Entity-Centric Abstraction and Modeling of Future Transportation Architectures

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Abstract

Presented is a foundational, embryonic frame of reference for contemplating future transportation architectures open to practically any configuration, seeking innovation in transportation not through a particular technology but through a new way of thinking. The approach foregoes the usual employment of a reductionism perspective in favor of the view that one must first understand the whole before the individual parts of a complex system are designed, for the essence of the problem likely appears only from this holistic perspective. Nevertheless, it does not necessarily make communication between the involved facets any easier. An effective lexicon is proposed to bridge the gap between understanding and communication across the multiple domains that under-gird transportation. The holistic perspective with an effective lexicon establishes the foundation for the primary thrust of the paper: the establishment of an entity-centric abstraction framework that allows practitioners and theorists to navigate, communicate, model and design collaboratively as well as produce a useful product to the decision makers. The framework effectively guides modeling in such a way that nearly any conceivable combination of transportation resources, economies or policies is admissible. Overlaid with socioeconomic data and utilizing an agent-based modeling technique, simulation studies are reported upon for the dual purpose of documenting the use of the entity-centric abstraction approach as well as to expose key findings concerning the potential benefit of emerging aviation technologies.

1. Introduction

A future transportation architecture is defined as a hypothetical representation of the National Transportation System (NTS) reconfigurable by cascading changes in economic, societal and technological development. The utopia for a future transportation architecture is an expansion in mobility, enabling new types of travel and commerce currently not affordable and thus inducing additional societal benefits while minimizing adverse societal impacts.

The overarching issue is that the NTS is indeed 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[2] in exploring its future state. In light of these general properties, the major consequences of each source of complexity in the NTS can be examined. The complexity in the NTS brought by system heterogeneity exists both within traditional disciplines (engineering: aerospace, civil, mechanical, etc) and across domains (engineering vehicles, economic business enterprises, governmental policy/regulation, etc). This source of complexity presents challenges to understanding (different languages), modeling (different design variables and time scales), and assessment (different stakeholders). Treatment of the second source of complexity, the distributed nature of the systems, alone is not intractable. However, in the presence of the third source, deep uncertainty, complications arise since—as the word 'deep' implies—the important system interactions are poorly understood. An example is dealing with multimodal transportation when the operational and economic interface between modes is unknown. Deep uncertainty inherent in the systems results in imprecise models. Finally, uncertainty resident in the environment gives rise to un-modeled feedback dynamics associated with the ultimate 'control' (a policy, a vehicle, etc.) chosen. Combined with the irreversibility of many decisions, the result is a partially controlled process with path and time dependency. The NTS as a complex system, then, might best be conceived as a 'living system': a collection of diverse things that evolve over time and are organized at multiple levels to achieve a range of (possibly) conflicting objectives, but never quite behaving as planned.

The typical strategy employed to study a complex system takes the position of reductionism, the philosophical dogma that has dominated the development of the modern sciences since Descartes.[3] This approach is rooted in a postulation that a system can be described in terms of its components and accordingly, integration of the components leads to understanding of the whole system. Although the felicitous achievements over hundreds years have surely testified its success, this approach is not complete for the study of complex systems. The reductionism strategy becomes simply impractical when a system is composed of unmanageable number of heterogeneous elements. But this is only a superficial reason. The fundamental error of reductionism comes from the fact that, as commonly noted, a mere sum is less than the whole.

An alternative to the reductionism is the holism, the view that one must first understand the whole. Such a perspective is particularly well suited for study of the NTS, where the various interrelated facets can be understood uniquely as an integrated system-of-systems. The essence of the problem—the hard-to-grasp insight—likely appears only at this elevated perspective. However, while a holistic approach may facilitate one's intuitive understanding of problem structure, it does not necessarily make communication between the involved facets any easier. An effective lexicon is needed to provide the bridge the gap between understanding and communication. For study of a system-of-systems like the NTS, the lexicon must ensure that 1) all parties understand the description, and 2) all relevant portions of the problem are covered. The lexicon bridge is critical since professionals from the various domains have one thing in common: they are typically trained to solve problems using methods and ideas prevalent to their own domain. This legacy is the source of the often-used term 'stovepipe' in reference to the narrow scope thinking in a particular area of specialty knowledge. It is also clearly an artifact of the reductionism mindset. The real NTS, however, can only be fully understood via 'across' stovepipes, spanning various columns of knowledge, and thus the holistic frame of reference is required for such trans-domain applications. The holistic perspective combined with an effective lexicon is the foundational tool for proper abstraction.

Abstraction is the notion of both classifying things (creating sets) and representing organization (forming networks) using articulate lexicon for the ultimate purpose of being able to conceive and examine at the holistic level. Abstraction aims for generic, universal, uniform semantics. Levels of abstraction are employed to adjust the vantage point of the holistic perspective. The abstraction framework allows practitioners and theorists of this field to navigate, communicate, model and design collaboratively as well as produce a useful product to the decision makers. Accordingly, an entity-based abstraction framework is proposed, as the vital step to tackle the aggressive challenge in response to the need for spurring the interdisciplinary and trans-domain research.

2. Entity-Centric Abstraction of the NTS

The first step in an abstraction process is representing organization, which can be carried out through various approaches. Depending on the implementation approach, the abstraction process may generate variations in the mental model, the extent of traceability, and the scope of understanding about the target system. Further, a distinct computational model will be created. With the belief that the organization of things is just as important as the things to be organized, the next discussion reviews three approaches to organization. Following, a set of entity classes for the NTS is presented. The section closes with an integration of all the objects into the final form of the abstraction framework.

Three Approaches for Organization

The most common and simplistic way of organizing is the *hierarchy-centric* approach. A system of interest is divided into its sub-systems and a sub-system is divided into its components and so forth. Conversely, the system can be an element of a higher-level system. The higher-level system can also have other system instances running parallel to the system of interest. This approach has several strengths. It is intuitive and shows the structure of the system with clarity. However, this clarity comes at the price of flexibility since this approach is fundamentally founded on reductionism, inheriting the limitations discussed before. Also, the creation of a lexicon could be problematic when a large number of strata are involved. (repetitive extensions as in the term system-of-systems)

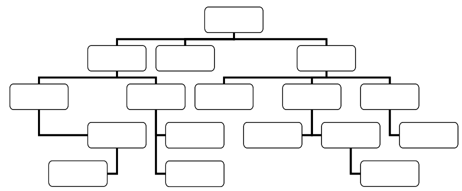


Figure 1: Hierarchy-centric view

The *flow-centric* approach has a somewhat different perspective, one in which the quantification of relationships is paramount. This approach emphasizes flows within the system rather than the components. Inside the boundary or control volume, the elements of the system are organized to reflect generating, dissipating and processing of the flows. The flow medium can have a variety of formats. For example, a model from a physics-based field can take energy, current, or other time-space variables. Recently, the use of System Dynamics methods to applied economics problems has been gaining in popularity. In this case, the flows can be money, information, or materials. Strengths include ability to capture dynamic behavior at high levels of abstraction, capturing so-called primary feedback phenomena. This capability is obtained at the expense of insight at the component level due to aggregation.

