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# ABSTRACTION AND MODELING HYPOTHESIS FOR FUTURE TRANSPORTATION ARCHITECTURES

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## Abstract

The goal of a future transportation architecture is an expansion in mobility, enabling new types of travel and commerce currently not affordable and thus producing induced societal benefit. From the design perspective, the complexity, high dimensionality and diverse nature of the design space make study of such architectures extremely difficult. An abstraction framework and modeling hypothesis are proposed, steps vital to the proper start of such an aggressive challenge. The core entities within a transportation architecture are abstracted: stakeholders (consumers, regulators, service providers, etc.), resources (vehicles, infrastructure, etc.) and networks (both explicit for resources and implicit for stakeholders). This abstraction leads to a general description for transportation that is useful from a conceptual modeling point of view – stakeholders employ particular resources, organized in networks, in order to achieve mobility objectives. The modeling hypothesis is created stemming from the description and focused upon the need to examine the architecture from a system-of-systems perspective, under the belief that the organization of transportation resources is just as important as the nature and performance of those resources. Subsets of the methodologies are tested on three exploratory research thrusts and the findings are used to project a future path towards full validation of the modeling hypothesis. Ultimately, decision-makers at multiple levels can use the methodologies to quickly understand and visualize the relative merits of alternative architectures.

## 1. Introduction

Beginning with the Wright Brothers and continuing through the efforts of many aviation engineers and scientists, the achievements of the first century of flight include not only the enabling of powered flight but also the availability of affordable air transportation to a large portion of the population. Looking towards the next century of flight, the new challenge for aviation technology may be to provide even greater mobility through innovative systems.

With enhancement in mobility, travelers can choose to spend less time on travel over a given distance, take longer trips in a given time, have more flexibility in where they live relative to workplace or daily activities, or travel in ways otherwise not currently possible or affordable. Further, an increase in their mobility, termed a 'mobility credit'[1], is likely to translate ultimately into societal wealth and benefits in numerous areas of quality of life. Such a positive scenario takes on an urgency as the rate of expansion of mobility under the current transportation system is reaching a limit, both on the ground and in the air.[2]

Hence, engineers, scientists and transportation policy makers are thinking about future transportation systems, focusing on technology issues and seeking innovations that could spur mobility enhancement. However, the temptation to look for innovation through advanced air vehicle concepts alone must be resisted. Systems thinking is required, looking instead toward efficient integration of various transportation resources, air vehicles and otherwise, as stated in NASA's Aeronautics Blueprint[3]:

> 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.

If the premise is accepted that a system-of-systems thinking process should be adopted, it also follows that it is not wise for new concepts to germinate solely from today's existing systems. An alternate approach must be found. In this paper, it is proposed that designers should contemplate the future without preconceived boundaries, essentially adopting the assumption that "*everything* is on the *table*." Two questions follow from this assumption: what is *everything* and what is the size of the *table*? Physical entities, such as vehicles and infrastructure, and organizational entities, such as public interest groups and industrial firms, must be examined together along with the networks that connect them. This approach is appropriate for the goal of making 21st Century transportation systems significantly better than the 20th Century's. At the same time, results that flow from the system-of-systems exploration process must

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Corresponding author: Jung-Ho Lewe [jlewe at asdl.gatech.edu] be concrete, targeted at identifying the research and development necessary to realize the most attractive transportation solutions.

Accompanying the challenge of adopting a system-of-systems framework is the recognition that the emergence of a new transportation system is neither instantaneous nor deterministic. Inherent uncertainty in the environment, un-modeled feedback dynamics associated with the ultimate control chosen, and the irreversibility of many decisions result in a partially controlled process with path and time dependency. The three paths sketched in Figure 1 are notional examples of the many possible paths targeted at the desired end-state for a future transportation system, each with unique path characteristics including time, cost and societal impacts. Some paths will never reach the desired end-state, regardless of the time or cost expended (e.g. path ❸ in Figure 1). Paths that do reach the end-state (e.g. paths ❶ and ❷ in Figure 1) may have important differences in their evolution over time, as shown in a notional way in Figure 2. The technology S-curve[4] concept is adopted, indicating level of mobility over time for each path. During a potential transition period, new mobility options will go through an incubation phase in which their growth is sustained and spurred by "first adopters". Over time, they become preferable to a large segment of the public as the transition is completed, although significant early advances (as in path ❸) may not guarantee attainment of the end-state at all. Path dependency, time variance and uncontrollable factors are dynamics that imply the need for modeling a "living system", instead of one that only offers a snapshot in time of a particular transportation architecture.

In summary, the high-level concepts that must be present to properly study future transportation architectures include a system-of-systems perspective and the ability to capture the dynamics of a "living system" with a proper representation of mobility credit. More specifically, the analysis and design tools to perform the studies must 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 is focused on formulating this design problem in more depth through abstraction, hypothesis of a solution methodology, and foundational research towards proving the validity of the hypothesized approach.

❶ "First adopters" will pay a premium for advanced vehicles which funds technology maturation of more affordable solutions and infrastructure. (akin to story of the automobile and Henry Ford)
❷ An AirTaxi and Rental market for air vehicles emerges after the development of a commercial runway-independent supplement, culminating in wide acceptance of advanced, semi-autonomous system designs.
❸ The inability to coordinate infrastructure, vehicle design, and market forces result in a failure to reach the desired end state.

