	(-0.60%)	(+140%)	(-7.10%)

SATS vision (code SATS)

NASA's Small Aircraft Transportation System (SATS) project envisions the use of small aircraft to alleviate congestion around large cities and enable new business opportunities by allowing access to communities

currently underserved by commercial aircraft while having usable, yet underutilized public-access GA airports. Adjusting for this vision of the future involved the enabling of easy-to-fly technology, reflected in a ten-fold increase in pilots licensed to fly the vehicle, and near-all-weather access to almost three times as many airports, shortening the travel distances to airports for those people in smaller communities. One other condition imposed for this scenario was price penalty of 25 percent to account for the cost of sophisticated onboard avionics. As expected, this scenario was the most dramatic in its effect on the transportation architecture. The results show that 2.5 percent of long distance travelers will find GAP the most attractive as their travel option. Table 9 details the overall modal split result.

Table 9. Overall Modal Share for Scenario SATS

	CAR	AIR	GAP	GAJ
SATS	74.30%	23.02 %	2.50%	0.18%
	(-1.57%)	(-1.24%)	(+147.5%)	(-10.46%)

However, caution is needed to interpret the result. Since SATS technologies were applied to NASA's advanced GAP. Scenario SATS is, in fact, a hybrid vision of both NASA's vehicle- and system-level goals. To separate the impact of the SATS technologies from this hybrid scenario, an additional simulation was run (code SATS*) which replaced NASA's advanced vehicle with the previous GAP, a vehicle representative of current general aviation aircraft. Hence, one can consider Scenarios PAV and SATS* to make up Scenario SATS. The SATS* simulation discovered an interaction that had not been predicted. As shown in Table 10, the impacts cannot be simply superimposed; that is, an additive assumption did not work. This behavior within the model shows there exists a close coupling of these technologies to future GA aircraft use, which highlights the capabilities of the ABM/S framework being used to model the transportation architecture.

Table 10. GAP Mode Share Changes from BSLN

|	PAV	SATS*	SATS
Modal Share of GAP	1.01%	1.04%	2.50%
(Sensitivity to BSLN)	(+140%)	(+130%)	(+447%)

Finally, the result from any scenario can be visualized in a market space plot, showing the distribution of the agents' mode choices over household

income and travel distance. Figures 12 and 13 portray the market spaces for Scenarios BSLN and SATS, respectively. From these plots, a decision-maker quickly monitors the changes in the potential GAP market region in a visual and dynamic way.

Figure 12. Market Space Plot of Scenario BSLN. Only 20,000 Agents out of Ten Million were Randomly Selected and the Data Points with Trip Distance Over 1,200 Miles were Discarded for Visual Clarity and Closer Investigation. Each Dot Represents a Unit Trip Party. Agents that Choose Cars and Commercial Airlines are Dominating.
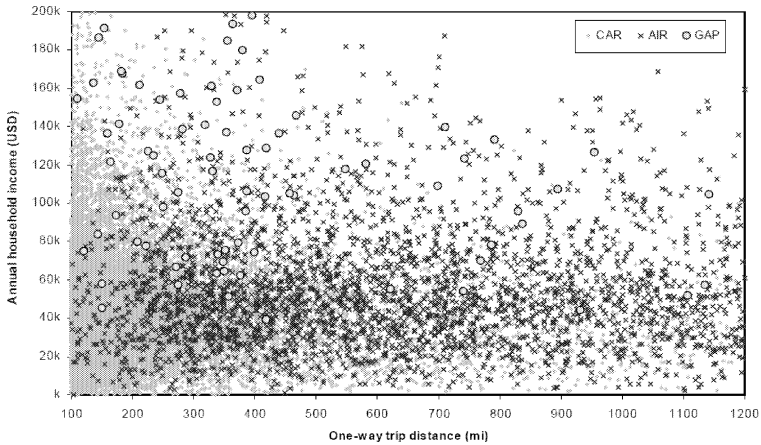
Figure 13. Market Space Plot of the SATS Vision Scenario. One Can Retrieve Useful Information from this Plot. For Example, a Circle Located in (120mi, $20K) was Found out to be a Business Traveler who has a Pilot License Flying with Two other Colleagues.
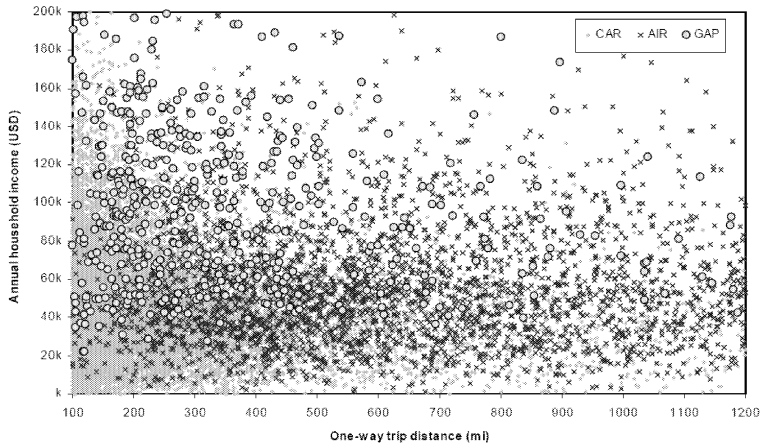
Modeling hypothesis for future work and a status