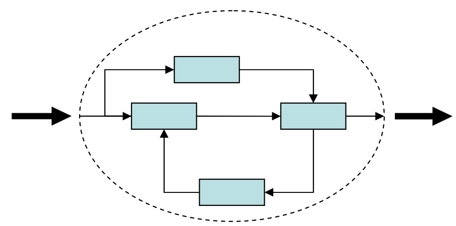


Figure 2: Flow-centric view

The third approach has recently gained momentum. The *network-centric* approach focuses on building nodes and links. For example, nodes are places (origins or destinations) while links are the characterization of what flows between places and how. This approach can flexibly define the elements in the system as well as their relationship. Unlike the hierarchy-centric approach, the network-centric model does not necessarily require monotonous nesting relationships. Instead, it only needs topological information between nodes. Also, it becomes quite natural to introduce the concept of the interface and layer. The whole ingredients construct a body of network as shown in Figure 3. The presented approaches are not exhaustive of the possibilities nor are exclusive of one another. As the abstraction proceeds, all three approaches are incorporated whenever and wherever appropriate.

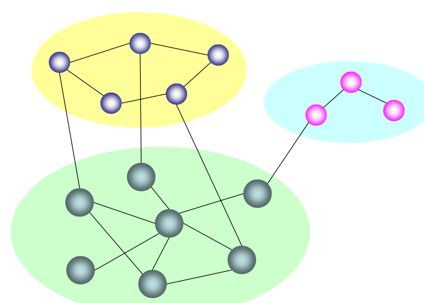


Figure 3: Network-centric view

The Modeling Entities

The three categories of entities emerge from the abstraction process for transportation architectures: *explicit entities*, *implicit entities* and *exogenous entities*. Vehicles and infrastructure are examples of explicit entities that consumers physically experience when traveling or sending shipments. However, there are other types of entities usually not accounted for by transportation engineers. For example, individuals and organizations that participate in transportation activities are examples of implicit entities that shape the transportation architecture and are recursively affected by the architecture. Explicit entities can be also embodied as transportation resources and implicit entities are embodied as transportation stakeholders. These two categories are considered endogenous factors in that they are the subjects and the objects for transportation activities. In contrast, the last category is called *exogenous entities*. These external entities encompass various factors traditionally considered given assumptions, circumstances and constraints about the transportation environment. (e.g., population, weather) All these entities are inter-webbed by networks that define the linkages amongst themselves. The explicit, implicit and exogenous entities with their networks are described in further detail.

(1) Explicit Entities: Resources and Network

Resources in the NTS comprise many types of vehicles and corresponding infrastructure. Traditionally, resources within a general category have been treated in their own realm. Further improvement in mobility will nevertheless demand an integration of these now distinct dimensions through the holistic perspective. Exploring a new mobility resource in this larger context can reveal its competitive advantage relative to existing resources and uncover the extent to which it is in harmony with a future transportation architecture. Consequently, a view that encompasses all resources in the NTS together is useful. The decomposition of the NTS follows the hierarchy-centric approach. In doing so, usual practices are adopting prefixes like sub-, super- and hyper- as well as using the circuitous phrase: i.e., system-of-systems. To avoid the confusion with ambiguous derivations, the lexicon employs the unambiguous use of Greek letters to delineate from strata of the hierarchy as shown in Table 1.

Table 1: Hierarchy descriptors

Levels	Descriptions	Examples
α	The base level of entities.	Cell
β	Collections of α -level systems, organized in a network.	Organ
γ	Collections of β-level systems organized in a network.	Human
δ	Collections of γ-level systems organized in a network.	Society

The basic building blocks are designated α-level for which further decomposition will not take place. Using this notation, the nesting structure of the resources in the NTS can be unfolded as described in Figure 4. The NTS (δ-level) is divided into multiple γ-level systems according to the primary mission space as shown. The air transportation system is a system-of-systems that has multiple β-level systems. In the figure, commercial transport and general aviation (including business aircraft) are treated as separate systems for they utilize different resources. Similarly, the ground transportation system can be split into several constituent systems as indicated. Towards the center of the figure is positioned a hypothetical new mobility resource, deliberately not attached to any existing β-level system. From design point of view, each level entails its own technologies, economics, and operational rules. The advantage of adopting the hierarchy descriptors is that a wide spectrum of decisions can now be unambiguously labeled, which facilitates trans-domain communications. For example, engine selection would be an α-level decision-making activity whereas the deregulation is a good example of a γ-level policy.

Inside of transportation resources is a connected-ness in the sense that a perturbation at any lower level (e.g. vehicle's attributes) will result in an impact on many stakeholders and thus permeate back into the entire system. This is so partly because all resources are bonded together via a topographical network that defines the physical connection between resources in which material (people or products) can flow. Additionally, trains, buses, automobiles and airplanes (and their respective infrastructure components) are connected in an economic sense, facilitating the intermodal and multimodal nature of transportation. Thus, proper abstraction should embrace the concept of the network that connects resources.

Within a network perspective, then, the flexibility and degree of interoperability between resources becomes extremely important. The ability of tightly linked vehicle resources to adapt their performance in response to modified input can increase the overall effectiveness of the architecture. Further, the characteristic of interoperability is realized through infrastructure, not through vehicles alone. Different types of infrastructure will offer varying degrees of flexibility. For example, a major hub airport may be viewed as a highly inflexible piece of infrastructure because it is difficult for such an airport to adapt to new vehicle types and operational schemes. Thus, the degree to which infrastructure resources are reconfigurable is an important design consideration. The combined consideration of resources and their networks is vital to achieve significant improvements in future transportation architectures. These explicit entities, however, are not sufficient to completely formulate the problem. There are subtler, yet still important issues.

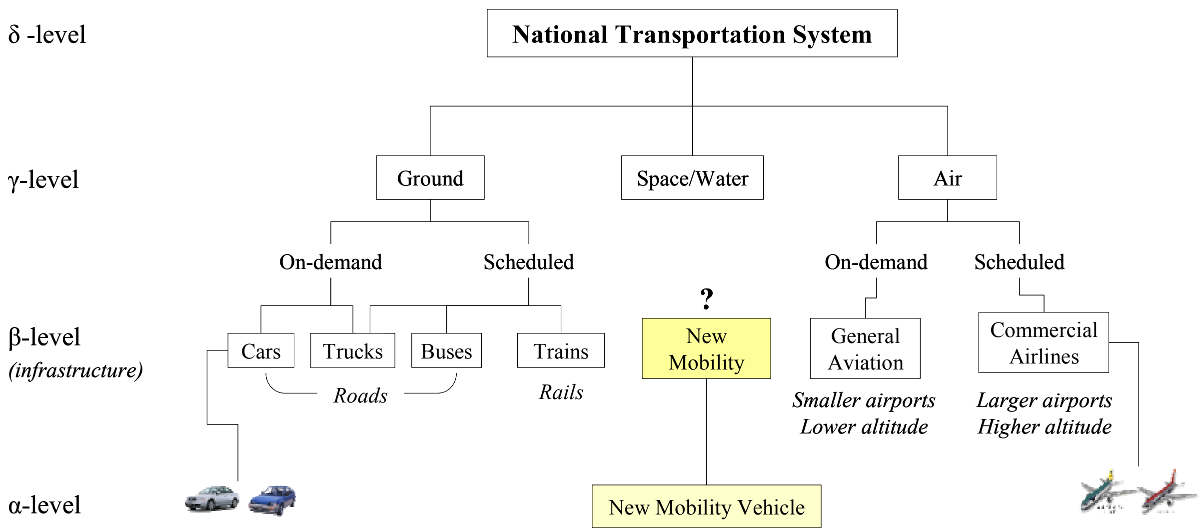


Figure 4: Transportation resource hierarchy

(2) Implicit Entities: Stakeholders and Network

The National Research Council pointed out that NASA's Small Aircraft Transportation System (SATS)[4] concept, with massive numbers of small aircraft operations, could entail adverse societal consequences including safety concerns and inefficient energy consumption per unit distance traveled per capita.[5] This case points to the need for consideration of 'other-than-explicit' factors—certain entities are present which desire to exert forces on the architecture for their own interests. These entities are called stakeholders, and in most circumstances their behaviors and decisions are not manifested in an explicit manner to the consumers; individual travelers only interact with resources when they travel. For the future transportation environment, the relevant stakeholders are identified in Table 2, where a broad abstraction has resulted in a collection of stakeholders in both private and public sectors, ranging from the actual consumers of transportation services to those involved in technology R&D. Each stakeholder has objectives that represent their interest and 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.