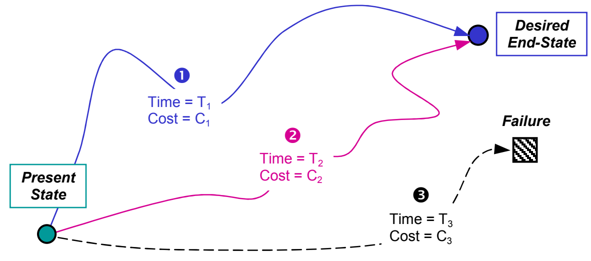


**Figure 1: Path Dependency in Alternative Transportation Solutions**

## Definitions

The introduction of certain terms so far requires clarifying definitions before a proper abstraction of the problem proceeds. A *system* is considered any independent entity that has a specific functional purpose. A *system-of-systems* is a collection of systems and the connective relationships between them. An *architecture* is a particular collection of system(s)-of-systems, including the interlocking, myriad connections among all constituent elements. It represents the "universe" for the particular problem under study. Thus, an architecture is an extended form of the more generic system-of-systems type, and may contain multiple instances of distinct system-of-systems.

The introduced definitions are relative, however, and depend on the scope and boundary of the problem. For an air traffic operator, for instance, an airplane is a *subsystem* or even a *component*; it is a system for an aircraft designer. Confusion associated with these definitions in the abstract can largely be eliminated when a specific problem and associated bounds are defined. However, legacy terminology will at times be unavoidable. For example, the current national transportation architecture is commonly referred to as the National Transportation System (NTS).

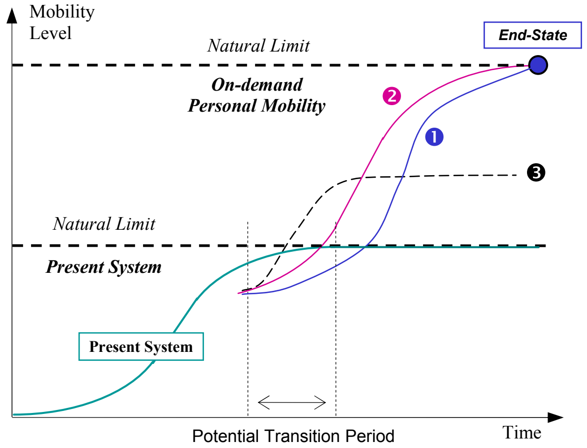


**Figure 2: Evolution of Mobility Performance and Technology S-curve Analogy**

## 2. Abstraction

Abstraction is essential to completing a successful system-of-systems study. The purpose of the abstraction is to rise above the stovepipes that typify the current paradigm so that future architectures can be imagined without prescribed boundaries. The abstraction level is a function of the desired model scope. While an airplane, an airport or the nation's transportation system may be part of the same continuum, the modeling challenges for each distinct level may be markedly different. Striking a balance in the selection of an abstraction level between the amount of detail for individual systems and the scope of system effects, thus bounding the modeling problem, is perhaps the most difficult task in adjusting to a system-of-systems perspective.[5] A study at any particular level will highlight questions that may only have answers at a higher or lower level of abstraction, leading to a revised abstraction level.

Two steps lie at the heart of the abstraction process. The first is the definition of the involved systems with their relationships. The second step is the identification of metrics that are measure of value for various levels of decision-making.

### 2.1 Modeling Entities

Two categories of entities emerge from the abstraction process for transportation architectures: explicit entities and implicit entities. Vehicles and infrastructure are explicit entities that consumers physically experience when traveling or sending shipments. On the other hand, there are other types of entities. For instance, individuals and organizations are implicit entities that shape the architecture and are recursively affected by the architecture. In this paper, explicit entities are embodied as resources and implicit entities are embodied as stakeholders. In addition, there are networks that define the linkages between and amongst explicit and implicit entities. Therefore, the abstraction of any transportation system proceeds as stakeholders (including travelers) employ particular resources (both infrastructure and vehicles) organized in networks (both explicit and implicit) to achieve a transportation objective. The explicit and implicit entities with their networks are described in further detail.

#### Explicit Entities: Resources and Network

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; research is conducted separately in the ground and air transportation area. Further improvement in mobility will nevertheless demand an integration of these now distinct dimensions through the system-of-system 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, as shown in Figure 3. The NTS is divided into the ground transportation system and the air transportation system according to the primary mission space. The air transportation system is a system-of-systems that has multiple systems. Commercial transport and general aviation (including business aircraft) are treated as separate systems since they utilize different resources. Similarly, the ground transportation system can be split into several constituent systems as indicated.

