AUTONOMOUS VTOL SCALEABLE LOGISTICS ARCHITECTURE (AVSLA)

PHASE II INTERIM REPORT

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PREPARED BY

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and

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AT GEORGIA TECH

PREPARED FOR
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Executive Summary

This final report documents the results of exploratory research conducted under a Phase II NIAC award on the potential for the use of autonomous vertical takeoff and landing (VTOL) vehicles for affordable package delivery. The specific application of Uninhabited Air Vehicles (UAVs) for package delivery served to focus the research. However, the broader theme of designing large scale system-of-systems "advanced concepts" is perhaps just as critical an undertaking. The increasing complexity of future commercial and military aerospace applications, from super safe and efficient air traffic management concepts to high reliability planetary exploration missions, underlies the pertinence of the research. In addition, it is a well-known truth the decisions made during conceptual design phases can "lock in" a majority of the eventual performance, cost, and reliability of the final product. The complexity of the problems and the consequences of one or more bad decisions early on present a challenge to all advanced concept designers.

With this larger motivation, the manner in which the team pursued these research goals is important to understand in addition to vehicle level technology findings. The temptation to focus exclusively on "neat" technology solution alternatives was resisted. Instead, with the objective of creating the ability to make solid recommendations to NIAC and NASA for future directions, a two tiered approach was adopted. The overall approach is based upon a design methodology developed at Georgia Tech which served as a structured roadmap for defining the problem and objectives, constructing system alternatives, being able to evaluate these alternatives against relevant metrics, assessing the need for additional technology infusion, and making decisions. These steps were executed in the context of an *automated VTOL scalable logistics architecture* (AVSLA). Though only a brief period of study, the Phase I results provided an excellent identification of the important issues to be addressed first in this Phase II effort. Primary among these issues was the need for a more detailed model of the network, economic, and vehicle triad for AVSLA.

A treatment of this triad was conducted in Phase II as the first tier is the system-of-systems layer for AVSLA. This tier encapsulates the interaction between major elements of AVSLA: economics, air traffic management, delivery network, vehicle capabilities, and a demand model. System dynamics techniques were employed to model this tier with the goal of extracting economic and operational/environment requirements for an economically viable AVSLA. The system dynamics model consists of several modules that capture the essence of the key elements. When integrated together, these modules are exercised to simulate the AVSLA dynamics under various scenarios to generate a vector of requirements. Different combinations and settings of primary parameters in the model represent specific operational scenarios of a future AVSLA mission concept. "What if" questions that invariably arise are now easily dealt with by changing the settings. This same capability is also used to assess robustness to economic and operational

uncertainty. *Preliminary results from several sensitivity studies indicate that, under current modeling fidelity, it appears that there is a non-linear relationship between the delivery radius and the number of customers in their effect on AVSLA profitability. In a sense, a "sweet spot" exists whose location is also sensitive to other parameters. One clear result is that it is always good to maximize the number of packages picked up from each customer.*

The second tier in the Phase II study again was derived from Phase I recommendations. This tier deals with generating potential technology solutions for each of the modules in response to the multiple sets of scenarios and requirements generated in the top tier. Within the scope of the NIAC Phase II study, the team focused primarily on the VTOL vehicle design at the second tier. Other areas, such as the air traffic management concept, were treated but to a far lesser extent. Estimated requirements from the top tier were used to methodically explore the feasibility and viability of various alternative configuration and technology concepts for the VTOL delivery vehicle. The Technology Identification, Evaluation, and Selection (TIES) process was employed for this purpose. *The initial execution of the tier 2 study resulted in the selection of a tailsitter UAV concept for the delivery vehicle. In addition, a technology roadmap was generated that lays out in detail what technologies may be needed to make this concept vehicle a reality. The roadmap represents a key deliverable from the Phase II study.*

The interface between these two-tiered activities addresses AVSLA system relevance and effectiveness by matching system concepts alternatives with scenario-based requirements. For example, a particular type of vehicle with a certain type of delivery network implies the need for a cost per package that is 20% lower than current system for several categories of high value-density categories for an urban region. The sensitivity of the relative merits of each alternative to such things as number of customers and delivery radius is easily computed. Such results are included in this report.

The progress made in the AVSLA modeling in this Phase II effort is promising. The initial results that emerged provided useful insight. However, more confident statements about the implications of the initial findings are not warranted until the fidelity of several of the modules is improved. Thus, recommendations for further work via the proposed option include a more detailed look at the system dynamics module inputs and structure. The team believes that the top level architecture and connections in the model are correct. However, more detailed study and modeling of the network topology, economics model, vehicle design characteristics, and linkage of all three are needed. *These more detailed results combined with the refined and expanded system dynamics model would be a package that NASA and DoD managers, as well as potential industry participants, could actually* ***use*** *themselves in assessing their view of the viability of AVSLA and its related technologies.*

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1. Introduction

The commercial transport of logistics in the United States is currently facilitated through the use of waterways, rail lines, highways, and aerial routes. Generally speaking, bulk goods with low value densities are transported using trains and ships; trucks and aircraft move items of higher value. The main reasons these modes are used are that the enabling infrastructures have been in place for many years, they are developed, people are comfortable with them, and most importantly they work. Unfortunately, a price is paid for the various vehicles used by the respective systems. The losses incurred for the current methods may be categorized into fossil fuel expenditure, en route inventory, damage to roadways[1], congestion at airports[2] and roadways, as well as others that have not been named.

A system study proposed by the Sikorsky Aircraft Corporation [1], AVSLA incorporates unmanned aerial vehicles (UAV) capable of vertical takeoff and landing (VTOL) flight into a delivery system that operates within the National Airspace System (NAS). Researchers in the Aerospace Systems Design Laboratory (ASDL) at Georgia Tech modeled and analyzed the system dynamics of the delivery architecture. Additionally, in-house tools developed at the ADSL were used to determine the probability of meeting vehicle level goals with current technology. The potential impact of technology infusion to increase the chances of meeting system objectives was also investigated. The methodology employed for these two steps is summarized in Figure 1.

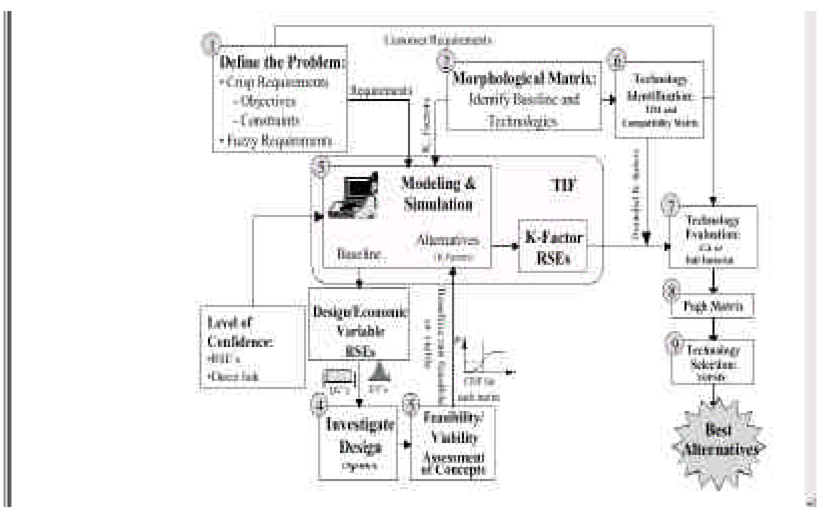


Figure 1 A Snapshot of the ASDL Design Method

[1] http://www.fhwa.dot.gov/policy/hcas/addendum.htm 40.3% of total highway allocation costs ($33B 2000) resulted from all trucks, 3.27% from trucks weighing less than 25,000 lb (1.5 equity ratio though).
[2] http://www.atwonline.com/Pdf/tables.pdf FedEx has the 2nd largest fleet (662 aircraft) in the world. ~14% of the world's commercial fleet is devoted to cargo. http://www.boeing.com/commercial/cargo Growth for each of the next 20 years is expected to be 6.4%

2. Design of AVLSA Infrastructure

The design of any system of systems must always begin with the identification of some societal, technical, or political need. There must be a reason why the effort is undertaken. The motivation for AVSLA, as already explained, is to revolutionize the transport of goods between parties that trade commerce. An investigation of the shipment of goods in the Southeast was performed using data documented in the Economic Censuses of 1993 and 1997. Consumer requirements were identified from this exercise. These initial requirements served as a starting point for the AVSLA study.

During the Phase II portion of this investigation, the dynamic behavior of AVSLA was modeled using VENSIM®, a system dynamics modeling tool. A detailed economics module was developed as were a logistics module, system architecture module, and vehicle configuration module. These modules are interconnected into a single system dynamics model to allow for the analysis of the whole system. Furthermore, a network simulation was developed to determine the effects of certain parameters on the network.

The network simulation was coded and run using MATLAB. A point to point architecture was chosen for this simulation. The network simulation was required to determine values for some of the inputs into the Vensim® model. These inputs included range, service radius, the number of customers, etc. Although educated guesses for these inputs were possible, using a network simulation was considered a better alternative. A design of experiments array for the inputs was run and a response surface was fit to the results. The response surface facilitated a linking of the Vensim® model to the results of the network simulation.

The whole system model included the economic, cargo, architecture, configuration modules in Vensim® and the response surfaces from the network simulation that were coded into Vensim®. Unfortunately, a single run of the whole model required between 7 and 80 minutes (dependent of number of customer on the route). Therefore another response surface, for the whole system, was fit to data generated using a face-centered central composite design of experiments design array to reduce data generation time. This response surface was then used in a Monte Carlo simulation to rapidly assess the effects of system variables on the system's responses for thousands of different cases. In this manner, an assessment was made of the system's sensitivity to the speed of the vehicles, the fee structure, the range of the vehicles, the number of packages picked up, etc. The development of the model and the results are documented in this section of the report.

2.1 Definition of Requirements

2.1.1 Commercial Requirements

An analysis of the commerce movement in the Southeast was completed and goals for the payload and range of the AVSLA vehicles have been extracted. These goals are based on the desire for AVSLA vehicles to be operating in an area of maximum “goodness.” A “goodness” metric was developed so that market growth, item value density, and total value of the items (on a per year basis) transported could be combined into a single objective criterion.

Before “goodness” was evaluated, it was necessary to identify a group of commodities (to transport) that represent the best niche for AVSLA to become profitable. The total number of commodities that are tracked by the economic census is forty-two. A Pareto analysis was employed to help reduce this large group of candidates to the nine most “good” from a value-density viewpoint. The concept behind a Pareto analysis is that a small number of predictors in from a larger group is typically responsible for a majority of the variability in the response of interest. The response in this application was the total value of the items transported. Additionally, it was necessary to normalize the total value by the total gross weight of the items in order to eliminate low value density items from the investigation. Clearly, an item such as rice could have a very high total value but because such large quantities are involved, it would be highly uneconomical to transport this commodity with an expensive, state-of-the-art system. A mode of transport utilizing railways or waterways would be better suited for a high value, low value density commodity. A Pareto Plot of cumulative value density of the forty-two commodities tracked in the 1997 Economic Census is displayed in Figure 2. The commodities are not listed on the Pareto chart for clarity.

As indicated in Figure 2, there are nine commodities which are responsible for the majority of the cumulative value density transported in the Southeast. These are tobacco products, pharmaceuticals, textiles, electronics, transportation equipment, precision instruments, machinery, vehicles & vehicle parts, and home furnishings. The percentages shown in the data labels on the pie chart represent the contribution of each category to the total gross value (in 1997 dollars) of all commodities being transported in the Southeast.

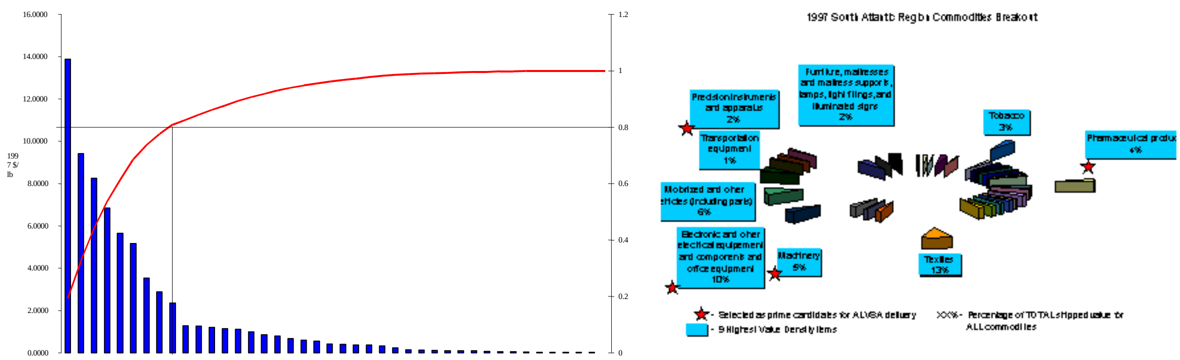


Figure 2 Pareto Plot and Pie Chart of Nine Selected Commodities

These nine commodity types were further reduced to only four through an evaluation using the previously mentioned "goodness" metric. This criterion gives a clearer picture of the economic health of a commodity type. The calculation of "goodness" is shown in an example. For example, a sample "goodness" of tobacco, textiles, and pharmaceuticals is calculated in several steps. The gross numbers are not the actual ones used for the final selection; they are unique to this example. The aggregate, dimensioned numbers are normalized using the Euclidean normalization formula shown in Equation 1. In the equation, the Y's can be any single entry in a vector of multiple responses (replicates in a sense). The gross and normalized values are reported in Table 1.

$$Y_{1norm} = \frac{Y_1}{\sqrt{Y_1^2 + Y_2^2 + \ldots + Y_N^2}}$$

Equation 1 Euclidean Normalization Formula

	Total Value		Value Density		Market Growth	
	Gross ($M)	Normalized	Gross ($/lb)	Normalized	Δ $M 1993-97	Normalized
Tobacco	50	0.19	18	0.43	-5	-0.64
Pharmac.	110	0.41	35	0.84	6	0.76
Textiles	240	0.89	14	0.34	-1	-0.13

Table 1 Normalized Value, Value Density, and Market Growth for Sample Problem

A subjective weight is placed on the importance of each economic metric. The value density and market growth were viewed as being the more important factors for affecting the profitability of the system. The reasons for this are that AVSLA would have relatively high operating costs initially (relative to existing vehicles), and there already are established delivery agencies which transport these goods. Only with high value-density items could AVSLA be economically justifiable and only in a fast growing market could there be room for AVSLA to easily acquire market share. The sum of the products of the weight and normalized score of the evaluation metrics results in the "goodness/health" indicator (higher is better). Tobacco has a score of –0.03, pharmaceuticals scored a 2.15, and textiles scored 0.93. Based on the data in this illustrative example (see Table 2), tobacco is a poor choice for transport while pharmaceuticals are the best.