Table 2: Transportation stakeholders

Stakeholders		Descriptions	Objectives
Public	Consumers	Individual travelers or shippers (for commercial goods) that are the end user for the transportation system.	min: travel time, expense, max: comfort, safety
	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	Owners of resources who sell transportation services to consumers.	max: profit, market share, consumers' satisfaction
	Manufacturers	Design, produce and sell transportation resources to service providers and/or consumers.	max: profit, market share, service providers' satisfaction
	Insurance Companies	Provide protections against mishap operation of transportation resources by collecting insurance fee.	max: profit, market share, customers' satisfaction
Government (Policymakers)	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

An intangible network can be imagined that defines the connection between stakeholders. This connected-ness comes in two forms. Firstly, one particular stakeholder may interact with another directly. Secondly, if a stakeholder influences a particular resource, after permeating through the resource network, the state of the transportation architecture will be modified. A consequence of the new state is a perturbation back to the originator and/or other stakeholders. This connected-ness, called the stakeholder network, can be hypothesized as a complicated web linking distinct organizations as nodes. Each link between the stakeholders possesses its own characteristics that depict the nature of an interaction: medium, polarity, strength and so forth. For example, the research agencies-to-manufacturer link may be expressed by monetary funding for research programs with developed product designs provided in return, which can be investigated by a System Dynamics model with the flow-centric mindset.

Traditionally, the scope of a particular resource design problem included only a subset of the stakeholders (e.g., Regulator–Consumer–Manufacturer–Researcher). However, in an evolving system-of-systems, the concern of all the stakeholders and the sensitivities between them must be tracked. While there has been no shortage of innovative air vehicle concepts proposed in the past, very few come to fruition partly due to the disregard of the broader group of stakeholders. Future innovations in transportation, then, seem unlikely to lie solely in radical resource designs, but also in understanding the compli-

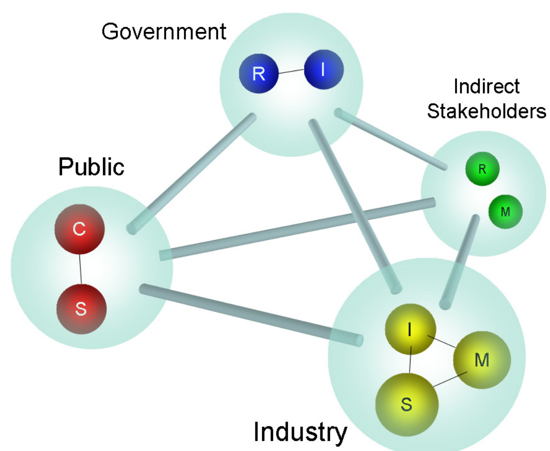


Figure 5: Implicit entity network

cated interactions stemming from the implicit entities and their networks. For concrete improvements to be made, each stakeholder must realize value. Such an approach motivates the exploration of new ‘value streams’ in transportation, a topic of growing research interest.

(3) Exogenous Entities

The description of the two entity groups has emphasized their generic, ontological characteristics. Nonetheless, it is obvious that actual transportation activities occur when those two groups have meaningful ties with the transportation environment—a container where all transportation-related events occur. In that environment, however, there exist even other entities within its boundary. If stakeholders and resources are considered *endogenous* building blocks in the sense that they are the subjects and the objects across transportation activities, within the transportation environment can be juxtaposed many *exogenous* entities of different types, which are beyond control of a transportation architect. In other words, from a design perspective, there is no control variable within exogenous entities since they have unidirectional influence (e.g., weather). Also, these entities typically have wide-reaching effects and take imperceptible feedbacks from transportation architecture, if any. (e.g., household income) The exogenous entities can be categorized into two groups according to how they affect the transportation environment.

The driver entity group is largely concerned with economic, societal and psychological circumstances that influence the stakeholder network. These include familiar economic factors such as household income and gasoline price, demographic-related issues including the population distribution profile and the trend of population concerning growth and migration to (or from) urban areas. In addition, a large portion of transportation activities are motivated by cultural and psychological reasons. With perturbation in any of the driver entities, each stakeholder seeks to adapt to changed circumstances. This will bring fundamental reconfiguration of the transportation architecture.

The disruptor entity group includes weather events and natural disasters. Weather influences the resource network on a daily basis. Visibility problems, icing, and thunderstorms are some of the primary issues that degrade timeliness and safety. Natural disasters also have their place in the transportation environment. Earthquakes, floods, or other catastrophic natural events will locally affect the environment, and some of the influence may cascade into the remainder of the national system. In contrast, there exist artificial disruptors 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 is a primary example.

In summation, in an analogy of the electrical circuit, drivers are akin to voltage sources which generate voltage and disrupters are akin to impedances which change the magnitude and phase of the voltage. These two groups together determine circumstances and constraints for all transportation activities. While difficult to predict, drivers and disruptors are significant transient parts of the NTS.

Table 3: Exogenous entities

Category	Effect	Entity Examples
Drivers	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
Disruptors	Causing delay and/or cancellation of transportation activities	Natural disruptors: weather related events that affect operational condition of resources Artificial disruptors: accident, terrorism, pollution

Network of Networks: A Transportation Architecture

It has been established that the abstraction of any transportation system proceeds as stakeholders employ particular resources organized in networks to achieve an objective under the various exogenous entities. In particular, the networks for resources and stakeholders give them a system-of-systems character. The transportation stakeholder network embodies the decisions concerning the status of the NTS, while the resource network determines how the NTS is actually configured when accessed by consumers. The dual network effects are co-mingled in the transportation environment. A transportation architecture results through the union of particular resource and stakeholder system-of-systems. The type, structure and size of the networks can be treated as architecture design parameters to the extent that such freedom is consistent with reality. Overall, the centrality of the architecture stems again from the recognition that the organization of things can be just as important as the nature of things to be organized. A series of locally optimized elements, combined together, does not guarantee a global (architecture) optimum.

The parsimonious description between the resource network, mobility stakeholder network and the time-variant transportation environment is provided in Figure 6. These depictions summarize the entity-centric abstraction of the problem formulation for synthesizing future transportation architectures.