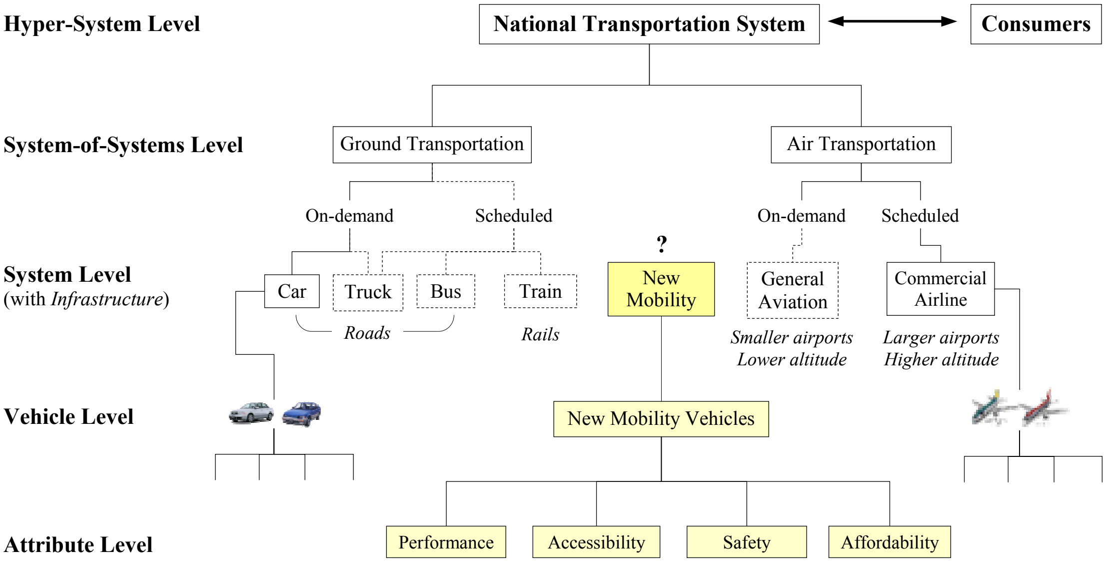


**Figure 3: Abstraction of the NTS Resource Hierarchy**

Toward the center of the figure, a hypothetical new mobility resource is positioned without linking to any existing system-of-system.

At the level of the NTS, there 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 the consumers. 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 describe the problem. There are more subtle, yet still important issues.

Implicit Entities: Stakeholders and Network

The National Research Council pointed out that NASA's Small Aircraft Transportation System (SATS)[6] 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.[7] 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 1, where a broad abstraction has resulted in a collection of stakeholders ranging from the actual consumers of transportation services to those involved in technology R&D. Each stakeholder has objectives which represent their interest and dictate the manner in which they influence the transportation architecture.

An invisible network can be imagined that defines the connection between stakeholders. This connectedness comes in two forms. First, one particular stakeholder may interact with another directly. Second, a stakeholder influences a particular resource, which, after permeating through the resource network, modifies the status of the transportation architecture. A consequence of the new status is a perturbation back to the originator and/or other stakeholders. Therefore, the transportation stakeholder network can be hypothesized as a complicated web linking distinct organizations, as indicated in Figure 4. Each link between the stakeholders represents an interaction. For example, for the research agencies-to-manufacturer link, this relationship may be represented by monetary funding for re-

**Table 1: Transportation Stakeholders**

| Stakeholder | Description | Objectives |
|---|---|---|
| Consumers | Consumers are individual travelers or shippers (for commercial goods) that are the end user for the transportation system. | Min: travel time, expense, Max: comfort, safety (i.e. Max: mobility credit) |
| Service Providers | Service providers are owners of resources who sell transportation services. | Max: profit, market share, consumers' satisfaction |
| Infrastructure Providers | Infrastructure providers plan and approve employment of infrastructure resources. | Max: capacity, Min. delay |
| Manufacturers | Manufacturers are firms that design and produce transportation resources. | Max: profit, market share, service providers' satisfaction |
| Regulatory Agencies | Regulatory agencies impose rules on the system that restrict stakeholder activity and resource characteristics. | Max: safety, security |
| Society | Society represents the aggregated interests of citizens, from research agencies, to communities, to the national level. | Min: noise, emission, Max: quality of life |
| Research Agencies | Research agencies develop transportation technologies. | Max: adoption of transportation enhancing technologies |

search programs with developed product designs provided in return. Transportation service providers, on the other hand, are more significantly impacted by consumer trends but do not usually have direct control over technology development programs.

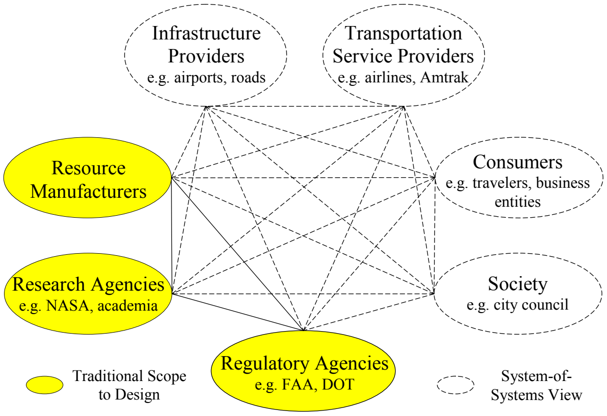


**Figure 4: Implicit Network of the Stakeholders**

Traditionally, the scope of a particular resource design problem included only a subset of the stakeholders (solid ovals). 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 complicated 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.

### Network of the Networks: An Architecture

It has been established that one needs to look at explicit as well as implicit entities together and that resources, stakeholders and networks are the three basic building blocks in the formulation. 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 comingled 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 from the recognition that the organization of things can be just as important as the nature of things to be organized.

The relationship between the resource network, mobility stakeholder network and the time-variant transportation environment is depicted in Figure 5. This depiction summarizes the abstraction of the problem formulation for synthesizing future transportation architectures. The abstraction serves to provide a unified "vocabulary" applicable to a wide variety of transportation challenges, especially those demanding interfaces between heterogeneous entities. Before solution approaches are examined, however, measures of success must be reasoned.

## 2.2 Transportation Architecture Metrics

After the level of abstraction has been determined and the entities and their interconnection identified, the final step in the system-of-systems problem formulation is to identify and/or create metrics by which the alterna-