Metric	Weight	Tobacco	Pharmaceuticals	Textiles
Total Value	1	0.19	0.41	0.89
Value Density	1.2	0.52	1.01	0.40
Growth	1.1	-0.73	0.73	-0.37
		-0.03	2.15	0.93

Table 2 Metric Weighting and Weighted, Normalized Goodness Value for Sample Problem

This same calculation was completed for the nine commodities of interest using data from the economic census. Using the goodness evaluation criterion resulted in a decision to focus on four of the nine commodities; pharmaceuticals, electronics, precision equipment, and industrial machinery. The transport of these four commodities offers the best chance for AVSLA to succeed. They have high value densities, their markets are expanding, and most have relatively large total values as summarized in Table 3.

	Total Value	Value Density	Market Growth	
Weight	1	1.2	1.1	
Commodity				Goodness
Tobacco	0.15	0.26	-0.21	0.231
Pharmaceuticals	**0.24**	**0.32**	**0.39**	**1.053**
Textiles	0.70	0.13	-0.03	0.823
Electronics & Office Equip.	**0.57**	**0.44**	**0.35**	**1.483**
Transportation Equipment	0.08	0.38	0.01	0.547
Precision Equipment	**0.11**	**0.64**	**0.4**	**1.318**
Industrial Machinery	**0.29**	**0.24**	**0.63**	**1.271**
Furniture	0.10	0.11	-0.22	-0.01

NOTE: The HIGHER the goodness, the better

Table 3 Four Commodities Selected Based on Value of "Goodness" Metric

The next questions to answer are, "how far should these items be transported?" and "what would be a good target weight for a payload?" These questions were addressed and answered by examining a mapping of the goodness criterion onto distance traveled and payload size (Figure 3). The summary of statistics in the economic census [2] included all the necessary information.

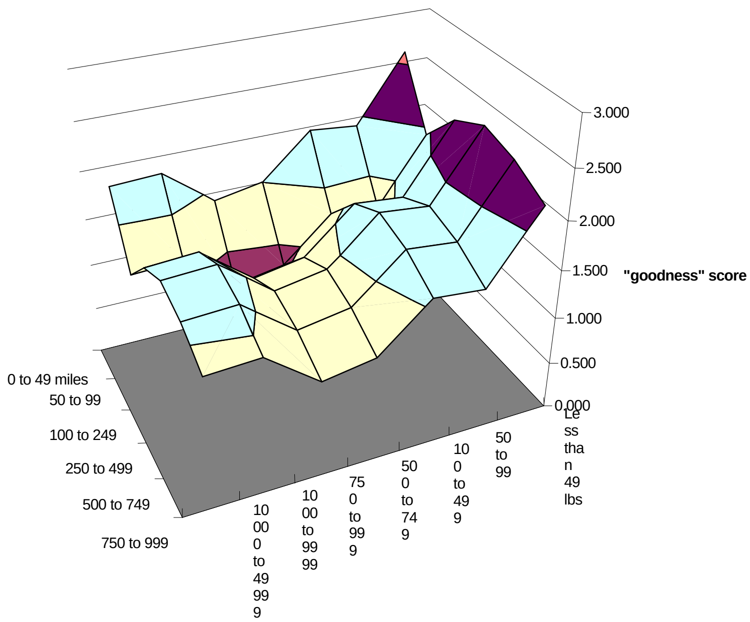


Figure 3 Goodness VS. Weight VS. Distance

By examining the relevant three-dimensional design space of goodness, weight, and distance, it is clear that the best missions to design for are ones involving payloads smaller than one hundred pounds and distances up to a thousand (statute) miles. However, a one thousand-mile mission radius is probably too large for a small VTOL UAV however. A smaller radius of 250 statute miles (500 miles total range) was used as a baseline instead.

Following the selection of payload and range target values, the target values for vehicle parameters were decided. Because the vehicle options were sized using the fuel balance method, the logical parameters to track and evaluate (and their respective initial target values) are the gross weight (500 lbs.) of the vehicle, the installed horsepower (100 hp), and the mission fuel weight (100 lbs.).

2.1.2 Possible Military Requirements

The US military has a number of needs which can be satisfied with UAV systems. The AVSLA system is expected to have a number of advantages for many of the needs.

Currently many of the US Army utility helicopter missions are logistic resupply. The UH-60 helicopter, in addition to the primary role of troop assault, often deploys with cargo loads such as ammo, fuel, water, and food. These missions are not well suited to manned flights – they place the pilots at risk during the flight, limited pilot assets and allowable flight time are used up on logistic missions rather than more critical combat or medevac mission, and the missions are boring. These missions are much better suited to a autonomous vehicle, which does not put personnel at risk and has no requirement for pilot rest time. Additionally, an autonomous system could significantly reduce operating costs as pilots and crew (currently 4 per aircraft for a UH-60) are not required.

The AVSLA system would be uniquely suited to the military logistics resupply mission. The same system dynamics model used for the commercial system could be used to optimize the routing of load requirements. The system will be somewhat different than the commercial system in that loads will depart from a smaller number of supply depots, but the delivery aspects are likely to be distributed in roughly the same manner as the commercial system. Some enhancements to the system could be made for military uses. For example, the distribution routing system could take into account areas of know threats to the helicopter (i.e. areas under enemy control) and automatically route the vehicles around these areas.

The requirements for a military UAV would differ from the commercial system, primarily as military loads are significantly heavier than commercial ones. For military uses, the tactical value of the load becomes more important than the dollar value of the load. For example, a significant number of Army loads are fuel, which has low dollar value but high tactical value on the battlefield. Current U.S. Army requirements for the Block 2 UH-60 are a 9,000 to 10,000 lb. payload and 275 to 500 km radius of action.

The US Army in the last year has significantly increased focus on UAVs. One of the key Army development programs, the Future Combat System (FCS), has an organic air vehicle as part of the system, providing reconnaissance and intelligence data to the local system. The FCS is designed as a light weight but survivable fighting system, providing improved deployability and mobility without sacrificing survivability and firepower.

The US Army, in combination with DARPA, is beginning a Unmanned Combat Attack Rotorcraft competition. This program is to develop the technology for unmanned combat attack rotorcraft. The AVSLA system provides some synergy with this program, as an attack can often be thought of as delivery of firepower (i.e. delivering a package is somewhat similar to delivering a missile). This synergy could reduce the cost of developing some of the relevant technologies as the user base would be expanded.

Sikorsky is currently exploring the use of UAVs with the US Army, including a concept similar to the AVSLA system. During the second half of Phase 2, these activities will be accelerated and matured to understand the military viability of the AVSLA system, as well as mature the commercial viability understanding discussed in the previous section.

2.2 Formulation and Analysis of System Dynamics Model

System Dynamics is a relatively new field. It is an alternative way of conceptualizing a problem and explaining how a system of disparate components work, different from a sequential “Spreadsheet approach”. Sometimes intuition and debate aren’t sufficient for explaining “how the wheels turn” in a complex system. System Dynamics attempts to tackle this by introducing cause-and-effect loops and feedback. However, in better words, R.G. Coyle defines System Dynamics as following:

"System Dynamics deals with the time-dependent behaviour of managed systems with the aim of describing the system and understanding through qualitative and quantitative models, how information feedback governs its behaviour, and designing robust information feedback structures and control policies through simulation and optimization." [3]

In the NIAC Phase I study, the economic portion of AVSLA system was sketched with the computer program Vensim©. The original intent for Phase II was to understand the model, work with it and modify it. While this model was useful for explaining the customer-supplier-delivery agent network, it did not include detailed vehicle or network information. Therefore, the model has been completely reworked. The new model tries to examine the feasibility from an aeronautical point of view, while still capturing the major economic aspects.

The benefits gained from the new system dynamics model will be the determination of the feasibility of the system and the inputs that influence that feasibility. Also, through modeling of different requirement scenarios, "what-if" games can be played, showing the system's key traits such as vulnerabilities and robustness.

Five separate modules comprise the system dynamics model as implemented in Vensim©. Each module is described in detail next.

2.2.1 Control Module

This module is like the captain's bridge of a ship, where only the commanding takes place and the vital functions for the movement of the ship are located elsewhere. The control module represents the top-level relationship between component systems and is where one can change variable settings and see immediate results. The control module as constructed in Vensim© is shown in Figure 4. The small rectangles on the right hand side are "slide bars" that allow a user to change a parameter value to see the effect on the system. The three plots in the upper right show the graphical output of these effects of interest. Thus, the effect of a value change of a variable can be viewed instantaneously on these plots. The diagram on the left shows how the other modules are related to each other. In the diagram, modules that are not boxed represent inputs for the model that are currently not as well defined as the four boxed entities.

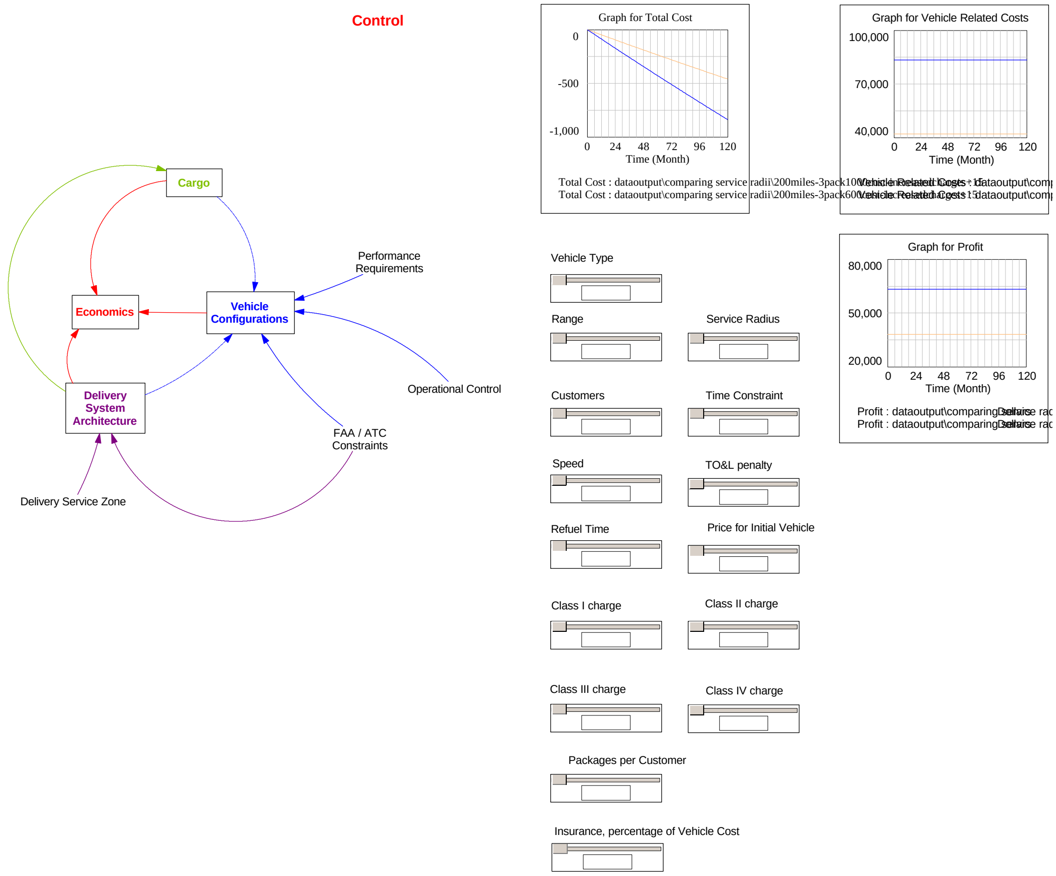


Figure 4 Vensim Control Module

2.2.2 Economic Module

This module models the economic dynamics of AVSLA. The arrangement of this module is depicted in Figure 5. Input is obtained from the delivery system architecture, cargo, and vehicle configuration modules. Since AVSLA will not exist until 20-25 years from now in an unknown market and unknown conditions, it was decided that the variables and ideas employed should be kept simple but with a broad range of applicability and extensibility. In addition, some parameters have been fixed for now, personnel cost is an example. All simplifying assumptions, however, were made in such a way as to easily allow them to become active variables in future developments.

The main output in the module is the system profit. The system profit determines if the system will lose or make money with the current settings. Two values feed directly into the system profit. These are revenue and total delivery cost. Notice that the lighter script accompanied with a pair of "<>" are values that feed in from the other modules. This is the case throughout the Vensim© model.