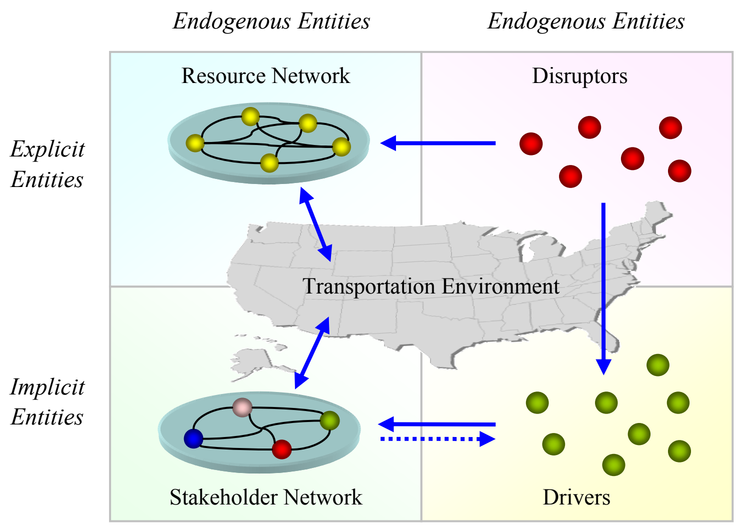


Figure 6: Transportation architecture with four entity groups—Solid bidirectional arrows indicates closed loop feedback structure (influence and be influenced) and thus the endogenous column. Unidirectional arrows characterize the exogenous column, although a weak influence is admitted from the stakeholder network to the drivers. (i.e., good economy has a direct influence in the transportation environment, not exactly vice versa)

3. Creation of the Virtual World

At the beginning of the introduction, the notion of a utopia architecture was introduced. To conceive of innovations over this long time horizon, this entity-centric abstraction is needed so that the whole variety of possible future architectures can be admissible. In more specific terms, the abstraction has pointed the authors to specific research questions to be addressed by modeling and simulation effort. In no particular order, these include the followings: Is it feasible at all to integrate data, objects and lexicon from the diverse domains that constitute the NTS? What are the relationships between the network topologies of the resource and stakeholder entities? By themselves, each of these already is the subject of separate treatment. In this paper, the first theme is addressed.

Entity Representations as Objects

The abstraction process embraced the concept of object-oriented thinking, derived from the computer programming domain. In this paper, the term object is defined as a concept or thing with crisp boundaries and meaning for the problem at hand.[6] This object-oriented philosophy plays a central role for representing the entities. Another benefit from this exercise is that the natural connection from modeling to implementation is inherently guaranteed, which is truly important when it comes down to programming.

(1) Resource Network

The resource network is a complicated web, providing means to transport people or products from origin to destination, essentially enabling door-to-door trips. The function of the resource network is supported by the operations of vehicles, portals, and enroute space that connects spatially separated points. These three elements, the most essential constituents of the resource network, can be visualized envisioning for a unit travel mission as portrayed in Figure 7. Two existing modes (airline and car) are most important in terms of traffic volumes currently handled if the emphasis is on long-distance passenger trips. A hypothetical 'new mobility mode' is infused into this unit network as the focal point to explore future transportation architectures as shown.

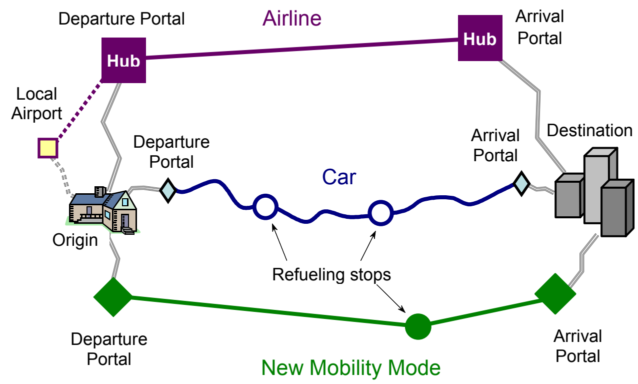


Figure 7: A simplified resource network

Vehicle is a primary object of the resource network to a traveler. Other resource elements, portals and enroute space often called infrastructure together, provide the settings in which a vehicle operates. Automobile is on-demand, cost-effective and suitable for daily, short-haul trips while business jet aircraft offers the most time-efficient method to traverse coast to coast. All in all, each vehicle can be regarded as an object that encapsulates its own attributes including technological / economic characteristics. A brief synopsis is given in Table 4. This is a template for representation of any vehicle. Other 'soft' factors—including vehicle comfort, perceived prestige and safety, emissions, 'coolness factor', security concerns, or practically anything else—can qualitatively modeled and added with relatively little effort.

Table 4: Vehicle attributes

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

Portals refer to the transition points between modes of transportation. They can be airports, bus and train stations, highway on-ramps, or whatever portal types are required by new forms of travel. A portal can be characterized by the type of vehicle it accommodates, maximum throughput per given time period, construction cost/time and required resources for operation. The operational scheme of portals varies: e.g. an airport operates under the centralized control system and on a scheduled basis while a highway ramp is purely on-demand.

Each portal consists of a set of time-related characteristics 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 a generic way in Table 5. The combined time at the destination portals are less than those at the origin portals since the 'wait-ahead' portion becomes negligible.

Table 5: Portal attributes

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

The *enroute space* of the infrastructure is made up of air routes, highways, rail lines as well as their associated rest and refueling points. These support points have their own effects on block speed—the ratio of combined travel time to trip distance. The enroute space can be conceptualized through an object representation as travelers make ways along. For example, a path length factor can be introduced to account for non-linear trajectory between points due to topographic, operational circumstances. The time-related attributes can also be modeled to allow the inclusion of a significant array of delays and slowdowns possible in the course of traversing any physical portion of the NTS. Refueling time, climb profiles, inner-city traffic delays, and other transient factors are the examples. Each enroute space has a particular degree of construction cost required, autonomy level, disruptor susceptibility and so forth.

The portals and enroute space share common characteristics: they are stationary, expensive to build and many stakeholders have to draw consensus in order to approve construction of them. They can have their own secondary properties. For example, a non-towered, rural airport is more susceptible to weather than one at a large metropolitan area. Similarly, unexpected catastrophic events may have different effects at different locations and for different types of portal and enroute space. Also, it should be recognized again that a harmony of the three elements of the resource network is much more important than their capabilities alone, to robustly satisfy a transportation mission.

(2) Stakeholder Network

The various organizational models introduced earlier can also be exploited for the stakeholder network. Recent investigations have focused on combining a System Dynamics approach utilizing stock-and-flow analysis and causal loop diagram[7] to capture the internal workings of a stakeholder. The use of agent-based modeling (ABM) is well suited for manifesting the behavior of a collection of sentient entities—the stakeholders. For now, this agent approach will be the subject of our discussion.

The idea behind ABM is that the global behavior of a complex system derives from the low-level interactions among its constituent elements. In ABM, it is encoded that attributes and behaviors at the individual component or microscopic level of the system. The system's macroscopic properties 'emerge' as a consequence of these attributes, behaviors and the interactions between agents and environment. Upon construction of a 'virtual world' on the computer, the user invokes the simulation and observes the result: i.e., "Let them play and watch". For this reason, agent-based modeling and simulation (ABM/S) can be thought of as a scientific reasoning scheme that complements deduction and induction.[8] The major strength of ABM/S comes from the fact that it is a simple and versatile method that is well suited for studies of complex non-linear systems. Whereas agent-based models can be made arbitrarily realistic by capturing processes or mechanisms that drive individual components, they can also be made quite abstract in an attempt to understand the essence of the problem.[9] Agent-based simulations can reveal both qualitative and quantitative properties of the real system, so ABM/S can be deemed as *computational laboratories*[10] to perform experiments to test nearly any kind of imaginable hypotheses.

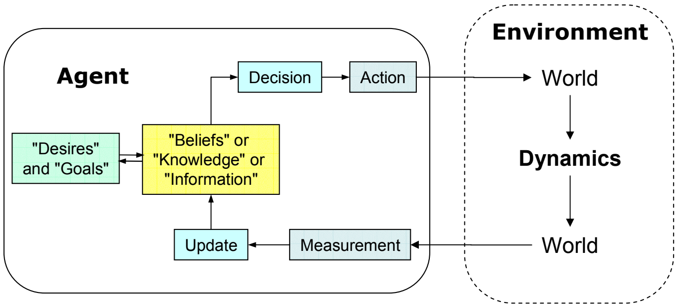


Figure 8: A single agent and environment – The agent sees the world, and then it makes a decision that entails an action. The world is influenced, however insignificantly, by the action. The same agent now senses a different world, and updates its knowledge, which may then cause a different action or even shifting its goal.