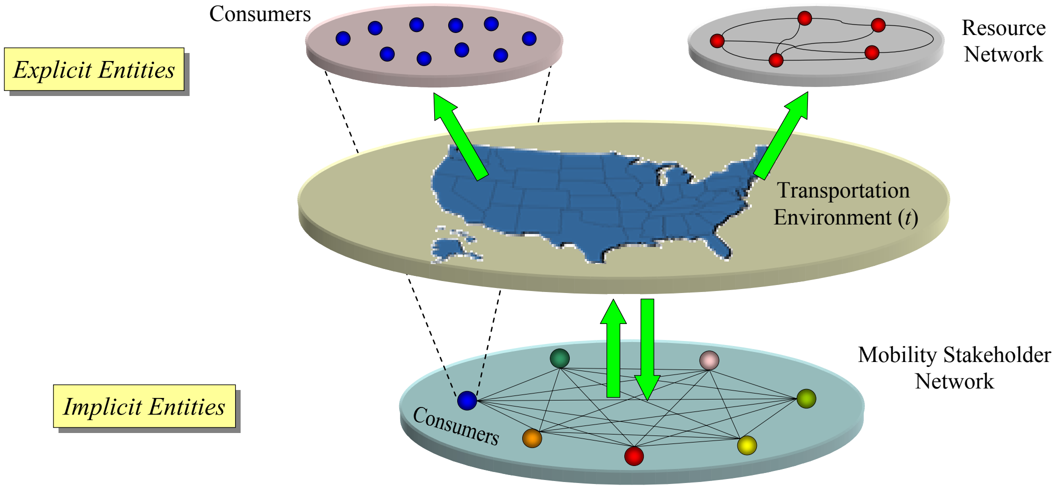


**Figure 5: Abstraction of NTS Architecture with Entity Networks**

tive transportation architectures can be evaluated. The previously introduced 'mobility credit' serves as an appropriate starting point, since it is in the form of currency, and the whole purpose of developing transportation technologies lies in enhancing mobility credit for future travelers.[8]

However, as indicated in Table 1, different stakeholders have distinct objectives. Hence, the concerns of other stakeholders not directly represented in the mobility credit must be addressed. Associated with each stakeholder is a collection of metrics by which they judge success (and failure) of a future transportation architecture. For travelers, besides the mobility credit, safety and reliability are primary values. For society, the aggregate noise, emissions, energy, cost and security are paramount. For service providers, the ability to make a profit while satisfying both consumers and society is the challenge. Further, there is a diversity of imperatives within particular stakeholder archetypes due to different geographical regions, different economic conditions, etc.

Finally, common sense dictates that the objectives of different stakeholders may be in conflict with each other. A prime example of confliction is between the goals of individual consumers and society as a whole – a system that maximizes mobility credit for individuals may also increase total transportation-related energy expended. Thus, as indicated in Figure 6, a Pareto front is likely to emerge. A Pareto front is the locus of non-dominated solutions. Certain myopic policy decisions merely perturb the current state along the existing Pareto front (solid line). However, the goal of future transportation architecture designers is to shift the entire Pareto front in the direction of the ideal state.

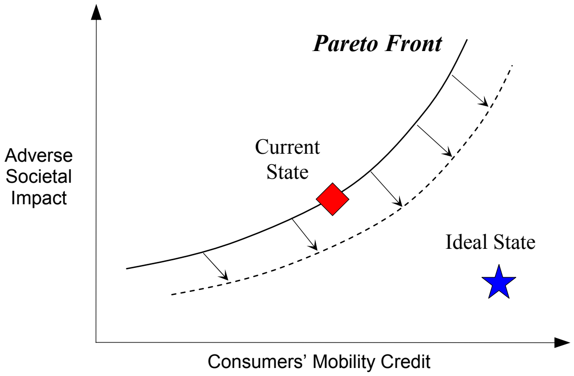


**Figure 6: Conflicting Criteria – a Notional Pareto Front for Consumer and Societal Perspectives**

## 3. Modeling Hypothesis

In response to the abstraction framework and problem formulation, the following modeling hypothesis is proposed. A modeling methodology treating the three major classes of transportation architecture entities (stakeholder, resource and network) can be created to synthesize alternative conceptual solutions and facilitate evaluation of the alternatives against multiple criteria. For the hypothesis to be proven true, the resulting methodology must be efficacious to decision-makers at multiple levels. Additionally, there are three other characteristics that must be tested to prove or disprove the hypothesis. All together, they are:

- Efficacy: The methodology must lead directly to required products and 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 and paths taken towards decisions reached.

The efficacy of the methodology can be measured by how well it represents the characteristics of the system-of-systems. For example, it must capture the time variant nature of the problem, including the simulation of latent effects due to feedback mechanisms and the consequences of uncertainty. The methodology must also possess sufficient modeling 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.

For the near term, the modeling hypothesis will remain unproven until significant research can be conducted. It does, however, point to the specific requirements that can guide the search for confirmation. To this end, initial research investigations have begun through the exploration of a variety of analytical approaches on subsets of the governing problem.

## 4. Exploratory Research Results

The abstraction process described above provides an integrative context for all transportation architecture modeling and simulation. It assists in clearly defining the boundary of relevance of individual modeling efforts. Boundary and context are important for two reasons. First, necessitated by the complexity of the challenge, modeling and simulation will be performed in distinct parts. The interface between these simultaneous efforts, thus, must be well-defined. Second, an understanding of the boundaries contributes towards a clear roadmap for future research direction.

The following exploratory research focuses on modeling and simulation within the particular realm of aerospace entities. The first subsection describes two vignettes that model the characteristics of explicit entities. This is followed in the next subsection by an implicit entity.

## 4.1 Explicit Entity Models

The start point for the exploratory research conducted over the past two years is a collection of prior work that characterized personal air mobility solutions in the context of mode choice and the value of time.[9,10,11] These studies, dating from the late 1960's, provided insightful results that served as a foundation for the current research. The concept of the value of time and a parameterized mission profile is adopted as the starting point for examining explicit entities, as portrayed in Figure 7. A new mobility resource is introduced as the focal point for exploring future transportation architectures.