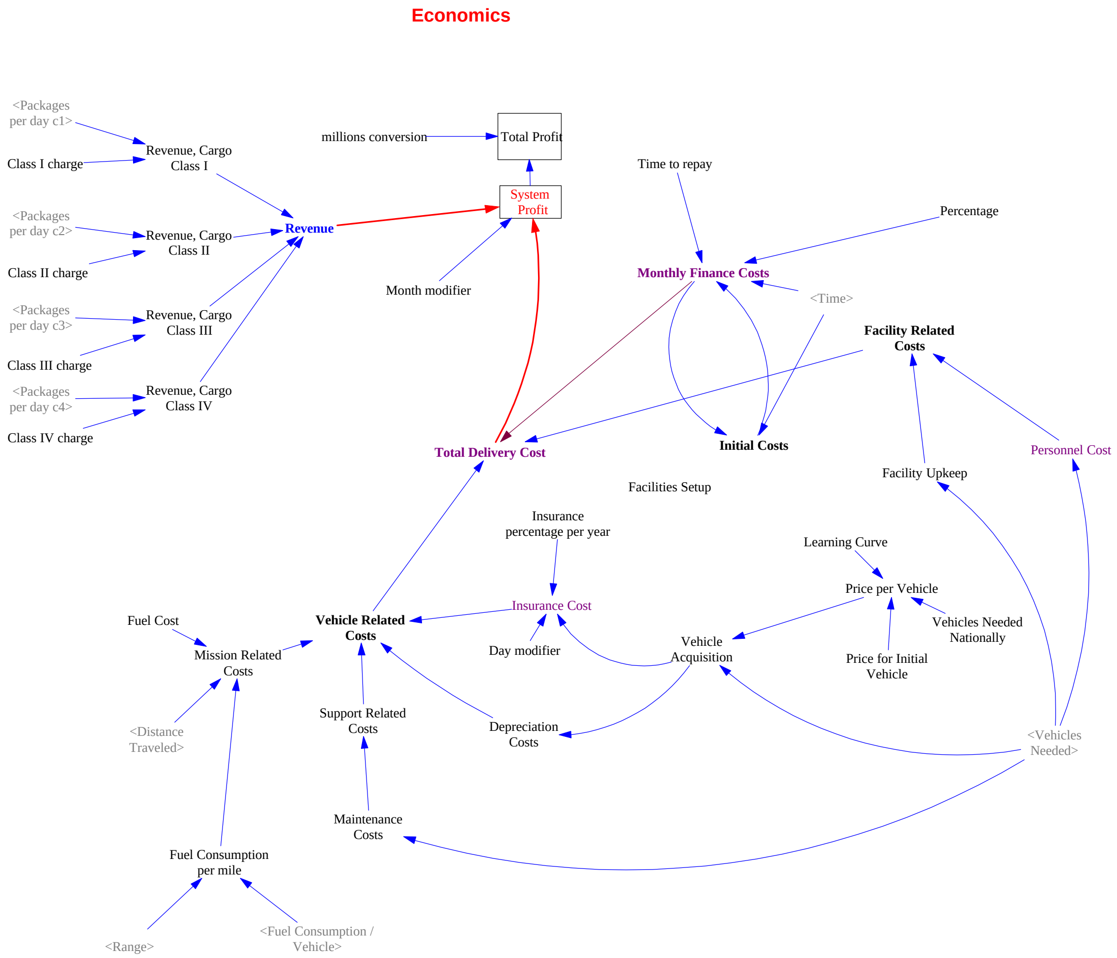


Figure 5 Vensim Economics Module

Revenue is income collected from customers for delivering their cargo. Total delivery cost is the cost of the system to operate. There are three inputs to the total delivery cost: vehicle related costs, facility costs, and financial costs. Each group has different subtotals, depending on the type of cost that is being calculated. Notice that the system dynamics model was originally planned for a per day basis, but later changed to a per month type operation. A calculation was included to implement this simple transformation.

2.2.3 Cargo Module

The main purpose of this module, shown in Figure 6, is to provide to the economics module the amount of packages in each of four classes so that the proper fare is assigned. The weight of each package can fall between four classes which range from 0-25, 25-50, 50-75, 75-100 pounds. The number of customers is an input from the Control module and is used here to determine the number of packages for each weight class.

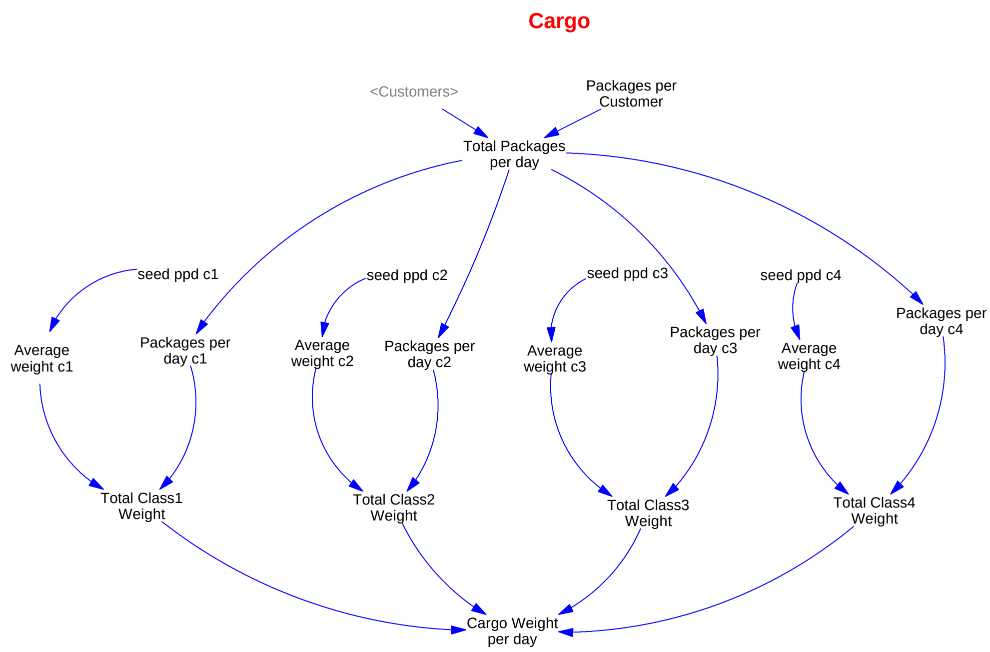


Figure 6 Vensim Cargo Module

2.2.4 Delivery System Architecture Module

This module was created to determine the number of vehicles needed for the specified operational scenario and the distance traveled by all vehicles during the delivery of all packages for each scenario simulation. The inputs in this module determine the scope and size of the network, even though the network type (at the present time) doesn't change. This module is embedded with regression equations that were obtained from a specially created network sizing computer program. A later section of this report describes this Network Simulation computer code. In summary, the Delivery System Architecture Module computes the number of vehicles needed and the distance traveled, and it then feeds both into the economics module. Note that the vehicle configuration module also shares the variable "speed". The Vensim© implementation of this module is captured in Figure 7.

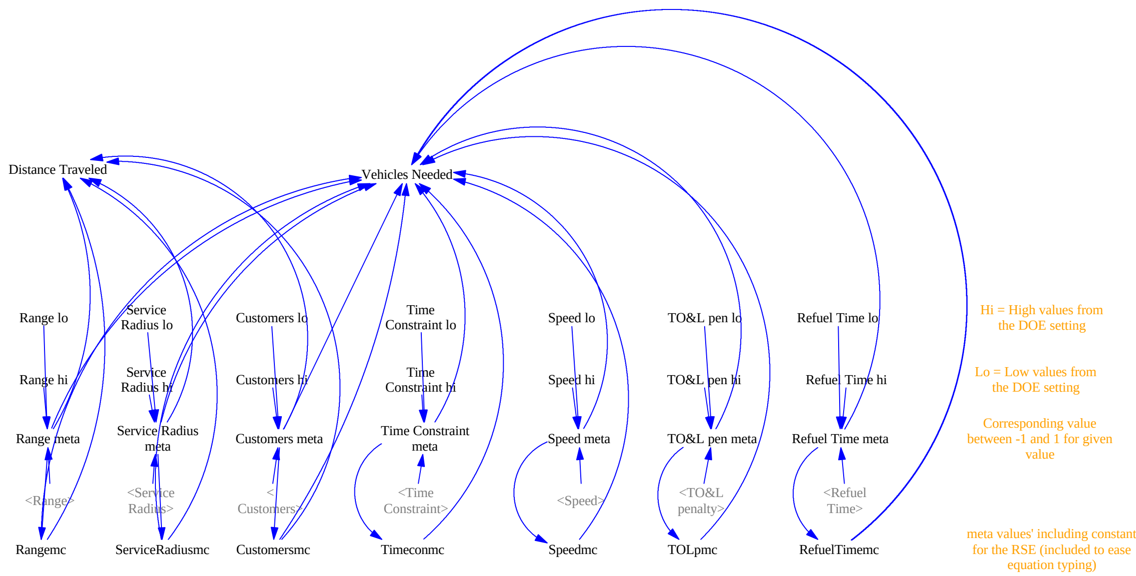


Figure 7 Vensim Delivery System Architecture

2.2.5 Vehicle Configuration Module

The vehicle configuration module is currently very simple. Its sole function is to determine the fuel consumed depending on vehicle type and network setting. Regression equations are present here as well, this time obtained from a parallel study conducted by a fellow ASDL researcher [4]. The fuel consumption level changes for the specified network configuration based on the range setting for the vehicle, since the range changes the mission profile used to size the vehicle and hence the fuel consumed per mile. A snapshot of the vehicle configuration module for two candidate VTOL vehicles (a helicopter and a tailsitter configuration) is displayed in Figure 8.

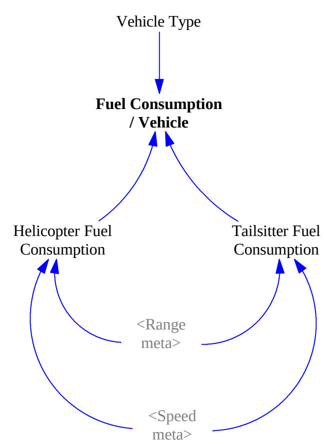


Figure 8 Vensim Vehicle Configuration Module

2.3 Network Simulation

Many of the variables feeding in and out of the configuration, architecture, and economics modules are vital to the results of the system dynamics model of AVSLA. *While the values of the variables could be in some cases approximated, assignment of meaningful values require a clear definition of the delivery network and the context that accompanies it*. Some of these key variables are:

- Number of vehicles required in a scenario
- Operations cost of this system model
- Distance traveled by each vehicle with a given network simulation

A computer simulation of the network was clearly needed in order to be able to determine the number of vehicles and the distance traveled by these vehicles for a predetermined type of operation. Resulting values for these variables would increase the accuracy of the system dynamics model. Therefore, a network routing design program was created for AVSLA. The vehicle routing program determines these very important values to an acceptable level of accuracy.

Assumptions made about the network in building the analytical tool are discussed next. Following that, the algorithms used in the program, the inputs and outputs are introduced. Finally, a short description of the program will be given, and the regression method used to incorporate the output from the computer simulation into the system dynamics model will be explained.

2.3.1 Network Type

In the Phase 1 AVSLA study, a point-to-point network (or a distributed service derivative) was found to have the best overall cost, and was therefore recommended for the delivery architecture. Thus, the network chosen for the simulation was a point-to-point network with a depot located in the middle of the delivery area. A certain number of customer pick-up and delivery points are randomly placed on the map, having met certain criteria. These criteria are that the customers' pick-up and delivery locations should be within a given radius, and that the total depot-pickup, pickup-delivery, and delivery-depot travel distance should be less than the specified range. One of the advantages of AVSLA would be the relatively fast delivery of the cargo. If the cargo were flown to the delivery location immediately after the pickup, this advantage would be kept. Keeping this advantage could be essential for the marketing of this system. No other delivery system or service today has the capability of delivering a package over a substantial distance within hours of the initial order. This advantage has been retained in the network simulation and the cargo is inbound for delivery as soon as it is loaded on the vehicle at the pick-up point. A representative illustration of a point-to-point network architecture is shown in Figure 9. For comparison purposes, a typical hub and spoke type network that is in use in the airline industry is shown in Figure 10.

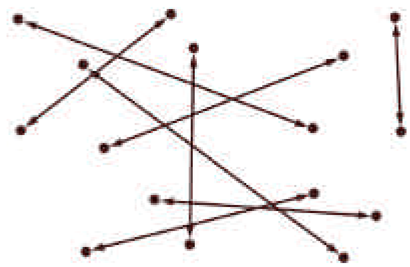


Figure 9 Point to Point Network

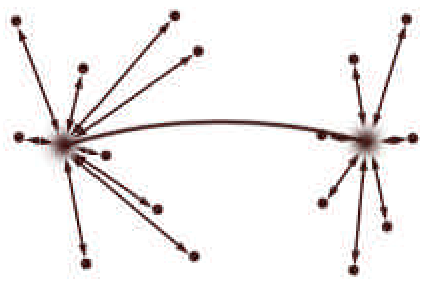


Figure 10 Hub and Spoke Network

2.3.2 Application of Heuristic Algorithm

A vehicle routing problem is essentially a traveling salesman problem, but with many salesmen instead of one. There have been many approaches to the problem over the years, consisting mostly of heuristic solutions. Optimal solutions can be found for small scale problems, but an algorithm that gives an optimized solution for large problems such as 500 nodes or cities still doesn't exist. Therefore, a heuristic that would give a feasible solution was pursued.

The AVSLA system with a point-to-point delivery network makes an unusual case due to the "right-away" delivery of the cargo after pick-up. Two algorithms are used together in this unorthodox approach. The first one uses a modified Clarke-Wright (C-W) type savings heuristic and the second one uses an insertion method. The Clarke-Wright savings heuristic operates by seeking optimal improvements to an existing route structure. In the original C-W heuristic, two routes are joined together where one of the routes finishes to form a new route that is shorter than the combination of the two original paths. For example, the two independent routes shown in the left side of Figure 11 can be connected together as shown on the right.

Figure 11 Merging of Routes as Done under the Clarke-Wright Savings Heuristic

The name for the heuristic comes from the "saving" that is associated with the connection of the two routes (and its two authors, of course [5]). A brief calculation can quantify the savings. The original cost associated with the routes, as measured by the distance traveled is:

$$C = 2c_{0i} + 2c_{j0}$$

where,

C	=	Total cost
c_{xy}	=	Cost associated with going from node x to node y. (Node 0 is the depot)

Now, instead the cost of the new route is only:

$$C = c_{0i} + c_{ij} + c_{j0}$$

so that a saving of ($c_{0i} + c_{0j} - c_{ij}$) has been achieved. It is assumed the cost of traveling from node x to node y is the same as traveling from node y to node x. Every possible feasible combination then is taken into account, placing one route where the other one ends, and the savings ranked from high to low. The highest saving is then implemented, the associated routes taken out of consideration, and the new highest ranking saving is implemented.

The second heuristic employed, the modified insertion heuristic, works in a similar fashion. However, instead of examining the savings associated with attaching each route to the end of another, the modified heuristic examines the savings associated with inserting a route anywhere along another route. Insertion heuristics are infrequently used in operations research because they rarely make sense. (Routes are almost always connected at the end of one and other, because of greater savings.) However, the direct pickup-to-delivery scheme of the envisioned AVSLA network architecture makes the insertion heuristic useful. For the network simulation, each customer is assigned one route. The insertion heuristic is run and the feasible solution with the highest savings is implemented. Then, any node in the new route is taken out of consideration for placement in another route. In other words, for an improved route, only new unimproved routes can be inserted, since the highest savings for those nodes already have been achieved.