Stakeholders in the NTS are agents by any sense and can be modeled through the analysis of goals and behaviors. For example, the travelers' ultimate goal is essentially to complete trips comfortably and safely with less travel time and money spent. A series of behaviors should be manifested to fulfill this goal. The most obvious one is moving themselves in a vehicle with their own route choices on the journey. An investigator may need to build a discrete event model attached to a physics-based environment to analyze this behavioral pattern. On the other hand, the travelers have other kinds of underlying behaviors to 'get there'. They have to select the most appropriate transportation mode; they need to choose (or cancel) some previously planned trips due to monetary constraints or other changing situations. These two behaviors require different treatments and can be set up by establishing a set of logics with decision-making algorithms. In this case, an abstract representation of a physics-based environment is sufficient since information is the real currency of interest.

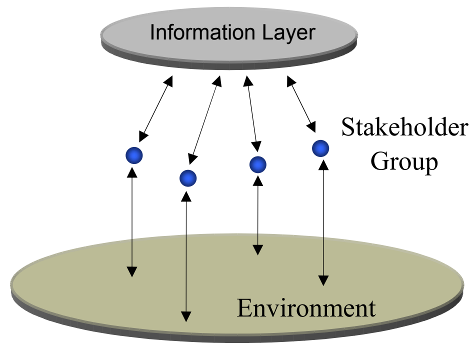


Figure 9: Representing the stakeholder network with ABM

Different types of stakeholders can be modeled in the same fashion. Upon completion of mental models for a group of stakeholders, the information layer is constructed through which the stakeholders can communicate, as illustrated in top of Figure 9. In the end, the stakeholder network emerges naturally without pre-specification.

(3) Exogenous Entities

As portrayed in the Figure 6, the drivers are underlying sources of the stakeholders' behaviors from economic, societal and psychological motivations. In market-driven world, a great measure of transportation phenomena is governed by many economic factors in a wide variety of formats. For example, GDP is a scalar metric to aggregately measure the nation's economic condition while household income should be provided in a table or distribution form. In addition to economic concerns, of significance are demographic factors: the locations in which people live, the number of members of an individual's household, and age/sex/worker composition of population, which can be represented in a multidimensional table. Further, much more than quantifiable factors go into transportation activities. 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 can also be captured through an object orientation including certain ordinal scale. It is very important, as encapsulation progresses, that appropriate interfaces are incorporated so that a particular stakeholder can access data of its interest. For example, again, while GDP has a valuable meaning to the policy makers, household income is much more important to individuals.

The disruptors primarily affect the resource network. They eventually reduce the efficiency of the resource network, disable particular nodes and links of the network, or even bring the entire system down.

The disruptor entities can be treated as an instance of discrete events, although their effects are time-dependent. All in all, they boil down to a few elements: strength, duration, and locality (narrow or wide). Uncontrollable factors associated with these elements can be treated probabilistically using the Monte Carlo method, supported by calibration from empirical data. As in the case of drivers, one thing to keep in mind is that each disruptor (or event) has varying degree of effect and influences a particular portion of resource network. For example, automotive travel is generally resistant to inclement conditions, while air travel is extremely sensitive to short-term changes in weather. General aviation aircraft are particularly sensitive compared to commercial air transport.

Since the exogenous entities encompass heterogeneous elements in the transportation environment affecting the resource network and the stakeholder network (and some drivers), the representation of these entities is not straightforward. However, the inclusion of interfaces for a corresponding link can properly encapsulate the entities under the object-oriented philosophy.

Integration

Architecting a virtual version of the NTS, where all entities reside, is the final step in creating a computational model. Regardless of being in the explicit/implicit or endogenous/exogenous category, all entities re abstracted from the transportation environment, the real world. Model fidelity depends on how accurately those entities are modeled. As in all modeling activities, simplicity is desired but balanced against the need for sufficient detail to ensure that the results are meaningful.

As noted previously, a container is needed where all entities are synthesized altogether in order to have a concrete, physical, real meaning. Here the concept of locale is introduced for that purpose. The locale is an abstract representation of a unit geographic environment. Depending on modeling granularity, each locale can represent a state, a county or an area with the same zip code. A unit locale encapsulates transportation resources and stakeholders, economic and societal circumstances, and disruptors.

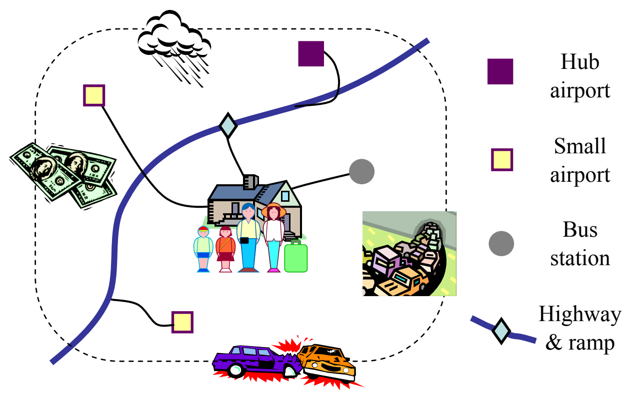


Figure 10: A unit locale

The NTS was abstracted into four entity groups, and the creation of the virtual world builds from these following the object-oriented programming methodology. First, all entities are defined as global components or templates in some cases. The global components constitute the virtual 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 depending on their nature.

The transportation environment is an abstracted representation of the geographic environment within the target modeling boundary. It is a set of discrete locales with the cardinality of *N*, and each locale encompasses many heterogeneous objects that traveler agents can interact with directly: vehicles, portals, events of delay, and so forth. These locales are instances of the classes and thus inherit most of their properties from the global components, but some properties should be tailored to reflect specific conditions for their respective entities. The resource and stakeholder networks are synthesized upon the creation of locales.

As a simulation progresses, the collective behaviors 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. This completes the conceptual mechanism of the virtual NTS, or the simulation 'universe' as portrayed in Figure 11, where the transportation environment is surrounded by the global components.

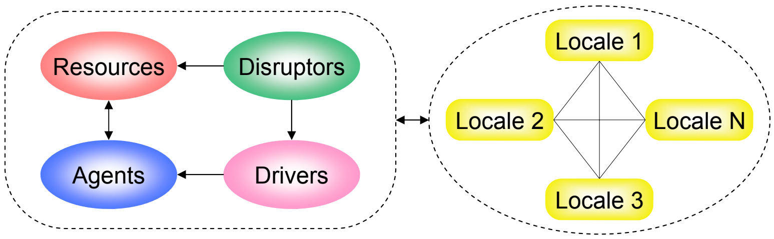


Figure 11: The simulation 'universe'—Representation of the Transportation Architecture

Creation of this simulation 'universe' allows a remarkable amount of information processed in an organized fashion. It is under this object-oriented philosophy that a wide variety of interactions and elements within the NTS at a host of different levels can be treated with enhanced flexibility. This feature will offer the manageable complexity of implementing a 'new universe' in response to a totally different situation or even a need for a better simulation granularity and fidelity.