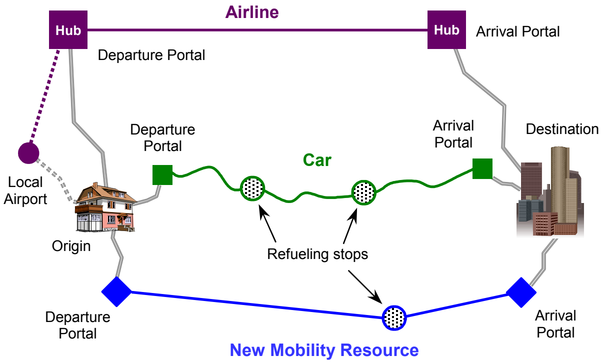


**Figure 7: Origin-Destination Mission Options**

The initial research outcome is embodied in the Benefit Exploration Tool (BET), its successor, the Benefit Visualization Tool (BVT), and an extension employing an agent-based approach. The first two tools are described together, while the more specialized agent-based approach is treated separately. In all three approaches, the tangible form of the new mobility resource is the concept of personal air vehicle (PAV).

### Benefits Exploration and Visualization Tool

The modeling boundary of the BET encapsulates a particular consumer and a simplified resource network. The BET examines the viability of a new mobility resource (PAV) based on the value of time. The tool computes doorstep-to-destination (*D-D*) time for selected travel distance along with parameters such as PAV speed (*V*), wait times (*TWAIT*), single or dual mode (roadability), and takeoff field length. Current commercial air and automobile options are included for comparative studies. (see Figure 8) In addition to *D-D* time, transportation affordability is a primary element of the mobility credit. The travel time saved by utilizing a PAV is used to compute the relative financial gains versus existing mobility options, which is depicted on an adjusted cumulative cash flow diagram as shown in Figure 9.

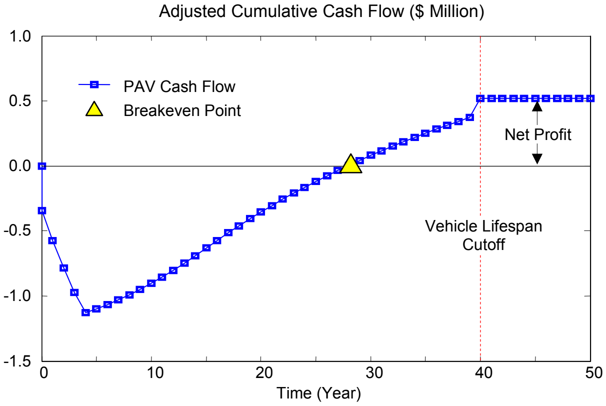
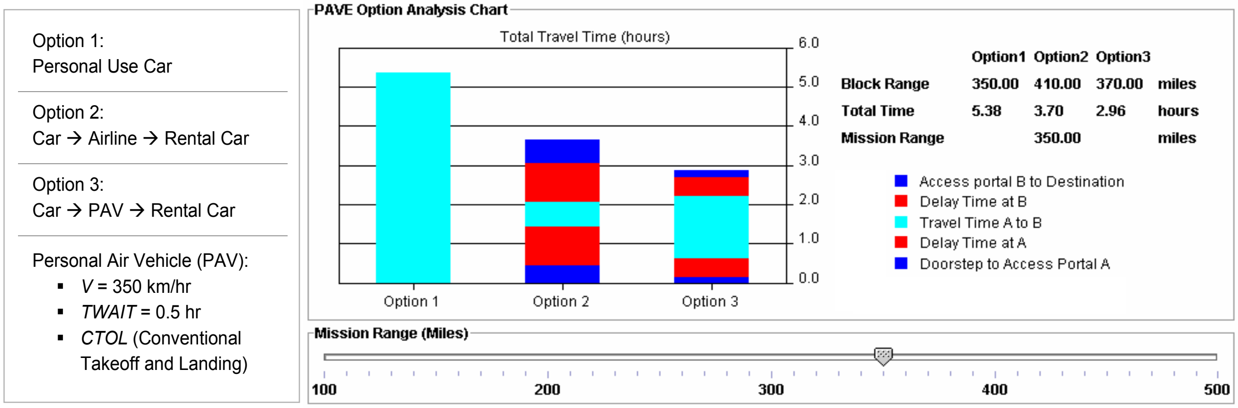


**Figure 9: Cash Flow Diagram**



Option 1:
Personal Use Car

Option 2:
Car → Airline → Rental Car

Option 3:
Car → PAV → Rental Car

Personal Air Vehicle (PAV):

- *V* = 350 km/hr
- *TWAIT* = 0.5 hr
- *CTOL* (Conventional Takeoff and Landing)

| | Option1 | Option2 | Option3 | |
|---|---|---|---|---|
| Block Range | 350.00 | 410.00 | 370.00 | miles |
| Total Time | 5.38 | 3.70 | 2.96 | hours |
| Mission Range | | 350.00 | | miles |

**Figure 8: Travel Time Visualization: One element of the Mobility Credit**

The BVT, an expansion of the BET, is equipped with the Unified Tradeoff Environment (UTE). The UTE is a generic parameterized environment generated by using a meta-modeling technique for examining the simultaneous effects of design variables, requirements and technologies.[12] The BVT allows designers to interactively explore the combined "trade-space" while remaining within meta-model boundary defined by user-selected ranges of variation.

The following example describes how the BVT can be used, although Ref [1] includes more detail. In this example, parameters such as travel distance, PAV acquisition cost, traveler income level and utilization are fixed while *V*, *TWAIT* and PAV direct operating cost (*DOC*) are examined within a given set of ranges. The goal is to achieve an adjusted breakeven point at year 5. Since there may be many combinations of the free variables that achieve the goal, the BVT is used to quickly explore and identify the more attractive combinations. As depicted in Figure 10, a typical outcome of the BVT, a shift of the design point **X** to feasibility (i.e. breakeven at year 5) is accomplished by a solution vector consisting of a small increase in *V*, a modest decrease in *TWAIT* and *DOC*. The BVT, employed in this way, illuminates the fact that increasing *V* alone cannot achieve the goal.