Though the initial results in using the TAF and associated simulation are encouraging, additional challenges remain in tackling this system-of-systems problem and generating a useful, quantitative output for the decision-makers. Thus, the next focus for the research should be on how the entity-centric abstraction framework realizes its full value. To guide this work, the following modeling hypothesis is proposed: *A modeling methodology treating the four major classes of transportation architecture entities can be created to synthesize alternative conceptual solutions and facilitate evaluation of the alternatives against multiple criteria.* While such a comprehensive hypothesis may difficult to prove (certainly in near term), strategies for testing the hypothesis can make use of the following four essential criteria (summarized in Table 11).

Table 11. The Four Criteria for Hypothesis Testing

Criteria	Description
Efficacy	The methodology must lead directly to required products in support efficient decision-making.
Flexibility	The methodology must be amenable to change in response to new customer requirements, new modeling constructs or new dynamics that emerge.
Comprehensibility	The methodology must be understandable, usable and interpretable by non-experts.
Traceability	The methodology must make transparent the rationale & path taken towards decisions reached.

The efficacy of the methodology can be evaluated by how well it represents the characteristics of the TAF. For example, it must capture the time variant nature of the problem, including simulation of latent effects due to the distributed nature, feedback mechanisms and consequences of uncertainty. The desired methodology must also embrace sufficient flexibility to support the emergence of revolutionary resource entity designs, the ability to impose or remove constraints easily and the capturing of all types of architecture design variables (vehicles, travelers, infrastructure, etc). Overall, the decision-support method must be able to adaptively employ the balanced level of abstraction that gives meaningful results without becoming overburdened by confounding detail—that is, it must be comprehensible. Finally, an often overlooked trait, but one that is generally found to be very important, is decision traceability. The ability to present rationale and trace the history of decisions reached can increase the legitimacy to external parties. The agent-based model *Mi* provides fidelity to the TAF in capturing essential entities in all four quadrants of the abstraction and proper links amongst them. However, the transportation environment is represented at a significantly aggregated level and the stakeholder network interactions are

simplistic. The modular architecture does point to significant flexibility in future studies. Other investigators are working towards essentially the same goal, although they employ different frameworks and with a deeper depth and a narrower focus. For example, Trani, Baik, Swingle, & Ashiabor (2003) proposes a nationwide, multi-modal, inter-city transport model (called TSAM) to investigate the viability of NASA's SATS project, as an extended form of the conventional transportation demand analysis. The TSAM treats resources, stakeholders, and drivers with a high geographic granularity in characterizing the transportation environment. But it has a limited capability in representing the stakeholder network since an agent-based approach is not adopted.

While the above approaches have the goal of improving the future transportation architecture taking into account the multimodal aspect, others have focused on the NAS perspective. The Airspace Concept Evaluation System (ACES) is the most crucial NAS model, which utilizes an agent-based modeling paradigm to cover aircraft operations from gate departure to arrival (Meyn, Romer, Roth, Bjarke & Hinton, 2004). The ACES seeks best concepts for the (air) resource network, suitable for capacity and delay issue examination that relate the dynamic between disruptors and the resource network. The previously introduced Jet:Wise model is capable of capturing the emergent behavior of the real airlines. For instance, the hub-and-spoke system emerged as an airline routing behavior without explicit mechanisms leading to that phenomena. These NAS related enterprises, however, do not deal directly with the dynamics within implicit entities and some exogenous ones. Nevertheless, one commonality found in these large scale modeling efforts is adoption of an agent-based modeling technique, indicating that the inclusion of flexibility and evolutionary mechanisms in the testing of the hypothesis is well-founded.

CONCLUSIONS

Under the expected high degree of complexity in the study of potential transportation architectures, the entity-centric abstraction framework was proposed as a means for comprehensive treatment without narrowly prescribed boundaries. The primary premise for the framework was the necessity of a holistic perspective, which was formed after a body of research on more restrictive assumptions was conducted. The four classes of entities abstracted are the network of resources, the network of stakeholders, the drivers and the disruptors. The concept of the TAF was set forth to properly connect them. In the absence of an omnipotent transportation architect, the ultimate goal of analysis within the TAF concept is to provide an effective means for stakeholders to make optimal decisions that are also robust to cascading perturbations.

An initial, simulation-based investigation is then reported in which a TAF model that concerns the most important entity groups in each of the four quadrants was built. The agent-based simulation model is fully calibrated and validated to the real data, successfully replicating the passenger transport activities of the whole U.S households on the continental United States. Results reported from the simulation quantify shifts in mode choice as a result of advances both in air vehicle designs and operational technologies (especially those from NASA SATS program). Additionally, interactions captured in the simulation due to its foundation in the TAF concept uncover the fact that changes due to these two different types of advances are not additive.

Based upon reflection of the initial exploration of the TAF, a general modeling hypothesis was formed directed towards the ultimate purpose of an ability to compute a wide variety of value metrics to delineate between alternative architectures.

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