Subsequently, savings are calculated again with the new options available for the rest of the nodes, and any savings linked to the nodes in the new route are removed. An illustration of the insertion heuristic is shown in Figure 12. Notice that now the savings associated with inserting node k into the route can take a different value depending on where in the route node k is placed. The associated savings with inserting node k into the route has the following savings for the respective placements of beginning, middle, and end:

$$C = c_{0k} + c_{0i} - c_{ik} \qquad k \text{ before } i$$

$$C = 2c_{0k} + c_{ij} - c_{ik} - c_{kj} \qquad k \text{ between } i \text{ and } j$$

$$C = c_{0k} + c_{0j} - c_{jk} \qquad k \text{ after } j$$

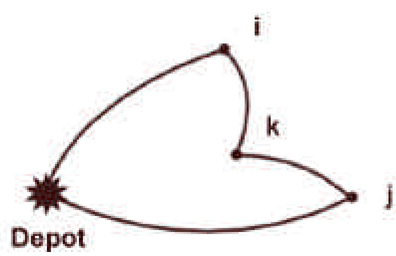


Figure 12 Insertion of New Route

2.3.3 Inputs and Outputs of the Network Simulation

There are seven primary inputs into the network simulation algorithm. It is immediately seen that each can potentially have a dramatic impact on the overall economic viability of AVLSA. These variables are listed below, with a short description following each one:

- Range: The range of the VTOL vehicle in statute miles.
- Service Radius: The radius of the circular area that the AVSLA network will allow customers to make requests.

- Customers: The number of customers serviced for one full simulation of the network. This also determines the number of pick-up and delivery points.
- Time Constraint: The time constraint determines the amount of time the network has available in order to complete all orders. It can also be considered to represent the maximum flight hours per day, or for how long the AVSLA network will be operational.
- Speed: This is the speed at which the VTOL vehicle cruises.
- Time Penalty: Used in the program as the take-off and landing penalty, this penalty is added to the time a vehicle takes to complete a route each time it makes a landing except for the depot.
- Refueling: Each time a vehicle returns to the depot and is ready to depart for a new route, this penalty is added to the total time a vehicle travels.

The outputs from the computer program are given below:

- Number of Vehicles: This is the number of vehicles needed in order to complete the delivery for all the customers within the given time constraint.
- Miles Traveled: This is the total number of nautical miles all the routes sum up to.

2.3.4 Program Explanation

Below, a step-by-step description of how the program works is given. Some of the detail has been withdrawn, but the main points have been explained:

Initialization

In this section, pick-up and delivery nodes are placed on the map. The number of customers specified equals the number of each type of node. These nodes are chosen randomly and both the pick-up and the delivery nodes are placed on the map if they both satisfy two requirements. First, either point has to fall within the service area that is determined by the service radius variable. Second, the distance from the depot to the pick-up node to the delivery node and finally to the depot must be less than the distance determined by the range variable. Note that the paths from each pick-up node to its delivery node have to be made, no matter what the solution is. Now, a route is assigned to each pick-up and delivery pair, so that the initial number of routes equals the number of customers. Notice that this is both the easiest and the worst of all feasible solutions.

One can make the line of reasoning that the nodes placed on the map should not be random, but rather representative of the socioeconomic map that the network is taken place. For example if the Atlanta region is being considered, the VTOL traffic involving the close city of Macon should probably be larger than a smaller suburb. However, when the nodes are placed randomly on the map, the worst case scenario for the selected region is being considered. *Hence, the random placement of the nodes makes the solution a conservative one, which can be considered as a safety buffer.*

Initial Savings Algorithm

Possible savings that can be made by inserting any other node in front of each node are calculated and placed into an array. This savings array usually has an approximate length of the square of the number of customers. So, the program is offered a million different options for a 1000 customer problem. Infeasible solutions are filtered out of the savings matrix and so the size of this huge matrix is reduced.

Insertion Algorithm

The savings matrix is used and the insertion algorithm is applied to determine the better savings options available. If an option is selected, the matrix is recalculated just for the possible new options, and the savings related to the node that was added to the path are taken out of consideration. The Insertion algorithm continues to loop until the last feasible singleton has been added to a path.

Final Path Addition

The insertion algorithm doesn't take into account the possibility of adding two tours together as only single nodes are considered a possibility. The final path section creates a new savings matrix, this time for adding two paths together if possible. The best combinations are added together to create more "efficient" paths. The previous paths are removed and the new longer routes are added to the list of existing paths.

Bin-packing

A first-fit bin-packing heuristic is employed to determine the number of vehicles needed in order to complete all of the routes within the certain time limit. The speed of the VTOL plays a role in this part, as the quicker it is, the faster it is able to finish the routes. The penalty for each take-off and landing, and the time it takes to refuel also plays a role.

Presentation of Results

In this section, all of the final paths are drawn on a single map that was created in the initialization step, and the output is parsed. This portion of the program also has some minor function calls and a "wrapper" to run all the different DOE cases. These small files have been included in Appendix B together with the main program.

2.3.5 Use of Regression Equations for Efficient Link to System Dynamics Model

For the results from the network simulation to be used, the system dynamics model and the network simulation had to be linked together *efficiently*. Since primarily only two outputs from the simulation were of interest, it was determined that the variation of these two outputs with changes in network design parameters could be captured through response surface equations (RSEs). The response surface methodology (RSM) is a multivariate regression technique used to model the response of a complex system using simplified equations. In the present study, the initial equation takes the form of the quadratic equation below from;

$$R = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^{\ 2} + \sum_{i=1}^{k-1} \sum_{j=i-1}^{k} b_{ij} x_i x_j$$

where

b_0	=	Intercept
x_i	=	Variables most important to variability/response of system
bi	=	Regression coefficients for linear terms
b_{ii}	=	Regression coefficients for quadratic terms
b_{ij}	=	Regressions coefficients for interaction terms

A regression, of course, needs data. For this purpose, the RSM contains the design of experiments (DoE) technique. A DoE is the setup of the experiments, or runs of computer code, so that the necessary number of experiments required for the generation of reasonable equations will be minimized. The experiments can be explained as designs analyzed at certain settings of the factors (variables) to determine a response. For the network simulation model, the particular DoE chosen was a Central Composite Design with seven variables and five outputs (3 of them were for statistical use.) resulting in 79 total runs needed. The ranges of the network simulation inputs that were used for the DoE are listed in Table 4.

		Bounds	
Name	Units	Lower	Upper
Range	miles	350	550
Service Radius	miles	100	250
No. Customers	--	400	1000
Time Constraint	minutes	430	600
Speed	knots	115	200
Time Penalty	minutes	10	20
Refueling Time	minutes	15	30

Table 4 Ranges for Variables

Running all the cases took a little over two days on a PC with a Pentium III 866 Mhz CPU and 256 Mb ram. Each case required between 7 and 80 minutes depending on the number of customers. This fact indicates the advantage of using comparatively simple response surface equations (RSEs) in the system dynamics model instead of more complicated real-time simulation runs that could take over an hour to finish! The collected data was fed into JMP, a commercial software package, to be analyzed and regressed.

The initial RSEs created, however, failed to give satisfactory statistical results, indicative of an insufficient amount of data in the DoE to produce an acceptable fit. More specifically, this poor fit was indicated by a low R^2 value. The R^2 value is a simple measure that determines how good the constructed model actual fits the data points. An R^2 value of 1 implies a perfect fit. Typically, R^2 values of greater than 0.95 are desirable. To address the problem, 21 more runs were included in the DoE and the data was reanalyzed. Once more, the RSEs created were not satisfactory so the complexity of the regression equation was increased yet again. Instead of a quadratic, a cubic polynomial was used. Finally, the R^2 values improved, and the equations that best explained the behavior of the system were constructed. These improved results are displayed graphically in Figure 13 and Figure 14, where the actual data points are plotted against their corresponding RSE prediction. A perfect R^2 value would result in all points lying on the diagonal line.

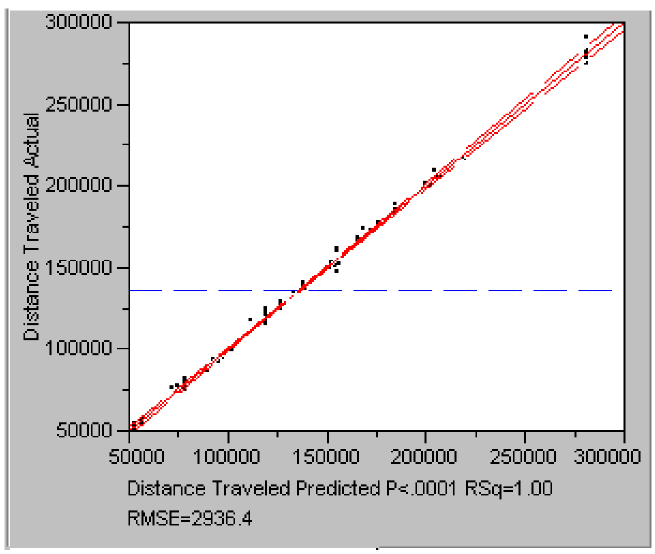


Figure 13 Comparison of Actual Data to RSE Predicted Response for Distance Traveled

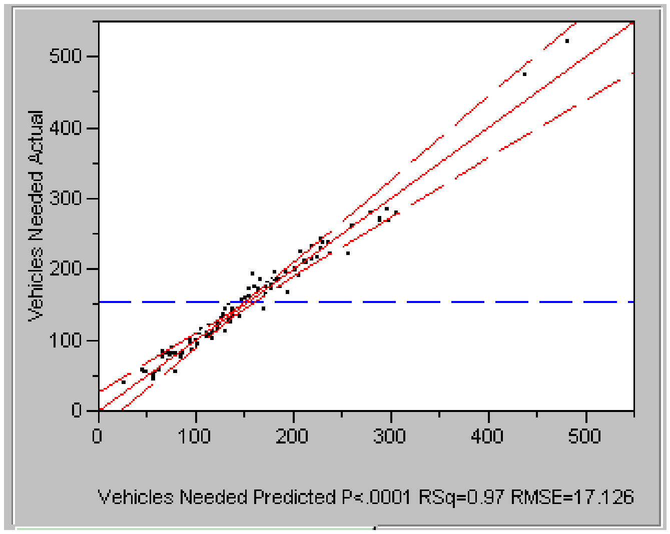


Figure 14 Comparison of Actual Data to RSE Predicted Response for # Vehicles Needed

Now that each of the modules within the system dynamics model has been described, the model can be exercised to explore the sensitivity of key parameters that will determine the ultimate merits of an AVSLA concept.

2.4 Parameter Sensitivity and Monte Carlo Simulation

A clear need exists to be able to explore different AVSLA scenarios with a sensitivity study, especially in light of the fact the 20-30 year time horizon for AVSLA implies significant uncertainty as to future conditions. There are many variables in the model whose values are difficult to assign accurately. Such variables include the number of customers, the fuel price, and the insurance to be paid for the vehicles, etc. Other variables, such as the price charged for package delivery, are interesting to vary for study purposes although one could determine their value in advance. By changing the values to these variables or constants, a sensitivity analysis is performed. *The sensitivity of key AVSLA objectives, such as profit, to the variety of design parameters is the most important result from the system dynamics model. These results also serve as a guide to the establishment of requirements from the component system design (such as the VTOL vehicle and the air traffic management concept).*

Monte Carlo simulation (also known as Multivariate Sensitivity Simulation) is a well-known approach to performing these sensitivity tests automatically. Vensim© employs Latin Hypercube sampling to do this, allowing faster testing on larger models or computers with low simulation speeds. Monte Carlo simulations were run on the system dynamics model in Vensim© under different situations.

2.4.1 Interactive Point Design Study

Before running the Monte Carlo simulations, however, some of the values on the dials in the control module (see Figure 4) were varied in interactive sessions. These sessions revealed that costs were minimized, and profits maximized for these network settings:

Range	=	550 nautical miles
Service Radius	=	100 nautical miles
Customers	=	1000
Time Constraint	=	600 minutes
Speed	=	200 knots
Time Penalty	=	10 minutes

Factors that reduced the **cost** the most were ones that **reduced the number of vehicles**. However, the number of vehicles needed was directly related to how fast one could get the job done. Theoretically, if one did not have a time constraint, one would only need one vehicle as one could do all the tasks serially. Of course, this is not realistic from a service industry point of view! Hence, the time constraint had a large impact on the number of vehicles and the 10 hour time limit was set. The speed of the vehicle was also very important, and the velocity of 200 knots turned out to be a very sought-after performance characteristic. The time penalty for take-offs and landings also affected the number of vehicles needed, and the minimization of the time spent on the ground should be a secondary, but still important goal. The range of the vehicle was chosen to be 550 nautical miles, the maximum, to obtain the best results. This makes sense as the shorter the range of the vehicle, the less customers it would be able to serve during one flight (and a higher unnecessary distance traveled would accumulate). These longer distances would then cause the number of vehicles to rise in order for the deliveries to be made within the time constraint.

The indication for a reduced service radius (100 nautical miles) *and* the maximum number of customers cannot be accepted so easily, however. Clearly, the costs do go down as that the distance flown from one place to another is reduced and the number of vehicles needed decreases. Nonetheless, it is somewhat questionable to assume that a smaller service radius can hold the same number of customers as an area that is quadruple the size. Only a market survey could determine the possibility of a large number of customers. This will be discussed further in later sections.

2.4.2 Sensitivity Study

The values determined in the above point design study were then fixed as constant values, except for the service radius and the number of customers, for the sensitivity study. For a sensitivity study, the parameters to be varied are given probability distributions corresponding to their expected variation. For this study, normal, triangular, and uniform distributions were selected. A list of the distributions and some example values that were given are summarized in Table 5. Note that these values were not always kept the same and were varied from scenario to scenario.

Variable	**Distribution Type**	**min**	**peak**	**max**	
Fuel Cost	Triangular	0.5	0.7	0.9	
Insurance percentage	Triangular	0.005	0.01	0.015	
Class I charge	Triangular	30	40	50	
Class II charge	Triangular	60	80	100	
Class III charge	Triangular	90	110	140	
Class IV charge	Triangular	132	145	170	
Variable	**Distribution Type**	**min**	**max**	**mean**	**Stand. Dev.**
Packages per customer	Normal	1	5	3	0.2
Variable	**Distribution Type**	**min**	**max**		
Veh. Needed nationally	Uniform	600	1000		

Table 5 Sensitivity Study Variables and their Assigned Probability Distributions

"Vehicles needed nationally" is a different variable than "vehicles needed". The former is taken into account when calculating the price of each vehicle, and it is the total amount of vehicles that will be produced, while "vehicles needed" is the number that will be used in the modeled service area. Of course, a larger production lot nationally will give a lower per vehicle unit price. Data associated with charges for each parcel were derived from the UPS price offers shown in Table 6. It was decided that the minimum value should be what UPS charges for its next day delivery.