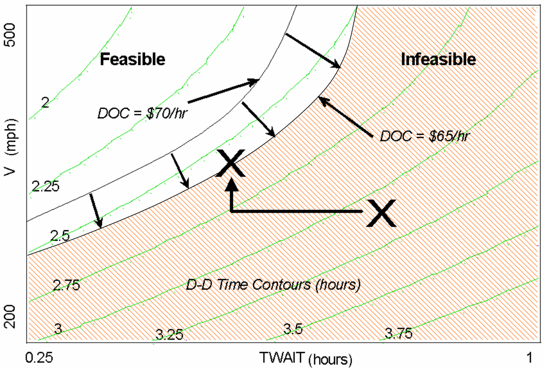


**Figure 10: BVT/UTE for PAV Example**

The BET and BVT are currently being integrated into a web-based environment* (called BEVT), evolving towards a user friendly tool that facilitates intelligent decision-making by vehicle designers and identification of key technology areas for successful concept vehicles. The tools together, through the UTE, give a fresh perspective over the traditional view of analyzing one vehicle system in a detailed manner. The abstraction framework identified this need to bring the resource network together with a consumer; it now further guides the methodology towards expanding the consumer stakeholder and resource network in a more realistic way.

Agent-Based Modeling Approach

A further extension of the BET was made by employing an agent-based modeling and simulation (ABM/S) technique. Agent-based modeling (ABM) is a bottom up approach that focuses on building an agency and couching it within an environment. The idea behind ABM is that the global behavior of a complex system is derived from the low-level interactions among its constituent elements. By taking advantage of this technique, the primary focus of this research thrust is on representing the explicit entities as a whole in which the boundary encapsulates the entire collection of consumers and the resource network, located on the upper portion of Figure 5. This was done by shifting a modeling perspective from physical entities, as usually seen in mechanical modeling attempts, to the travelers, more precisely, the behaviors of the traveling public. Governmental organizations periodically investigate the status and trends of the NTS, and the resulting data is useful in constructing the agent-based model.

A traveling party is treated as a unit agent, and the infrastructure environment in the NTS is conceptually represented in the model. After creating the virtual world, a new mobility resource of interest can be arbitrarily created and inserted in the transportation environment. Then, the adaptive agent selects its best travel mode through a choice mechanism. This selection process continues until an investigator ensures that a sufficient level of representation of the real world is achieved.

The following application gives a snapshot of the simulation results documented in Ref [13]. In this study, a baseline PAV was chosen whose design requirements are listed in Table 2.

**Table 2: Baseline PAV Design Requirements**

| Design Requirements | Settings |
|---|---|
| Nominal cruise speed (km/hr) | 350 |
| Number of seats | 4 |
| Refueling range (km) | 900 |
| Easy-to-fly technology | ON |
| Roadability | OFF |
| Takeoff and Landing Category | CTOL |
| Direct Operating Cost ($/hr) | 100 |

The baseline PAV was incorporated in a future transportation architecture and the simulation was carried out with one million agents. The output is voluminous. For example, an investigator can visualize the distribution of agents' mode choice over household income and travel distance in a 'market space' plot as portrayed in Figure 11 and 12. Each mark represents a unit agent – a single travel party of between 1 and 6 people. An agent's choice is indicated by a small dot

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*Visit URL:http://www.asdl.gatech.edu/teams/pave (car), cross (airline) or circle (PAV). The baseline PAV simulation result is depicted in Figure 11[†].

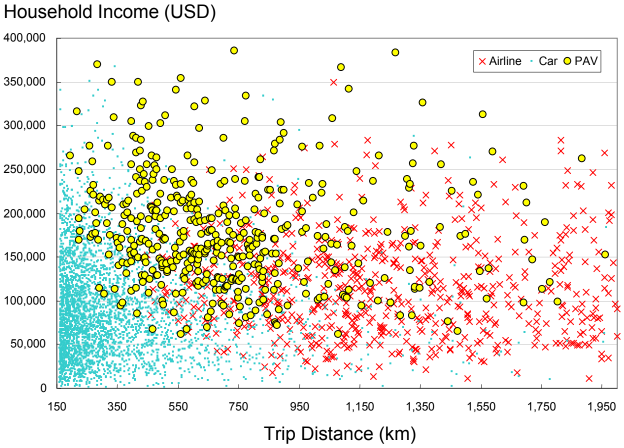

**Figure 11: Baseline Market Space Plot (*DOC* = $100/hr)**

This baseline PAV simulation serves as a foundation for the further study. An immediate application is the sensitivity of mode choice to changes in design requirements (ask/answer "what if?" questions). In Figure 12, the impact of increasing *DOC* by $50/hr is illustrated. It is obvious that increasing PAV price reduces its attractiveness, but the point is that the simulation can confirm this fact quantitatively and visually. The decision-maker is now able to quickly monitor the changes in the potential PAV market region in a dynamic fashion as contrasting the two market space plots.