4. Simulation Studies

Scope and Data Sources

The time and space boundary of the modeling exercise for this paper is quite large: the entire continental United States over a single year. Due to the authors' background, long distance, passenger transportation activities are examined first, considering intercity trips of 100 or more miles. Before constructing a working model, database review was done. The U.S. government has been always interested in the trends and characteristics of the NTS. The most important database used was the 1995 American Travel Survey (ATS)[11], a study by the Bureau of Transportation Statistics that interviewed approximately 80,000 randomly selected household nationwide. Other databases include the 1995 Nationwide Personal Transportation Survey (NPTS), an important database that treats daily travel in the U.S.[12]; TranStats, an extensive intermodal transportation database[13]; the 2000 U.S. Census and several other sources. These databases contain information used to construct the model such as delays caused by weather and other factors, which are built into the analysis modules in the model. One disadvantage of using several disparate sources in the creation of the agents is that not all of the data agrees on certain traveler characteristics. So care must be taken with the construction of models, but it is inevitable that a certain amount of uncertainty exists in the data and the model.

Model Descriptions

Four vehicle groups were considered. 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 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 since the area of concern of this work is primarily the interface between cars, commercial airlines, and general aviation. Previous work, however, has shown an agent-based model is capable of handling any of these vehicles.[14]

All model components fit themselves 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 uses four locales as a physical space of small- and medium-sized cities, large metropolitan areas, and rural areas. Travelers 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 outcome is summarized in Table 6. Four distinct locales have different portal accessibility and the amount of delay. Also, the origin-destination matrix reveals the travel demand profile in terms of spatial distribution.

Table 6: Locale characteristics

(a) Portal accessibility

Locales / Access distance	Large metro (L)	Medium metro (M)	Small metro (S)	Non-metro (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

(b) 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%

Any stakeholder 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 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 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 best alternatives for a trip, which is mathematically modeled in the following steps. Envision an agent i considering M alternatives. Then, the attributes for a travel option m comprise the amount of cost $C_i(m)$, time $T_i(m)$ and nuisance $N_i(m)$ (level of impedance due to an agent's concerns of safety, comfort, etc.), perceived by this particular agent i. Then, the utility for agent i for mode m can be represented as follows:

$$U_i(m) = -\{c_i\, C_i(m) + t_i\, T_i(m) + n_i\, N_i(m)\}$$

where three positive weights (c_i, t_i and n_i) reflect the agent's value of money, time and nuisance, respectively. They are dependent on the attributes of agent i. For example, if an agent considers the cheapest trip cost the most important, the value of t_i and n_i for the agent would be simply zero. The choice problem could be tackled using the simple weighted sum method from a multi-attribute decision-making perspective as in previous work.[15] The issue is that the modeler has incomplete or unobservable information. For example, $N_i(m)$ cannot easily be quantified, especially by outside observers. Random utility theory recognizes this and adds an uncertainty term. Hence, the utility is given by $U_i(m) = V_i(m) + \varepsilon_i(m)$ where $V_i(m)$

represents a deterministic utility term, and $\varepsilon_i(m)$ is a random utility term that contains uncertain, immeasurable quantities like $N_i(m)$. For simplicity, the model used in the study assumes $c_i = 1$ for all i, so t_i is the only tuning parameter for calibration use later. The deterministic (or systematic) utility is now given by

$$V_i(m) = -\alpha \{ C_i(m) + t_i T_i(m) \}$$

where α is a constant for selection logic calibration. Then, the multinomial logit (MNL) model, a widely accepted discrete choice method because of its simplicity, can estimate the probability of agent i choosing the mode m, given as follows[16]:

$$P_i(m) = \frac{e^{V_i(m)}}{\sum_{k=1}^{M} e^{V_i(k)}}$$

Simulation Code and Scenarios

To implement an agent-based simulation framework in the context of the NTS, a simulation code has been developed. The code, named ***Mi***, is an objected-oriented tool implemented in Java™. While the code is capable of generating runs over a multi-year period, for the purposes of this study only, a single-year run was required. The simulation speed is quite fast—on the order of one minute for one million agents. Initially, the code was calibrated to year 1995 since the majority of the data was for that year.

Based on the calibrated model, infusing a new mobility solution and perturbing several assumed conditions allows a simple sensitivity study as changes are revealed by differing agent behaviors within the simulation. Eight simulation scenarios (besides the calibration scenario), shown in Table 7, were established exploring economic, social, and technological issues to showcase the capability of the methodology. This was done by altering vehicle design requirements, infrastructure conditions, license requirements, household income, the fraction of the travel motivation, and population distribution. Each simulation scenario presents a 'what-if' question in an attempt to observe the behavior of the NTS.

Table 7: Simulation scenarios

Code	Description
CALB	Calibration simulation
BSLN	NASA's tail fan personal air vehicle
LINC	Poor economy
HINC	Strong economy
LMET	People are moving out to rural area
HMET	People are gathering to large metropolitans
LBIZ	Smaller number of business travelers
HBIZ	Larger number of business travelers
SATS	NASA's Small Air Transportation System

Calibration Results

Calibration of the code was rather simple, though 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 code. 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.

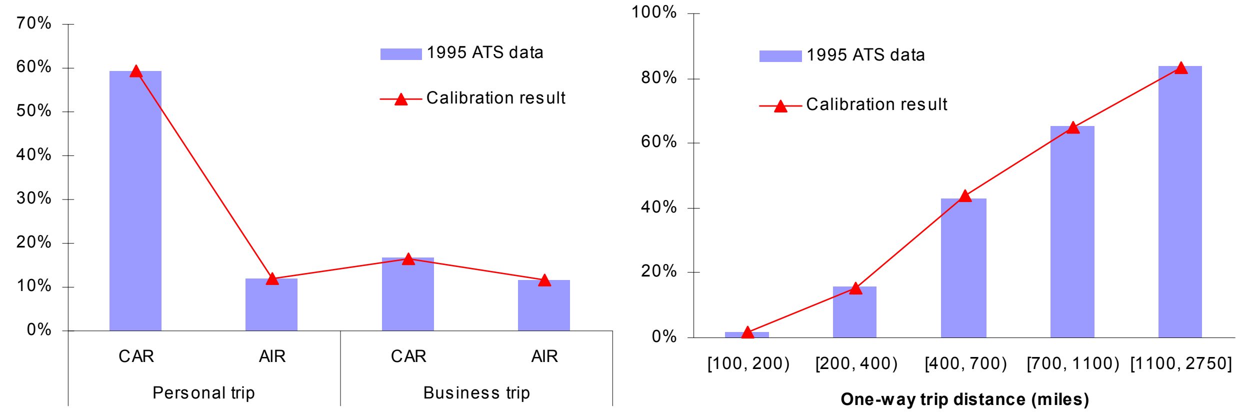
The most important response monitored during the calibration was overall market shares of the four transportation modes, shown in Table 8. The result is satisfactory, but this modal split result should also correspond to the real behaviors of the traveling public, which necessitates closer investigation from different angles. Acceptable results are also shown for the chosen mode with respect to the travel motivations, as revealed in

Table 8: Overall mode share result

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

*No further breakdown available in the ATS database.

Figure 12(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 12(b).



(a) Trip purpose and modal split

(b) Market share analysis result for airline

Figure 12: Calibration result plots

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

Baseline Simulation (BSLN)

The baseline simulation consisted simply 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 right, with its target performance characteristics.

Cruise Speed: 200 mph
Range: 500 miles
Passenger Seats: 5
Acquisition Price: $75,000

Figure 13: NASA's low-cost, tail-fan concept GAP

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 9. The numbers in the round brackets indicate the net relative changes or the sensitivities of the market shares in comparison to Scenario CALB.