UPS Next Day Air Prices
* Rates for Customers Who Receive a Daily UPS Pickup

Weight	Zone 102 Price	Zone 103 Price	Zone 104 Price	Average Price
Letter	12.25	13.50	14.25	13.33
1	14.50	16.50	19.50	16.83
5	18.75	20.75	28.75	22.75
10	22.50	26.25	39.50	29.42
15	26.50	32.00	49.50	36.00
20	30.25	36.00	57.00	41.08
25	34.00	40.50	64.75	46.42
30	38.25	44.25	73.00	51.83
35	42.50	49.50	81.50	57.83
40	46.25	53.75	89.50	63.17
45	50.50	58.50	84.75	64.58
50	55.00	64.25	93.00	70.75
55	60.00	71.25	101.50	77.58
60	65.50	78.25	109.75	84.50
65	72.00	86.50	118.00	92.17
70	78.75	94.75	127.50	100.33
75	85.50	103.00	137.25	108.58
80	92.75	112.25	147.75	117.58
85	100.00	121.25	159.50	126.92
90	106.25	131.00	172.00	136.42
95	113.00	139.25	183.75	145.33
100	119.25	147.25	194.75	153.75

Table 6 UPS Next-Day Air Prices for Different Distance Zones

The most interesting Monte Carlo simulations are presented next. In Figure 15, the sensitivity graph shows the fluctuation of profit/loss over time with all the inputs (including the network settings that were fixed) having distributions around their baseline values. The bands of color define confidence intervals. For example, the narrowest band (light green) is only a 50% confidence. As time progresses, the uncertainty compounds and the bands widen, indicative of the fact that longer term prediction is always harder to do well. The profit is in millions of FY2001 US dollars.

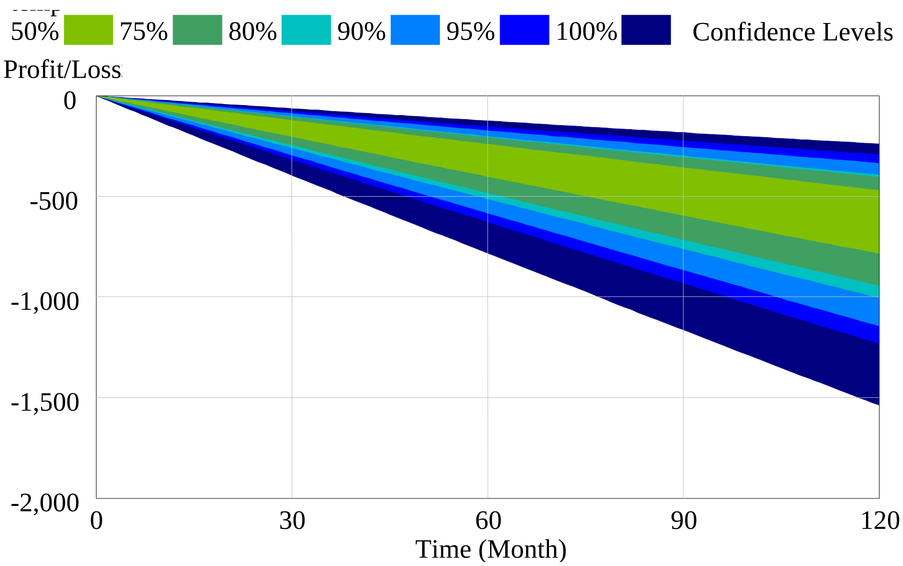


Figure 15 Profit/Loss Variation for Initial AVSLA Simulation

The number of vehicles needed to operate this initial system remains constant over time, though the precise number of vehicles needed lies within confidence bands as well as shown in Figure 16.

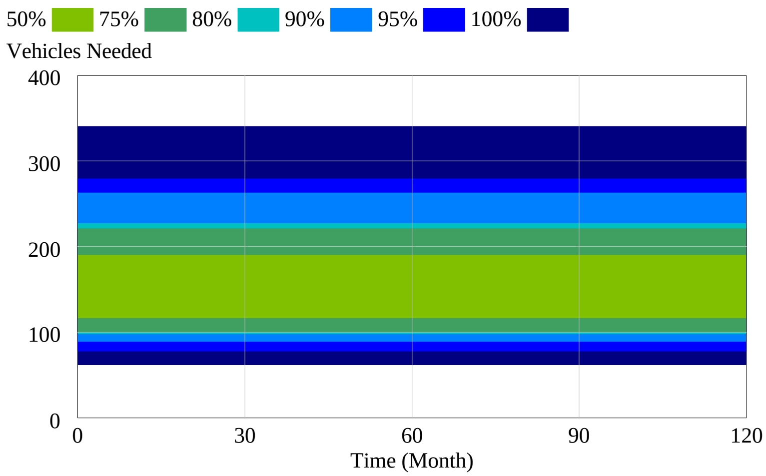


Figure 16 Number of Vehicles Needed for Initial AVSLA Simulation

Is there any path to profitability? There is if all of the parameters in Table 5 are fixed at "optimistic" values. In this case, AVSLA looks much more promising as shown in Figure 17. Note also the reduction in the width of the confidence bands due to the elimination of significant uncertainty.

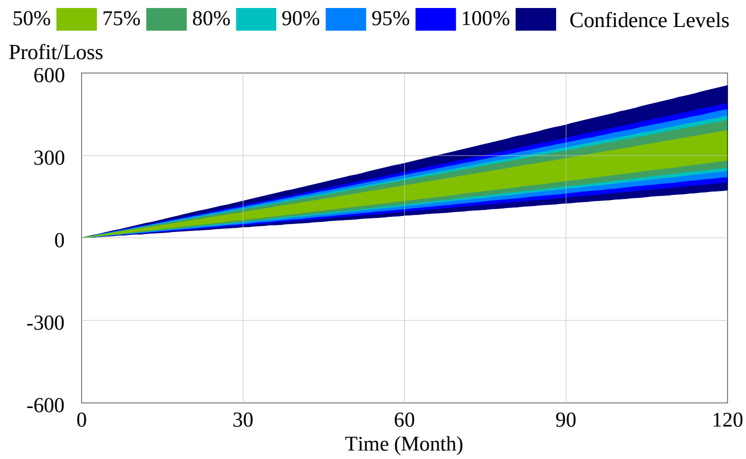


Figure 17 Modified Profit/Loss Variation with Fixed, "Optimistic" Network Parameters

The previous discussion indicates that a more detailed investigation into the nature of the driving parameters on overall AVSLA performance is needed. In other words, within our "AVSLA Space", we have some profitable alternative concepts and some not profitable. Thus, further explorations have been conducted.

One of the most interesting results involves the number of packages that each customer orders. In order to make the system feasible for any kind of operation (with the exception of the VTOL vehicles being ridiculously cheap!), profitability is enhanced when each customer ships more than one package. With one more simulation, one can show the sensitivity to the number of packages.

The large change in the probability of achieving profitability when the number of packages per customer is increased is illustrated in Figure 18. The figure is a CDF (Cumulative Density Function) that plots the probability on the Y-axis and the Profit values on the X-axis. It is desired to minimize the probability of profit values less than zero (equivalently maximize the probability of profit greater than zero). The figure shows that for an increase in 1 package per customer in the probability distribution's mean value, the probability of making a profit increases by about 80 percent! Whereas there was essentially no chance of making a profit with one package, with two packages there's approximately 95 percent chance of making between 40 and 80 million USD. This is due to the drastic improvement in efficiency of the system in gaining revenue at little to no cost (a vehicle is already going to be flown to that location.).

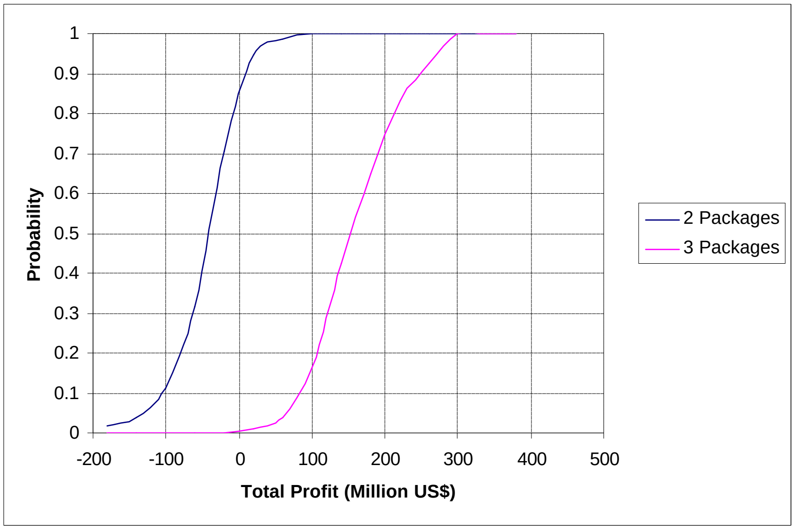


Figure 18 CDF Depicting Change in Probability of Making a Profit

Returning to the issue of the service radius, again it may be unreasonable to have many customers in a relatively small 100 mile radius. Therefore, a more realistic radius of 200 nautical miles was modeled next to serve a larger area and a sensitivity study to number of customers was conducted. This is important since, in our Southeast model, a circle with a 100 mile radius with the center in Atlanta covers mainly Macon and Chattanooga. However, a circle with a 200 mile radius covers almost the entire state of Georgia, 2/3 of Alabama, 2/3 of Tennessee, and 1/3 of South Carolina, making it more of a regional system. An interesting result of the system comes to light. Although it is more profitable to have 1000 customers in a 100 mile radius, as the radius is extended to 200 nautical miles it becomes more profitable to reduce the number of vehicles (and thus customers!). This is illustrated in the CDF sensitivity results shown in Figure 19. The probability of making a profit increases as one cuts down the number of customers from 1000 to 600, but then drops back again as one passes a certain number of customers down to 400. There is an inflection point. This may also be indicative of the fact that as the delivery distance grows, a hub and spoke topology becomes more viable than a point-to-point.

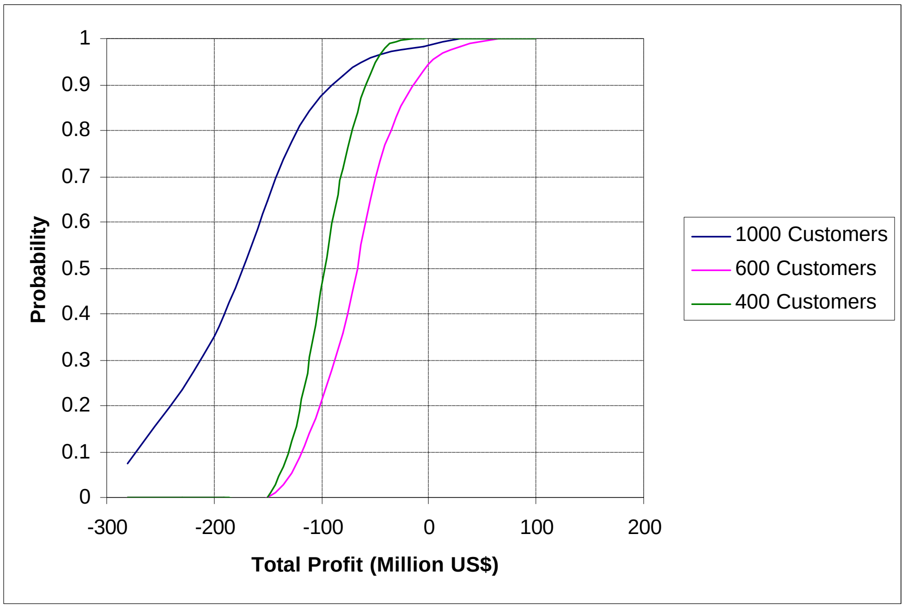


Figure 19 Profit CDF Sensitivity to Number of Customers for 200 nautical miles Delivery Radius

Perhaps this result is not so intuitive at first, since more customers should generate more profit. The reason for the presence of the inflection point in profit with respect to number of customers is the product of a combination of variables. When the time constraint we have chosen (10 hours) is combined with the service radius (200 nautical miles) and the assumption of 1000 customers in the simulation, the number of vehicles needed increases significantly. Alternately, as the number of vehicles needed is reduced by decreasing the number of customers, revenue drops. After a certain point, revenue decreases more than the costs decrease, and this is the saddle point for the profit calculations for these settings. The number of customers that seemed to give the best profit was approximately 600 customers. However, notice on the graph that even with 600 customers, the chance of generating positive net income was roughly 5%! The decrease in number of vehicles needed can be seen in Figure 20.

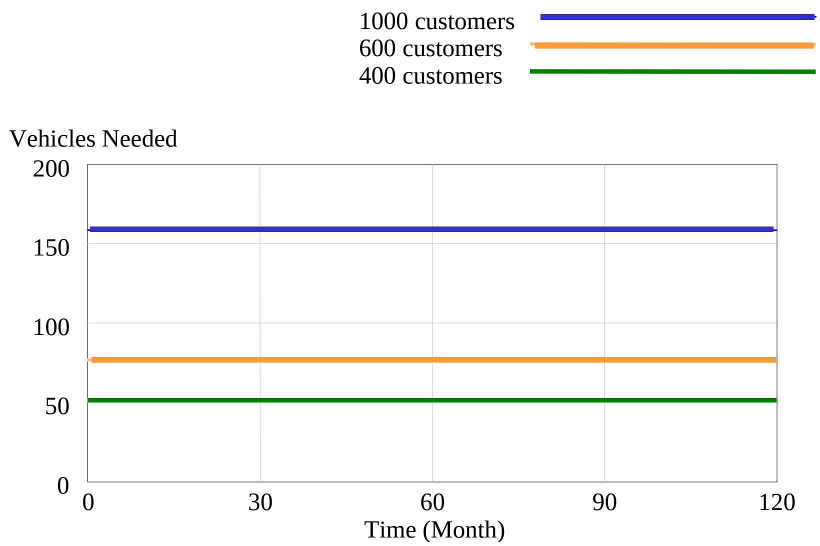


Figure 20 Reduction of Vehicles Needed Given a Reduction in Customer Base

In Figure 21, a Monte Carlo simulation with an increase in the mean of the number of packages per customer is illustrated. Note how probability of making a profit increases as the number of packages per customer is increased from a mean of 3.5 to 4. With four packages per customer, the chance of making profit increases from about 55 percent to 95 percent. Again, is it unreasonable to assume 4 packages per customer? Perhaps it is not, in such a large area with only 600 customers. One further assumption to note is that in this analysis it is assumed that if "x" number of packages are picked up at a node, those same number are dropped at the next node.