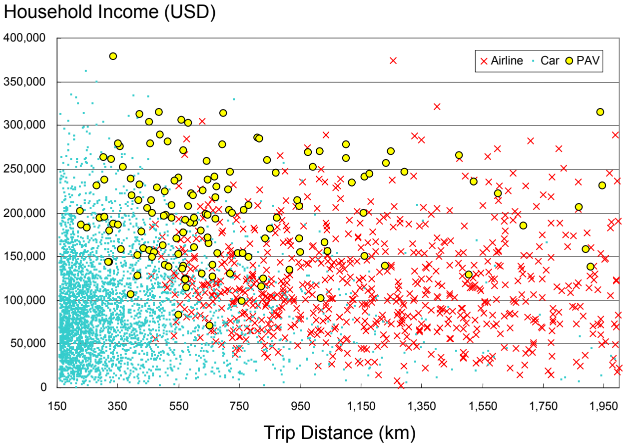

**Figure 12: Market Space Plot (*DOC* = $150/hr)**

Numerous simulation scenarios can be made focused on other design requirements. For instance, the PAV speed can be varied by ±50km/hr, keeping the other design requirements the same (including the *DOC* bracket), and the simulation repeated. The result of this scenario is shown in Figure 13. The value of this plot lies in its ability to convey the benefit of a design requirement in terms of marketability, which is a universal metric for a wide variety of vehicle concepts. Larger gaps imply greater potential benefit from changing the corresponding requirement.

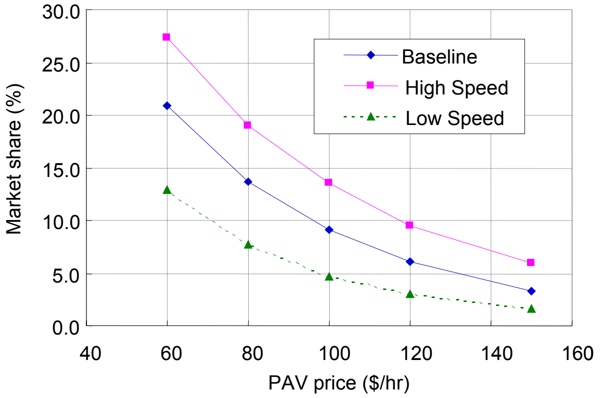

**Figure 13: Speed Sensitivity Plot**

Results of independent sensitivity analyses can also be expressed in a highly visualized format through a so-called tornado chart. The impacts on marketability compared to the baseline PAV due to changes in various design requirements are summarized and shown in Figure 14. This plot reports the magnitude of the effects of vehicle-level design requirements and system-level technologies together in a most efficient way.

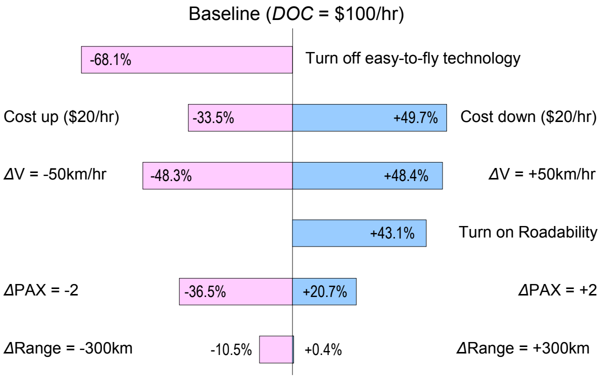

**Figure 14: Tornado Chart**

The ABM approach creates the powerful capability to measure the effects of vehicle-level design requirements, system-level technologies, and changes in conditions from infrastructure as well as environment on the marketability of a PAV system. Furthermore, this methodology can be logically extended to enable a direct, quantitative comparison of multiple vehicle concepts, an elusive capability to date. The abstraction process exposed the most critical direction to expand the modeling boundary beyond the BEVT, and this

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[†] For a clear illustrative image, only ten thousand out of one million agents are randomly selected. Also, the original outputs had upper bounds of 4,400 km for the abscissa, the approximate distance from Seattle, WA to Miami, FL. Then it is zoomed in for a close investigation.

guidance was used to confidently implement the ABM studies.

However, both BEVT and ABM approach were limited in that they treated the explicit entities only. As implied in Figure 5, the full realization of the abstraction requires the complete integration of all the explicit and implicit entities. This full integration remains a future goal and certainly a grand challenge; for now, it serves as a desired destination. It guides, nevertheless, the initial research into the world of implicit entities.

## 4.2 Implicit Entity Model

The range of stakeholders and their role was introduced in Table 1, and has also been the subject of pilot research. In particular, a study has been conducted to examine a sub-portion of the stakeholder network.

### System Dynamics Approach

In seeking formulations to study the dynamic behavior of the implicit entities and their network, the System Dynamics technique was identified as an applicable modeling technique. System Dynamics is a methodology founded in the 1960's and since matured into an active field of system study and policy analysis.[14] It facilitates the simulation of feedback mechanisms within a complex system over a prescribed period. It is also well suited to the level of modeling detail necessary at a conceptual design level.

The System Dynamics model of the new mobility resource development cycle established in this research represents a portion of the stakeholders portrayed in Figure 4. The problem specifically considers dynamic interaction between manufacturers and research agencies and attempts to identify promising operational policies. As a first step, a causal loop diagram is generated to understand the main features of a product development cycle, as shown in Figure 15.

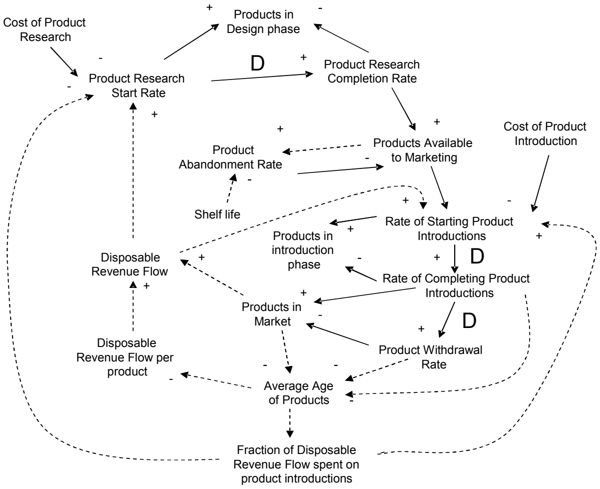

**Figure 15 : Causal Loop Diagram**

The solid lines refer to a physical flow of material while the dashed lines represent a flow of information. A positive sign at the end of each arrow signifies a reinforcing relationship while a negative sign refers to a balancing relationship. The primary feedback presented in this example is the flow of Disposable Revenue from current products in market back to product research.