Table 9: Overall mode shares of Scenario BSLN

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

Income Perturbations (HINC/LINC)

Simply changing the income distribution profile was the first, and simplest, perturbation. A twenty percent net increase in personal wealth (code HINC), distributed across the population, had a dramatic effect on use of GAP as well as GAJ. Net 'effective cost' as a function of income was reduced, so people were more willing to use nontraditional travel methods to save time. Decreasing the public's income by the same 20 percent (code LINC) had the expected chilling effect on the use of GAP and GAJ. AIR was also significantly affected as CAR picked up the balance. The detailed result is shown below with sensitivity information which, throughout the remaining scenarios, measures the net relative amount of changes with respect to BSLN. The impact on GAP, in terms of market share, from both scenarios in comparison to Scenario BSLN, is portrayed in Figure 14 where very similar trends can be observed with different amplitude for each case.

Table 10: Income perturbation result

	CAR	AIR	GAP	GAJ
HINC	73.69% (-2.39%)	24.56% (5.58%)	1.49% (47.18%)	0.27% (35.05%)
LINC	77.44% (2.58%)	21.82% (-6.36%)	0.60% (-40.47%)	0.14% (-30.75%)

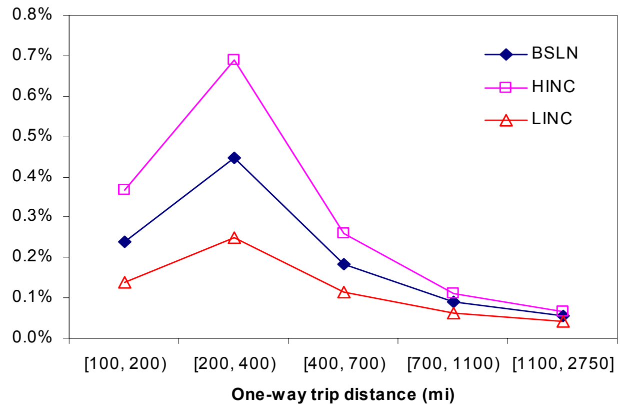


Figure 14: Income perturbation impacts on GAP

Personal/Business Travel Motivation (HBIZ/LBIZ)

According to Ref. [11], about 30 percent of trips are motivated by business concerns. Simply changing this ratio up and down allows a rapid exploration of the different effects business travelers have on the national travel landscape. Increasing the percentage of business travelers by 20 percent (code HBIZ) caused an expected increase in the number of travelers using GAJ (hence the name, *business* jet). GAP also tended to do better, as time-critical business travelers hired pilots to fly the smaller planes even when they did not meet the licensing requirements themselves. CAR was the big loser as commercial air travel also increased 5.33 percent. One telling piece of data, however, was that the AIR traveler increase was, in terms of raw numbers, 14 times more significant than the GAP and GAJ traveler increase combined. Decreasing the business travel percentage (code LBIZ) had the expected opposite effect, though it was slightly more pronounced in the GAP travelers.

Table 11: Travel purpose perturbation result

	CAR	AIR	GAP	GAJ
HBIZ	74.19% (-1.73%)	24.55% (5.33%)	1.06% (5.09%)	0.24% (17.75%)
LBIZ	76.77% (1.70%)	22.08% (-5.26%)	0.96% (-5.23%)	0.17% (-17.72%)

Population Shifts (HMET/LMET)

This simulation revolves around the long-standing trend of Americans to migrate to large metropolitan areas and create them from smaller metropolitan areas. If this trend is accelerated, the results may be a significant increase in delays at the largest airports and a desire to build larger, denser infrastructure components throughout large cities. If, on the other hand, this progression can be arrested, and the American rural landscape again becomes populated, the population dispersed, what sorts of new transportation technologies will be needed to accommodate an American public accustomed to instantaneous gratification?

A population shift to the cities (code HMET) did instigate a small-scale migration towards AIR travel as more people are now within driving distance of a hub airport. Movement to rural areas (code LMET) involved a small shift away from AIR travel as access to large airports became more difficult. The other modes, especially GAP,

Table 12: Population perturbation result

	CAR	AIR	GAP	GAJ
HMET	75.28% (-0.28%)	23.53% (+0.97%)	1.00% (-1.51%)	0.20% (+0.11%)
LMET	75.63% (+0.19%)	23.15% (-0.68%)	1.02% (+1.20%)	0.20% (+0.86%)

became more important, gathering customers away from AIR and allowing more thorough use of rural roads and airports. This may indicate that affordable GA travel is one of the reinforcing drivers towards a 'de-urbanization' of the nation.

SATS Vision (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.[4] 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.

Table 13: Overall modal share for Scenario SATS

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

As expected, this scenario was the most dramatic in its effect on the NTS. The results show that 2.5 percent of long distance travelers will find GAP the most attractive as their travel option. Table 13 details the overall modal split result. This overwhelming impact of the SATS technologies is visualized in Figure 15. The general profiles are very similar to those in Figure 14.

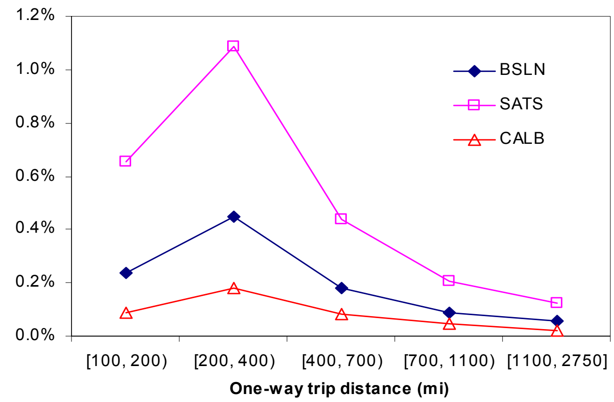


Figure 15: Impacts of SATS on GAP travelers

Result Summary

The results from all the independent scenarios can also be summarized in an ordered way by constructing a so-called tornado chart. The impacts on the market share of GAP compared to Scenario BSLN are expressed in Figure 16, which reports both magnitude and polarity for each scenario's sensitivity information. While the population shift has the lowest sensitivity, Scenario SATS shows anew the most dramatic impact on the virtual NTS. 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. Now one can consider Scenarios BSLN and SATS* to make up Scenario SATS.

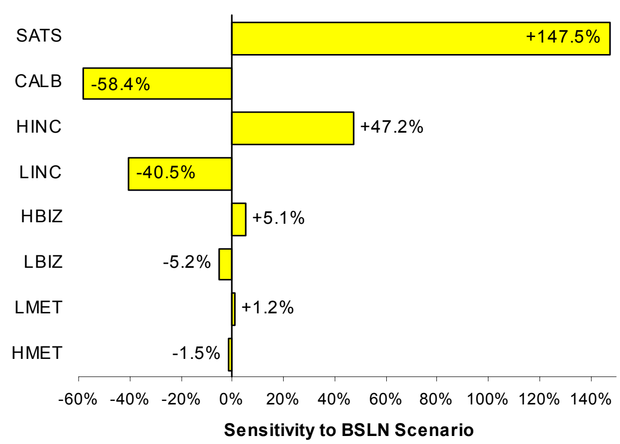


Figure 16: Tornado chart

Table 14: GAP mode share changes from CALB

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

The SATS* simulation discovered an interaction that had not been predicted. As shown in Table 14, the impacts cannot be simply superimposed; i.e., an additive model does 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 NTS.

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 A1 and A2 on the last page of this paper portray the market spaces for Scenarios CALB and SATS, respectively. From these powerful plots, a decision-maker quickly monitors the changes in the potential GAP market region visually and dynamically.