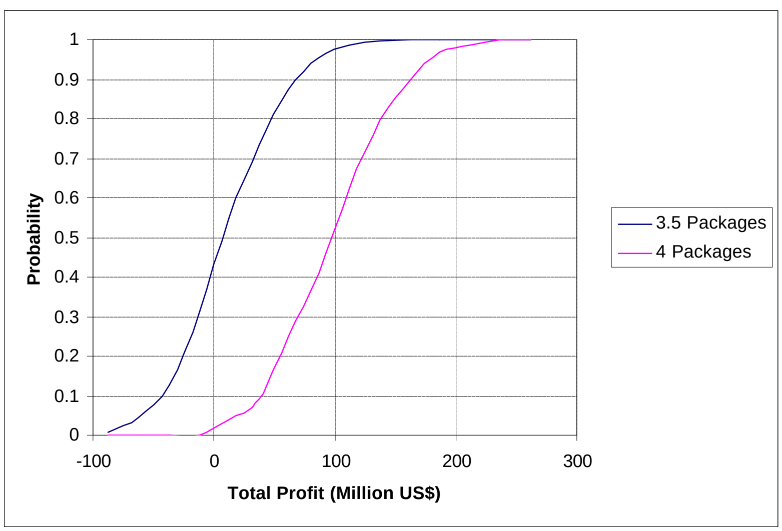


Figure 21 CDF Showing Increase in Profit with Increasing Number of Packages per Customer

Sensitivities to revenue related parameters may also be investigated. For example, the charge per package is critical on both the revenue side and the demand side. A simulation was conducted in which the mean of the probability distribution for the customer charge (see Table 5) was moved positively 10 USD for each package. The results are displayed in Figure 22. The charge increase results in an approximately 30 percent increase in the probability of making a profit.

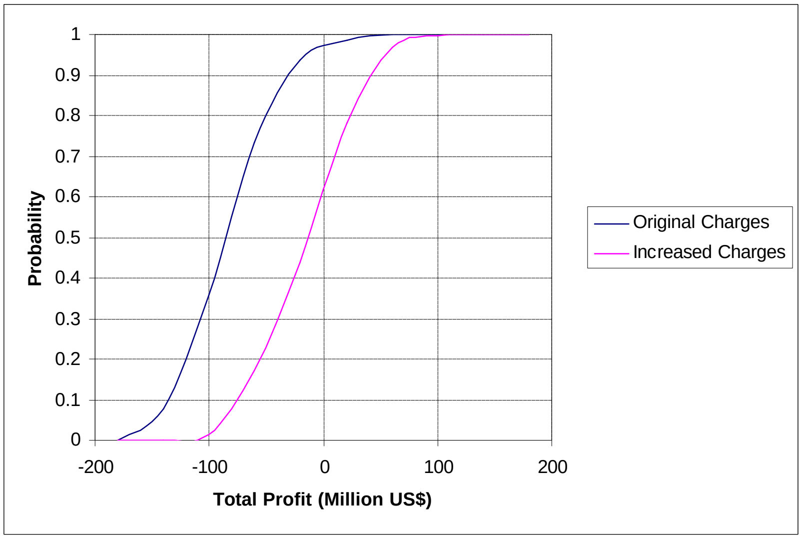


Figure 22 Sensitivity of Profitability CDF due to Increased Shipping Charges

The significance of the sensitivity simulation results reported in this section is two-fold. First, initial insights concerning the optimal settings for important parameters such as number of customers and delivery radius have been obtained. This lends guidance to "where to look next" for continued AVSLA evolution. *Second, and at a higher level, the results illustrate that the team now has the ability to rapidly make these trades through exercise of the system dynamics model.*

2.5 Integration of AVSLA into the National Airspace System

An investigation of the Federal Aviation Administration (FAA) modernization plan for the national airspace system has been carried out. Of the nineteen programs that support the modernization, eight have been identified as being relevant to AVSLA development. Further clarification of these programs and their impact on our proposed system will be focus of this section. The modernization effort is critical to very feasibility of our proposed system, without the components necessary for "free-flight" in place there is no way AVSLA would ever really get off the ground. The earliest year AVSLA could enter the national airspace is 2010, this date is based on the proposed nation-wide availability of "free-flight". However, 2010 is not a realistic entry date for AVSLA since other vehicle-critical technologies probably will not be widely (and cheaply) available by then, 2025 is probably a better estimate for an entry date.

2.5.1 Deployment of Advanced Security Equipment

As part of FAA efforts to counter terrorism and do its part in promoting national security, the FAA is acquiring more Explosives Detection Systems (EDS) and Explosives Trace Detection devices (ETD). In addition to acquisition and deployment, the agency is also examining how to maximize the effectiveness of these systems.

If an autonomous logistics transport system were ever deployed and used on a wide scale by civilians then the operators of the system must be acutely aware of their responsibilities to ensuring the public's safety from the system. The potential for those, both homegrown and foreign, seeking to terrorize the population to tamper with the system and create widespread panic is a possibility that must be proactively combated. Advanced security equipment used on AVSLA agents must be at least as effective as those used by the FAA at airports, in truth the system must be more effective. At an airport, many levels of security can be cascaded with each level checking the results of the others. At a remote pickup location this is certainly not the case, the items being transported may only be checked once or twice before the vehicle is cruising away over a populated area. The security of the system will have to be demonstrated repeatedly before deployment.

These security systems apply more to commercial applications of AVSLA than military ones since the entire point of a military mission may very easily be to transport explosives to front-line troops. That being said there should still be some type of screening system for the military vehicles so that equipment is handled and stowed properly.

2.5.2 Information Systems Security

The FAA recognizes the potential for threats from cyber attacks in the future. To combat this ever-changing threat, the agency is recruiting and training a workforce capable of detecting, preventing, and responding to such attacks. R&D activities will create and deploy tools and tactics to combat future cyber attacks. AVSLA will be primarily reliant on information sent to it from outside parties (ground control, NAS systems, customers, etc.) to make decisions. Extensive safeguards will be required to combat tampering by an unknown party with bad intentions. For our commercial vehicle we need the same (if not better) level of protection as the FAA from cyber attacks.

2.5.3 GPS Implementation

To enable a more accurate and flexible navigation system, the FAA is investing capital to promote the space-based Global Positioning System (GPS) to a level where it can meet required availability, accuracy and integrity goals. Ultimately, an integrated global system capable of being the primary means for en- route navigation is what is sought. The complete, integrated system will be composed of three main components, the Wide Area Augmentation System (WAAS)[3], the Local Area Augmentation System (LAAS)[4], and a 2nd GPS[5] signal intended for civil aviation.

Metric	Requirement	Current Status
Availability (%)	99.9	98
Accuracy (m)	< 3	~100
Integrity (sec)	<10	>900

Table 7. FAA Goals For GPS

The WAAS will improve basic GPS accuracy to approximately 7 meters vertically and horizontally, improve system availability through the use of geostationary communication satellites (GEOs) carrying navigation payloads, and provide important integrity information about the entire GPS constellation. The WAAS is based on a network of approximately 25 ground reference stations that covers a very large service area. Signals from GPS satellites are received by wide area ground reference stations (WRS). Each of these precisely surveyed reference stations will receive GPS signals and determine if any errors exist. These WRS are linked to form the U.S. WAAS network.

The LAAS is intended to complement the WAAS and function together to supply users of the U.S. NAS with seamless satellite based navigation for all phases of flight. In practical terms, this means that at locations where the WAAS is unable to meet existing navigation and landing requirements (such as availability), the LAAS will be used to fulfill those requirements.

The 2nd GPS signal is meant to promote accuracy, availability, and reliability of the GPS for domestic and worldwide flight as a component of the worldwide Global Navigation Satellite System (GNSS) WAAS. To enable the attainment of this goal, the frequency spectrum requirements for a second civil aviation system signal will be drafted. Additionally, the signal will be tested and proven to not interfere with other signals. Finally, the signal will be universally adopted; other countries will have to reserve the frequency for only the civil aviation signal.

AVSLA will most deal with WAAS and the GPS signal, LAAS is an augmentation system local to airports. The navigation signals that AVSLA receives will need to be corrected for their intrinsic error. The

[3] http://gps.faa.gov/Programs/WAAS/waas.htm
[4] http://gps.faa.gov/Programs/LAAS/laas.htm
[5] http://204.108.10.33/strategic/achp01/SP-Suppl-01.html

corrections to the WAAS coordinates can be made using second signals from reference ground controllers (analogous to present "differential GPS" systems) or by onboard sensors that make corrections based on visual cues like roadways, street signs, large buildings, or other objects with positions that are known a priori.

2.5.4 Air Transportation Oversight (ATOS)

The FAA is developing a new safety and risk management protocol aimed at reducing fatal accidents involving operators of aerial goods transport systems by a factor of 5. The new protocol will apply to FAR 121 carriers and will require OEI capability. The required certifications for AVSLA remain unclear; there is no UAV protocol as of yet because there have not been enough feasible commercial applications for UAVs to warrant developing certification procedures.

The FAA has addressed this issue though and the bottom-line is that the agency will address UAV certification when a commercial application becomes apparent. It is believed that they will be open to dialogue and the AVSLA community may want to take advantage of that so that we have a voice in the early stages of drafting the protocols.

Safety is a primary design driver for a commercial AVSLA; OEI, and auto-rotative capability, use of parachutes, and encasement of dynamic components will be rigorously examined along with other, as yet unstated, safety features. Public perception of these vehicles must be extremely positive in order for them to have any chance of success.

2.5.5 Free Flight

Free flight is a system being developed that will allow the operators of aircraft to choose their own routes. This will dramatically impact the whole airspace as pilots will now have greater freedom to avoid bad weather and fly the shortest routes. Free flight is being "officially" deployed in two (really three, Phase Two has a two parts) phases. The goal of Phase One is to develop, deploy, and evaluate a core set of 5 operational capabilities.

	Component	Acronym	Entry	Relevant to AVSLA?
	Surface Movement Advisor	SMA	In Service	NO
En Route	User Request Evaluation Tool	URET	FY02	YES
	Collaborative Decision-Making	CDM	FY01	YES
	Traffic Management Advisor	TMA	In service	NO
	passive Final Approach Spacing Tool	pFAST	FY01	NO

Table 8. Free Flight Components

The Phase Two activities will focus on the geographic expansion of Phase One components and capability throughout the NAS. At the end of the first part of Phase Two, the national airspace should be ready for nation-wide free flight. The second part of Phase Two will be an ongoing activity aimed at upgrading components, enhancing capabilities, and inserting new technologies as they become available. Phase One will conclude in 2003, Phase Two part one in 2008, and the rest of Phase Two will be active indefinitely.

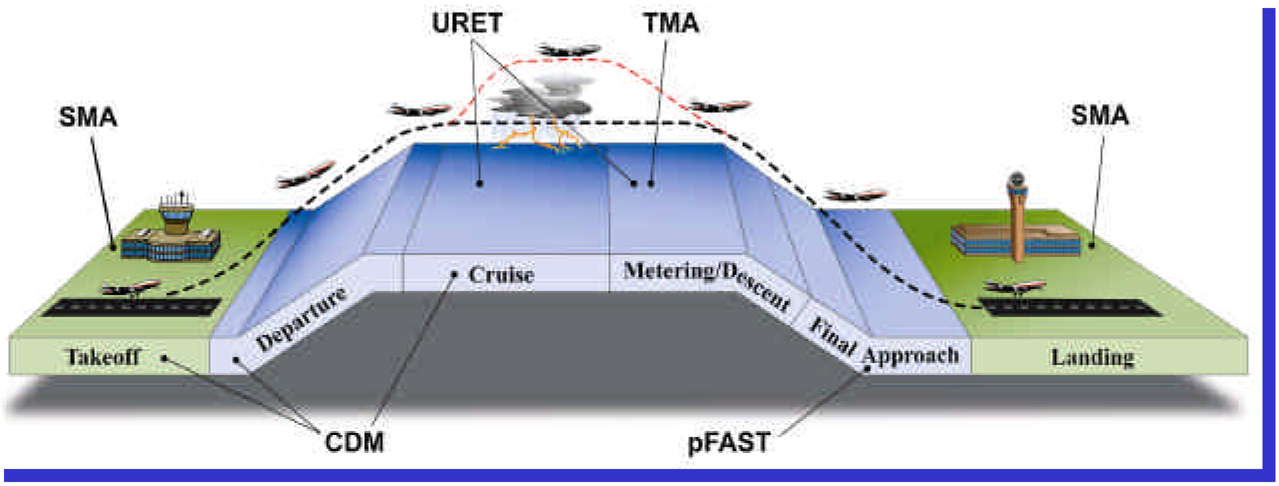


Figure 23. Free Flight Components In Action

Free Flight is a critical capability of the NAS in terms of enabling AVSLA deployment nation-wide. The components that would be most relevant to our system are CDM, URET, and TMA. Since AVSLA does not exclusively operate from airports, we are most interested in integration with traffic that is already en route. By automating certain parts of the air traffic environment, the FAA is also enabling an increased load to be effectively handled by the NAS. The Phase One proposal for this NIAC study suggested perhaps more than 180,000 AVSLA agents in the NAS at any one time as a maximum capacity. If air traffic control operators had to individually interface with each of these vehicles, in addition to the burden created by manned aircraft, then widespread usage of AVSLA would be infeasible.

2.5.6 National Airspace Redesign

National Airspace Redesign is an activity focused on a systems analysis approach to intelligently designing and evaluating the modernization of the nation's airspace system. This project includes the development of a comprehensive vision and a strategic management of assets to both efficiently and effectively bring the NAS into the 21st century. This eight year effort will utilize state-of-the-art computer airspace modeling and environmental analysis to check new routes in a timely manner. The teams charged with performing the review, analysis, and ultimate redesign of the airspace will interface with users of the airspace and members of the affected communities to ensure cooperation between all parties by giving everyone a voice.

2.5.7 Improved Weather Information

The FAA already works closely with the National Weather Service (NWS) to provide the most accurate and timely forecasts possible, the activities of this effort will be a continuation of this partnership. For users in the terminal area, the products developed will offer improved forecasts, detection, and reporting of low level wind shear, thunderstorms, icing, ceiling and visibility, winds, micro-bursts, gust fronts, and precipitation types. En route, the users of the system will be able to access data regarding turbulence, icing, thunderstorms, ceilings and cloud tops, and widespread low visibility. This set of projects will improve the detection, forecasting, processing and delivery of aviation weather to operators through the implementation of four key programs.