Based on the causal loop diagram, a stock-and-flow model is developed, which maps the flow of a product through its design and certification stage as well as the revenue flow for the manufacturer. The influencing variables act as control valves that regulate the flow of material. This stock-and-flow diagram is shown in Figure 16.

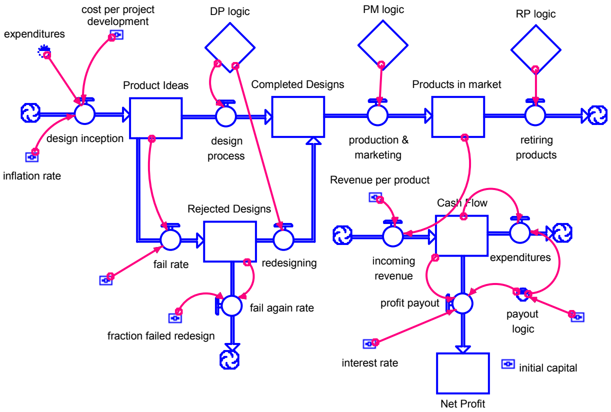

**Figure 16: Stock-and-Flow Diagram**

Many policies can be explored through simulation. For example, reducing the certification failure rate through quality initiatives increases the number of completed designs but at the expense of increases development lead time. Is this policy of reducing failure rate advantageous to profitability in light of the competing effects? The simulation result, shown in Figure 17, answers this question. The manufacturer's success is more sensitive to lead time, thus the policy of reducing failure rate should not be adopted. The implied result should be tested in additional circumstances, but is already relevant to the planning of manufacturer concerning the introduction of a future technology concept.

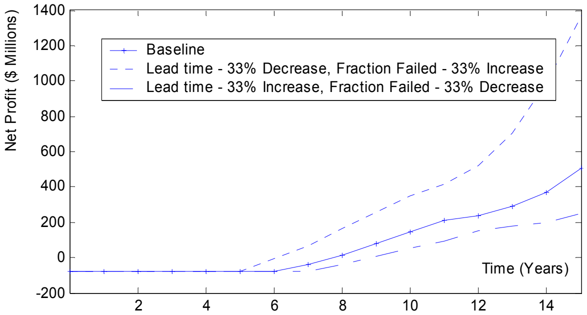

**Figure 17: Simulation Result**

The primary advantage of the System Dynamics approach is the ability to unveil the hidden dynamics that exist within and between stakeholders. Through the above scenario, simulation of the stock-and-flow feedback model exposed a policy solution for the manufacturer stakeholder that indicated the potential for profitability. In the future, interconnections to other stakeholders can be formed in an effort to span the complete implicit network. At that time, policy investigations made along the way should be re-examined.

## 5. Reprise and a Look to the Future

The design of future transportation architectures represents a tremendous challenge, one that surely requires the wisdom and innovation of many different research communities. To meet this challenge, academia should provide frames of reference, thought processes and problem formulations. It is from this motivation that the present paper has been written.

The primary premise introduced was the necessity of a system-of-systems perspective for the study of the future of transportation. Further, the term architecture was defined as that which contains multiple system(s)-of-systems. So the future transportation architecture was established as the focus of study. Under the expected high degree of complexity for this problem, an abstraction framework was recommended and introduced to study potential transportation architectures without prescribed boundaries. The two instances of a system-of-systems abstracted are the network of resources and the network of stakeholders. It appears that the abstraction described is universal, covering any conceivable particular architecture. After the abstraction process, a modeling hypothesis was presented as a long-term research goal. The abstraction and modeling hypothesis are directed toward the ultimate purpose of an ability to compute a wide variety of value metrics to delineate between alternative architectures. But more broadly, it is the hope of the authors that the ideas will also spur interest and facilitate research collaboration between normally disconnected disciplines: aerospace engineering, civil / transportation engineering, business, public policy and so forth.

The abstraction process illuminated the particular elements of the hypothesized methodology to examine first, resulting in three pilot research thrusts. Although certainly in their infancy, these pilot studies produced useful insights. The exploratory nature of the Benefits Visualization Tool proved effective at identifying requirement boundaries on resource entities. With sufficient modeling abstraction, an agent-based approach demonstrated the ability to represent the explicit entities as a whole through observance of the emergent behaviors of consumers in presence with a new mobility resource. In order to capture the dynamics of stakeholders, including the latent effects due to feedback mechanisms, a System Dynamics approach was applied and appears to be promising.

Immediate future work will focus on the synthesis of these methods. Specifically, research is underway to embed System Dynamic models with agent definitions to dictate their rules of behavior in a more realistic manner. This would enable the characterization of the time dependent nature of problem, the existence of feedback with the system, and possibly emergence of visionary designs. Further, models must be expanded to cover the entire spectrum of stakeholder behavior, network structure and resource characteristics. This expansion will be based upon an object-oriented philosophy. The modular objects within the virtual environment can then be linked together easily, in order to examine the properties of the larger architecture. Complex behavior can then be analyzed within individual modules or from a system-of-systems perspective.

However, despite the best intentions, it is the authors' view that the entire transportation 'universe' can never be modeled completely. Even if this task is accomplished, the result could be far from the real 'universe'. 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.

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