5. Conclusions

An approach for considering future transportation architectures open to practically any configuration has been presented in this paper. The 'grand challenge'[17] of modeling & simulation for the National Transportation System (NTS) and the subsequent challenge of identifying and achieving the best of the possible architectures (a utopia) are significant, perhaps daunting. Both the complexity of the NTS and the absence of a means to resolve conflicting objectives amongst stakeholders are two primary reasons. A look askance to the Internet, however, finds a complex architecture that has no central architect, yet it grows in size and functionality because a basic common structure and communication protocols exists as a foundation for which individuals can access, experience, and shape the Internet. The prime objective of this paper has been to establish such a foundation for future transportation architectures. The germination of this foundation is the entity-centric abstraction process.

The context for and primary elements in the abstraction process were presented in detail. This description included treatment of both entities (the 'things' in the NTS) and their interconnections (the organization of 'things'). In doing so, the lexicon was created aiming at an effective communication between transportation stakeholders. In later sections, the value of process was demonstrated by guiding actual implementations to study several scenarios involving air transport innovations using an agent-based modeling approach. The example application gives evidence of the potential for modeling without boundaries that come from stovepipes, towards a destination when nearly any possible alternative is admissible.

However, even if the best and most comprehensive simulations were available, it is recognized that, unlike in the development of a particular technology, static solutions and approaches will never be able to fully solve a problem concerning a future transportation architecture. This is because it is a living system; the architecture evolves and is reshaped by the environment. And history has certainly shown that no single agency, program, or technology alone can solve a system-of-systems type problem. History is also replete with examples of 'unintended consequences', in which the careful analysis of the interactions between technology, policy, and economics was absent. Ultimately, then, the ideas contained in this paper have the promise for improving future transportation architectures not through promotion of a single piece of technology or combinations of technologies, but instead through the provision of a new 'calculus', a new way of thinking.

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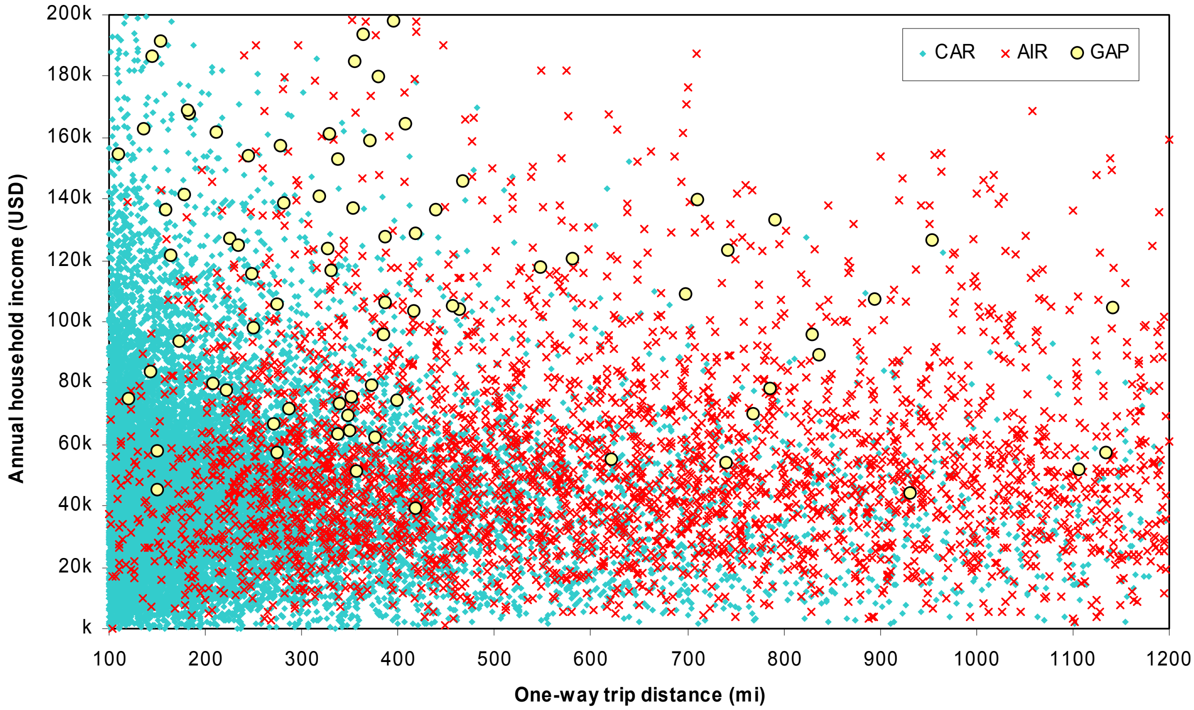

Figure A1: Market space plot of Scenario CALB. Only 20,000 agents out of ten million ones were randomly selected and the data points with trip distance over 1,200 miles were discarded for visual clarity and closer investigation. Each dot represents a unit trip party. Agents that choose cars and commercial airlines are dominating.

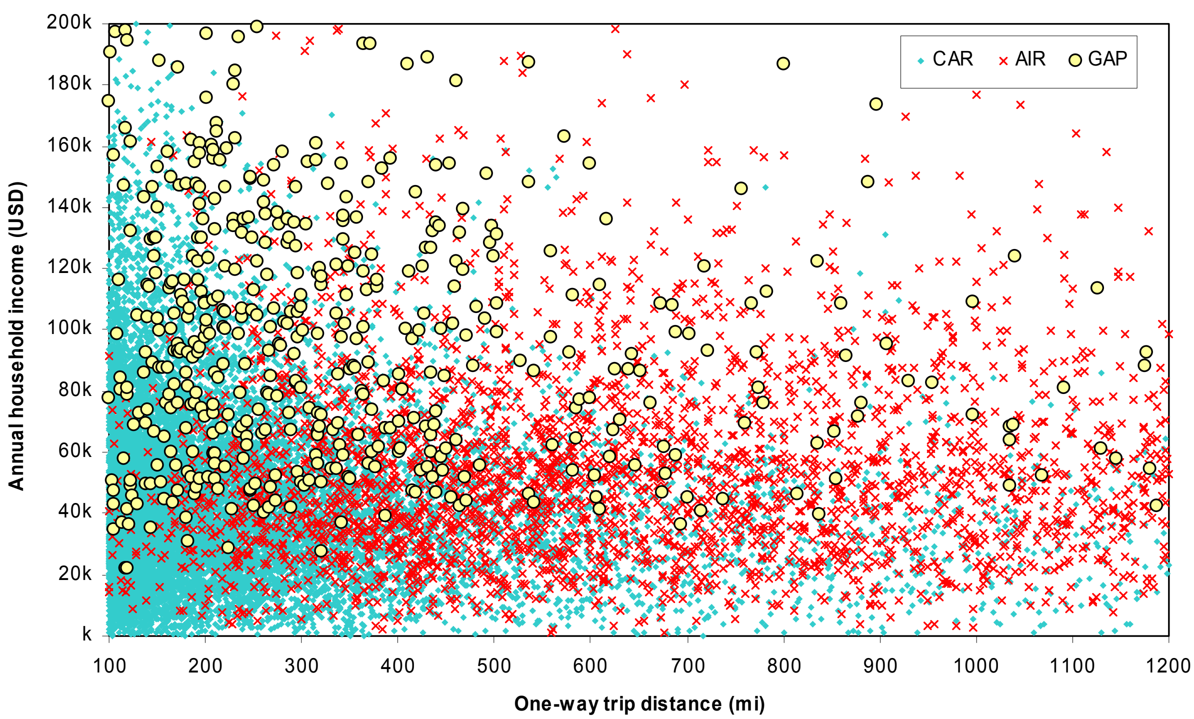

Figure A2: Market space plot of the SATS vision scenario. One can retrieve useful information from this plot. For example, a circle located in (120mi, $20K) was found out to be a business traveler who has a pilot license flying with two other colleagues.