	Component	Acronym	Entry	Relevant to AVSLA?
Near Airport	Low Level Windshear Alert System	LLWAS	FY03?	NO
	Weather System Processor	WSP	FY03	NO
En Route	Integrated Terminal Weather System	ITWS	FY07	YES
	Weather and Radar Processor	WARP	FY03	YES

Table 9. Improved Weather Information Components

The AVSLA system would have to be robust enough to operate effectively when dealing with daily variations in weather. The advanced weather systems being developed for the NAS will transmit precise data in real-time to the vehicles that are loading the airspace. Weather data obviously has a huge influence on the routing and scheduling of pick-ups and deliveries. The FAA's deployment of precision sensing equipment and making the information available to all users of the airspace is an important enabler for AVSLA.

2.5.8 Capacity Improvements

The FAA has set a goal of increasing the capacity of the air transportation system by 20% within the next ten years. This translates into a net increase of 17.5 million additional operations per year over the current 87.5 million per year (240,000 per day). The proposed capacity for 2010 is over 290,000 operations each day. If we assume a more modest growth after 2010, perhaps 5% every 5 years, then by 2025 the NAS will be handling 336,000 operations each day. The Phase One report proposed having between 50,000 and 185,000 vehicles operating each day[6]. At the low end (in 2025) the extra burden of the AVSLA system is

[6] These numbers were based on averaged trucking statistics, NIAC Phase 1 Report

15% of total operations and at the high end it is 55%. At first pass this seems like a significant burden on the airspace but this may be deceiving. Since our vehicles would only be using certain parts of the NAS and flying at much lower altitudes and probably not going exceptionally far, AVLSA may not burden the NAS too much after all. A more definitive conclusion can only be drawn after this evolution of the NAS has concluded and a clearer picture of the post-2010 future can be seen.

2.6 Federal Aviation Administration Considerations

2.6.1 Understanding the Airspace Geometry

Geometry of airspace allocation is dominated by Class B airspace structure. These airspace fixtures are like upside-down wedding cakes sitting over major airport facilities such as Hartsfield International Airport in Atlanta, Georgia. In some instances the structure is influenced by noise and in some instances they are influenced by uncontrolled urban growth around the facility that was there first. There are instances of VTOL fly-through corridors in the existing Class B airspace structures. Washington D. C. is a good example; there is a low-level VFR helicopter ingress and egress corridor under the control of the Washington National/Regan tower. Specific routes along the interstate highway system and the over the Potomac River provides a low-level route used frequently by helicopters.

IFR vs. VFR is an issue but it can be dealt with by postulating that the UAV route system will operate continuously under IFR precedence. The rationale for this is based upon the premise that by adhering to one procedure for all weather conditions the overall procedure will be less complex than a procedure incorporating rules for both IFR and VFR. Also, by adhering to a single set of rules, the ATC workload will not fluctuate based upon visibility and ceiling variables.

2.6.2 Communication and Navigation Links

New levels of reliability for on-board technology will become a requirement. ADSB will be one of the primary systems technologies because of its ability to depict targets behind urban terrain obstacles as well as self-broadcast position to any listening ADSB system within 90 nautical mile radius. Further discussion of the reliability factors is found in the internal vehicle factors section that follows. Equipage-level will be a major issue for the UAV fleet. Once the functional requirements are agreed upon the certification criteria will be developed and every vehicle in class will have to be equipped to the level that achieves compatibility with the standards.

Security has become a major concern due to recent events. The major technical question that must be addressed is the functional concept of the control system for the UAV fleet. If the control is from the ground there will be a serious vulnerability issue related to the security of data link. Anti-jam and secure data link technology exists but its never been placed in the operating mode of a controlling station for a fleet of UAV systems in an urban environment. In the urban environment there will issues of sensitivity of the control system to extraneous RF influence. If the control system is autonomous the method by which the control system can be compromised is a different issue in that the interdiction by a potential terrorist will come from a different threat scenario. That scenario is based on personal access to the ground control and maintenance activity and is a different problem set than the electronic interference issue.

2.6.3 Air Traffic Management Requirements

Separation of aircraft in-flight is the foundation of the in-flight ATC problem. Therefore if the new UAV fleet possessed the characteristic to self separate the ATC issue would be less severe. A primary concern in today's system is the routing of aircraft due to Class B restrictions and the environmental issue of noise. Also the security aspects of flying aircraft over major populated areas is now a major concern.

A potential contentious issue with ATC for the UAV systems is the notion of responsiveness of the vehicle to ATC direction. In other words the controller wants to see the aircraft respond to his guidance in an expeditious manner. If the control system for the UAV fleet is autonomous therein lies a technical challenge as to how the ATC controller could interact with the vehicle and the vehicle be responsive to the guidance from an external source. Research into this issue could potentially identify modes of implementation that would satisfactorily meet ATC expectations as well as meet requirements for the integrity of the control system of the UAV.

2.6.4 FAA Impact on Vehicle Design

The receiver and antenna weight for a credible system in the today's technology will be approximately 4 lbs. This will include wiring and other small items that will be in the kit for the GPS system. Power consumption will vary based upon TSO implementation but the average power consumption for the various systems is around 10 watts. The capital cost for a functional system is difficult to forecast due to unknowns with regard to the level of sophistication of the communication protocols that will have to be implemented especially if there is a ground associate technology in over-watch mode. To purchase a functional system that would consist of a ground station and with a receiver and terrain database and multiple aircraft systems with data link the following is a good first order estimate:

Ground station:	$15, 000
Air Items:	$5, 000 each
Install:	$9, 000 per aircraft
Total:	$29, 000

The primary mission of ATC infrastructure is to make controlled airspace safe. In this endeavor, separation of aircraft in flight –maintained with minimum separation criteria—is the primary functional goal of ATC. Therefore if any form of influence from ATC on a notional UAV network is to be anticipated, it should be focused in the willingness of ATC to separate the UAV traffic under the most limiting criteria of separation. This is where the performance of the vehicle must be carefully considered; cruising speed, turning rate, descent/ascent rates, acceleration/deceleration and others. Perhaps the most important consideration is the potential conflict between a commercial passenger aircraft in Class B airspace and a prospective wayward UAV. The UAV must be designed to ensure this scenario is extremely unlikely.

The question that needs exploration is the unknown ramifications of multiple UAV's operating in a relatively confined airspace. One or two aircraft would not present a problem. However, 3 or more aircraft may present a problem in terms of flight path conflict. With appropriate and timely information as to each aircraft position a ground or cockpit associate could sort out the appropriate trajectory correction (which includes time!) necessary to deconflict the airspace dedicated to the UAV's.

However, there is a more difficult problem that must be addressed. It is well known from HELLI-Star, and other experiences, that equipage level is very important for low-altitude air traffic management. Accordingly, the aircraft that are equipped with ADS-B equipment will self report their position as per the established norm for the local operational area. It is important to note that the latency of the data link is sensitive to the number of aircraft that are on the network. Therefore it is critical to understand where the saturation point is for the future UAV network that will be dedicated to tracking and navigation requirements.

2.6.5 Security Issues

By establishing self-separation standards, the potential hazard of collision with other UAVs can be minimized. Also, by utilizing ADS-B operating protocol, where position is broadcast to everyone in the operating environment, conflict resolution algorithms can be applied to de-conflict potential collisions. The problem really is the unknown target that is not equipped for ADSB operational protocol and therefore is unavailable for the conflict resolution program. The current airspace categorization is good example of the type of issue that is imbedded in the problem of collision avoidance. Class B airspace requirements specify equipage level for respective users of Class B airspace such as: UHF, VHF radios (one each), encoding/radar altimeter, transponder etc.

The only fail-safe measure to insure that ATC and UAV controllers are aware of offending traffic is to provide surveillance radar that has coverage to the appropriate sectors and geometric configuration of airspace of interest. Bird strikes are a hazard to all aircraft. However there are means to frighten potential interfering birds away from the route using acoustic or RF energy. These measures do bring up tangential issues that are just as serious as the bird strike would be by itself. These issues are demonstrated in the experience that NASA and DOE had with the windmill farms in California. Many of the windmill sites had to be taken out service due to the number of birds that were killed by the rotating windmill. This example also involves the problem of noise. Local residents complained about the low frequency noise that was propagating from the windmill sites to their neighborhoods. Once again sites were taken out of service because of the offending noise. Noise is a very important evaluation criterion for choosing the UAV configuration.

As a result of the events of Sep 11, '01, we have a vivid example of how lethal a fully fueled aircraft can be when put into the hands of terrorists. The true threat of a terror scenario can not be fully described here however there are some descriptions worthy of consideration. Guiding a UAV to a specific target would require compromise of the control system of the UAV. If the vehicle has full autonomous control on-board, this scenario would be extremely difficult for a potential terrorist to accomplish. Nevertheless by seizing the opportunity to compromise the control before the UAV took off, the would-be terrorist could potentially accomplish the objective. By emphasis on the ground handling and maintenance of the vehicle the potential for a terrorist act to be accomplished by tampering with an autonomous self-contained control system becomes highly improbable. Maintaining a vigilant oversight of ground operation, such a threat can be minimized.

Engine failure mode issues for commercial aircraft invoke the argument of one vs. two engines. The old adage that states, "two engines are better than one," is not a rigorous remedy to the concern about a total power failure. Fuel contamination can strike a twin or triple engine aircraft just as easily as a single engine aircraft. By taking away the fuel contamination issue, the two vs. one issue is pretty much straightforward. The probability that both engines would experience failure at the same time is highly improbable though not impossible. This is where the UAV proponency argument may have to invoke the notion that the UAV should not be forced to meet higher levels of reliability than the manned aircraft counter parts. However there are some special considerations having to do with how many aircraft, how frequently are they operating in proximity to inhabited sites that will have to be dealt with in the process.

Other failure modes that must be dealt with are just as important and yet not quite as recognizable as the power failure mode. Airframe integrity will be a major concern given the fact that these aircraft will be operating outside the normal load factors associated with manned aircraft. Fatigue will be a major concern in light of the operating loads and frequency of loads associated with the operating scenario. Avionics and control system sensitivity to electromagnetic interference will also be a concern, given the fact that in urban areas these aircraft could be operating close to power transmitting towers and large power sub-stations. There are known techniques by which the system can be hardened against these threats. New criteria for this issue will have to be developed and standardized for certification purposes.

The underlying issue from the FAA perspective is,“ how can the aircraft be safely and expeditiously landed if there is major system failure?” In this sense, the FAA is looking for back-up systems or redundancy that satisfies the six “9’s” (six sigma) criteria of reliability. With this in mind, designers can provide robust systems that can address this overall concern. The difficult nature of this challenge is to be able to meet these levels of reliability while meeting cost effectiveness goals in overall system design to cost and weight constraints.

2.6.6 Incorporation of FAA Considerations into System Dynamics Model

Several options exist for incorporating the FAA restrictions and regulations into a system dynamics model of the AVSLA system. The first and most desirable possibility is that of free flight. Unfortunately, this scenario is purely futuristic because no present implementation of purely free flight exists. However, it permits a very streamlined analysis of the delivery system as it would be unaffected by air traffic control commands and airspace violations.

Another option is to model current airspace restrictions, especially in the Class B airspace, and incorporate these areas as 'obstacles' where AVSLA vehicles may not enter. Such a construction demands vehicles to evade the obstacle and go around it, incurring in a time and fuel penalty in so doing. This is the most restrictive approach and is used to model the present day conditions where Class B is essentially impenetrable for UAV systems.

By mapping the airspace in several regions, including the Atlanta Metropolitan area and the entire Southeast region, the locations and sizes of prohibited airspace are determined. Then, a percentage of the total volume of available airspace is calculated as unusable by the vehicles. Given enough vehicles traveling throughout the given airspace (either local or regional), the percentage of airspace unusable affects an equal percentage of vehicles assuming an even distribution of flights inside the service area. Then each affected flight is penalized due to the presence of an airspace restriction. This penalty comes in the form of a time penalty; the time it takes the vehicle to circumnavigate the obstacle and return to its original course.

These restricted airspaces have been studied for the Southeast region, but can be extrapolated to other areas and serves as a good first estimate of how much airspace is currently prohibited to AVSLA vehicles.

The incorporation of fly-through corridors allows some time reward and serves as an intermediate stage between present-day conditions and future free-flight scenarios. The general situation still follows current airspace regulations with the added benefit of making certain areas accessible quicker to the delivery fleet.

3 Design of AVSLA Delivery Vehicles

The design of the AVSLA UAV began with an information search to determine what types of vertical takeoff and landing (VTOL) vehicle configurations are currently being tested or in use. Once an understanding of what is possible was gained, an effort was made to document the basic functions that a VTOL UAV had to perform. This functional decomposition focused solely on the most general activities that the UAV had to perform to fly; electronic and decision-making capabilities were omitted from this very preliminary study and will be examined in the second half of Phase 2.

A morphological matrix [15] was used to identify and document different ways that an air vehicle could perform the functions necessary for operation. After identifying some potential candidates, the Pugh Concept Selection Method [14] was applied to perform a qualitative assessment of the different candidate vehicles to evaluate the ability of each type to satisfy a set of evaluation criteria. The evaluation criteria included economic, performance, and public considerations. A tailsitter configuration was chosen using this qualitative assessment.

Feasibility criteria were then developed to define the bounds on what constituted a feasible design. A baseline tailsitter was sized using the Georgia Tech ASDL Rotorcraft Sizing Program (GTASRP), which was coded during this study to enable the sizing of a variety of VTOL concepts. Since the baseline tailsitter failed to satisfy the feasibility criteria, the design space was explored using a response surface method. This was done to find the proper mix of settings that either enabled the vehicle to meet the constraints or at least provided a better baseline that was closer to the feasible region. Since the re-sized vehicle still failed to meet feasibility criteria, a technology search was performed to identify potential technologies that could improve the cost and performance of the UAV. The focus of the search was on advancements in propulsion and material technologies.

Technology factors, or "k-factors [15]," were calculated to map the impacts (both positive and negative) of the different technologies onto the outputs from GTARSP. Again, a design space exploration was performed and modeled using a response surface method. The response surfaces were then used to perform an evaluation of all the possible technology combinations with the goal of selecting those technologies that showed the most promise, i.e. a technology sensitivity study. The Technique for Order Preference based on Similarity to an Ideal Solution (TOPSIS) [15] was applied to facilitate the technology selection. With a group of technologies selected, it was then possible to put together a potential roadmap for the development of the vehicles.

3.1 Configuration Selection

A morphological matrix (MM) was developed to identify different vehicle configurations. The MM is a tool that maintains structure during the brainstorming in the early stages of conceptual design. The row headings of the matrix represent different system functions that come from a functional decomposition of the system; the system in this case was a rotary wing vehicle. Through brainstorming, different ways to perform those functions that constitute the vehicle system are identified. Each unique combination of ways to perform the different system functions represents a concept. The concepts identified using the MM were a single main rotor (SMR) helicopter, a coaxial helicopter, compounded versions of the two, a tailsitter, and a tiltrotor. Table 10 shows candidate vehicle concepts that resulted from investigating the different possibilities identified by the MM.

	SINGLE MAIN ROTOR	TILTROTOR	TAIL SITTER	COAXIAL	COAXIAL (COMPOUND)	SINGLE MAIN ROTOR (COMPOUND)
	A	B	C	D	E	F
Inflow - Forward Flight	EDGEWISE	AXIAL	AXIAL	EDGEWISE	EDGEWISE	EDGEWISE
Inflow - Hover	AXIAL	AXIAL	AXIAL	AXIAL	AXIAL	AXIAL
Primary Lift Device	SINGLE-ROTOR	WING	WING	MULTI-ROTOR	MULTI-ROTOR	SINGLE-ROTOR
Primary Propulsion	SINGLE-ROTOR	MULTI-ROTOR	MULTI-ROTOR	MULTI-ROTOR	MULTI-ROTOR	SINGLE-ROTOR
Auxilliary Lift Device	NONE	NONE	NONE	NONE	WING	WING
Auxilliiary Propulsion Device	NONE	NONE	NONE	NONE	PROP	PROP
Engine Type	PISTON	TSHAFT	T-SHAFT	PISTON	T-SHAFT	T-SHAFT

Table 10 Table of Candidate Vehicles

After identifying different concepts, a subjective evaluation of each was performed using Pugh's Concept Selection Method. This method enables a qualitative evaluation of concepts relative to some baseline in a number of categories. Generally, these categories come from a quality function deployment (QFD), although in this case the categories were selected based on engineering judgment (Table 11).

Evaluations between the candidate concepts and a datum concept, which may come from the initial candidate pool, are made with respect to the different categories using a qualitative "P," "N," or "S." These letters stand for "positive," "negative," and "same as." The positive and negative represent that the concept is better than or worse than the datum, respectively. For this evaluation, the datum concept was a single main rotor helicopter UAV.

		A	B	C	D	E	F
Econ.	Fuel Efficiency	DATUM	N	N	S	N	N
	Number of Dynamic Components		N	N	N	N	P
Perf.	Cruise Efficiency		P	P	N	P	P
	Hover Efficiency		N	N	P	P	N
Public Concern	Safety (Can Rotor Be Shrouded?)		P	P	P	P	S
	Vehicle Compactness		P	P	P	P	S
	Noise Levels		N	P	S	N	S
	Σ (-)		**4**	**3**	**2**	**3**	**2**
	Σ (=)		**0**	**0**	**2**	**0**	**3**
	Σ (+)		**3**	**4**	**3**	**4**	**2**

Table 11 Pugh Concept Selection Matrix

In making the evaluations between different concepts and the datum, a decision matrix was used. This simple tool was useful for making rational evaluations based on the way that the candidate vehicle performed the functions identified from the functional decomposition of the MM. The colored boxes identify a relationship between a function and an evaluation criterion. In making the comparisons, the letter of the better concept was entered in the colored square. If the concepts were viewed as being basically the same, the box was left blank. Table 12 provides an example.

	F	E	Fuel Efficiency	Number of Dynamic Components	Cruise Efficiency	Hover Efficiency	Safety (Can Rotor Be Shrouded?)	Vehicle Compactness	Noise Levels
Inflow - Forward Flight	EDGEWISE	EDGEWISE							
Inflow - Hover	AXIAL	AXIAL							
Primary Lift Device	SINGLE-ROTOR	MULTI-ROTOR				E			
Primary Propulsion	SINGLE-ROTOR	MULTI-ROTOR		F	F		E	E	
Auxilliary Lift Device	WING	WING							
Auxilliiary Propulsion Device	PROP	PROP							
Engine Type	T-SHAFT	T-SHAFT							

Table 12 Decision Matrix

Table 12 shows the tailsitter and compound coax with the highest scores. The helicopter configuration is superior for hovering flight but is ill suited for forward flight. Helicopters often must carry a large amount of fuel resulting from the fact that they are inefficient forward flight machines, especially at higher speeds. This adversely affects the helicopter's performance in the areas of the response metrics, gross weight and fuel weight. The tailsitter flies like a fixed wing aircraft in cruise, and rotates its body ninety degrees to give it vertical takeoff and landing (VTOL) capability. The noise advantage of the tailsitter configuration resulted in its choice over the coax.

The tailsitter configuration was the best configuration based on cost, performance, and public considerations. Public considerations have not yet been mentioned but clearly they must be addressed for any civilian system, especially an autonomous one. It was felt that the vehicle must be compact, quiet, and have as few exposed rotating parts as possible in order to minimize the public's wariness. The capability to shroud the rotor allows for progress to be made in these three areas and this was weighted heavily in the evaluations.

For the purposes of modeling in GTARSP, some assumptions needed to be made about the vehicle. The vehicle employs a tri-rotor system. The first rotor is a shrouded, three-bladed, gimballed, coaxial rotor. This rotor produces 50% of the thrust generated by the vehicle. There is no net torque generated by this rotor system. The other two rotors evenly split the remaining 50% of thrust required and they are not coaxial. These are three-bladed, gimballed, single-disc systems. These rotors spin in opposite senses; this is done to ensure that there is no net torque produced by the rotors on the vehicle.

A benefit from the tri-rotor system is that the individual rotor systems are small enough to be shrouded. This addresses safety and noise concerns and also creates a performance benefit. Depending on the amount of average lift produced by the disc, the rotor can operate with only 83% of the power required for an open rotor system [7]. There is also the potential to produce lift with the shrouds/ducts in forward flight thus either reducing the required size of the wing or enabling greater payloads to be put on board.

The tailsitter configuration is not a new concept, the first VTOL flight by a tailsitter was performed by the Convair XFY-1. Numerous takeoffs and landings were completed by test pilot James F. Coleman, however there were many deficiencies in the stability of the platform. The XFY-1, and also Lockheed's XFV-1, had very high disc loading because they were propeller aircraft. A high disc loading (37 lb./ft^2 on each propeller, 75 lb./ft^2 over the propeller pair) degrades handling qualities at low speeds. Additionally, a high vehicle power loading (0.49 hp/lb.) is required as the disc loading increases. This is evidenced by the Pogo (XFY-1), a 15,000lb aircraft, which required 5,850 shaft horsepower for VTOL operation[7]. This concept was regarded as dangerous by many, including Kelly Johnson[8]; the reason being that the pilot had a

[7] http://www.nasm.edu/nasm/aero/aircraft/convair_pogo.htm
[8] http://www.airspacemag.com/asm/Web/Site/QT/X13Hover.html

very difficult time landing in VTOL mode. Clearly there were many issues that needed to be addressed but the concept was proven to be possible.

The initial baseline tailsitter being proposed addresses some of the problems encountered by the test vehicles of the fifties. The tri-rotor tailsitter has significantly lower disc loading (a proposed 15 lb./ft^2 on each rotor vs. 37 lb./ft^2 for the propeller disk) this implies a lower vehicle power loading, both factors result in more favorable performance characteristics near the ground. The tri-rotor is a hybrid vehicle, drawing elements from both fixed and rotary winged aircraft. This leads to an important distinction between it, a rotary winged vehicle in VTOL operation, and the test vehicles of the fifties, which were strictly propeller driven vehicles. Propellers are not rotors, they can only produce thrust (only 1 DOF – pitch). Rotors on the other hand, have three degrees of freedom, pitch, flap, and in-plane oscillation. A tailsitter that utilizes rotors, or prop-rotors more accurately, will be much more controllable and by extension, safer. Rotors provide not only thrust, but also control moments and lift (in the case of a helicopter). Also, since there is no pilot, the issue of disorientation after transition between flight modes does not play a role.

3.2 Definition and Analysis of Feasible Design Space for the Chosen Vehicle Type

As mentioned earlier, the main focus of the vehicle conceptual design work was to determine the best way to meet feasibility criteria. In order to be feasible, the design must address several characteristics and capabilities, these and the method by they are addressed are summarized in Table 13.

Feasibility Constraint	Target	Vehicle Impact
Cost Efficiency		
Up-front cost	minimize	Minimize Installed Power
Recurring cost	minimize	Minimize Fuel Weight
Noise	minimize	Rotor Shroud
Safe Customer Interface		
Controllablity	maximize	Use Rotors, Low Disk Loading
Rotating Parts	minimum exposure	Shroud
Foreign Object Damage	minimize	Low Disk Loading
Security from Tampering in Operation	maximize	High Level of Autonomy
Compactness	12 X 10 X 8 ft (a driveway)	Minimize Gross Weight

Table 13 AVSLA Vehicle Feasibility

The Life Cycle Cost (LCC) of the vehicle is a combination of RDTE, acquisition cost, operating cost, and retirement cost. The RDTE cost can be minimized through the extensive use of modeling and simulation in an inter-disciplinary environment and through the intelligent leveraging of off the shelf technology. Operating costs (recurring costs) are generally divided into direct and indirect operating costs. Direct operating costs are largely composed of the salaries of employees, fuel costs, etc. Indirect operating costs are dependent on insurance rates, time spent in repair facilities, etc. For this conceptual design study, the only recurring cost that was addressed was the fuel cost (a direct operating cost), the threshold for this quantity was 100 lb. of fuel. 100 pounds (14.92 gal.) of JP-4 at roughly 1.50 $/gal. (FY2001), the cost (~ $23.00) is roughly 30% of the value of a full load of the cheapest item identified from the market analysis (industrial machinery) and 11% of the most expensive item (precision equipment), and 20% on average. Acquisition cost (up front cost) is dependent on a number of things but it follows a trend with the installed power; the lower the amount of installed power, the lower the acquisition cost. This was shown by Harris and Scully (NASA Ames) in their paper [8]. A goal of 100 horsepower installed was set for the AVSLA vehicles. This goal is based on an observed rule of thumb for rotorcraft performance. There is roughly a 1:1 relationship between the installed power (in horsepower) and the fuel capacity (in pounds) of a helicopter.

A problem inherent to rotorcraft is establishing safety for the people who are outside the vehicle and must interface with it. This issue can be addresses by placing dynamic components (the rotors) high above the people or by shrouding (ducting) these components. Since the vehicle size is also a constraint, shrouds are the best way to improve safety. Shrouds can also be used to improve the efficiency of thrust generation, acting as a duct, and control the noise of the rapidly spinning components. Another safety related issue is foreign object damage to the surroundings caused by loose rocks, gravel, etc that is kicked up by the rotor downwash. This type of damage can be mitigated through the reduction of the disk loading, a direct result of a lower disk loading is a slower, less energetic downwash. In exploring the feasible design space, the disk loading was limited to an upper bound of 15 pounds per square foot.

A high level of security must be guaranteed in any commercial system utilizing UAVs. If a party with ill intentions had the ability to control the AVSLA agents, these vehicles would be highly effective flying bombs. With the low speed agility and payload capacity that these vehicles are designed to possess, it is not outside the realm of possibility that the vehicle could be precisely flown to a strategic location and the payload be detonated (a really smart bomb). At the vehicle level, effective deterrents to tampering are bomb detection devices, borrowed from airports, and the incorporation of a high level of autonomy into the vehicles. More things can be done at both the system and vehicle level, these will need to be addressed in later investigations.

The final feasibility criterion that was addressed was the issue of vehicle size. In order to be able to operate in confined areas, the vehicle size is limited to fit in a box that is 12 feet wide, 10 feet long, and 10 feet high. Since the sizing tool being used to evaluate the vehicles is basic, the size constraints were translated into a gross weight constraint. Based on data collected in a survey (Figure 24) of existing UAVs [9], a gross weight of 500 pounds will probably put the vehicle within the ballpark of the size constraint. There was a clear trend evident for wingspan and fuselage length with respect to the gross weight in the group of UAVs surveyed.

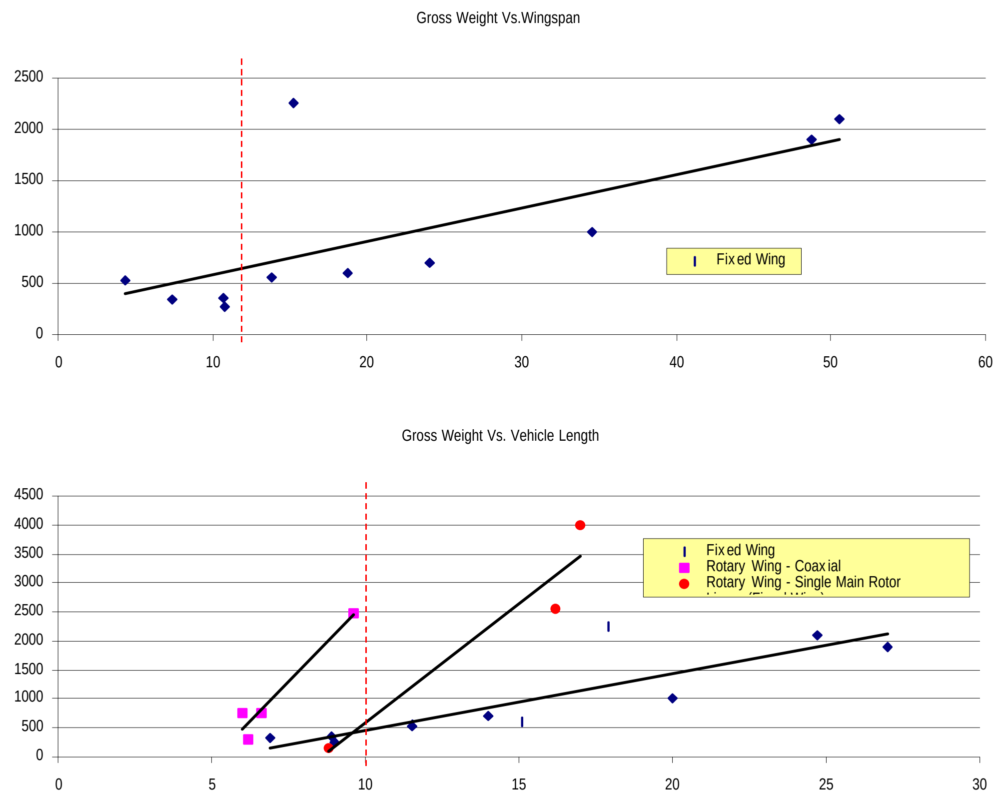


Figure 24 Size Vs. Weight Trends

In summary, the feasibility criteria for the vehicle are listed in Table 14. The gross weight, fuel weight and installed power were the primary characteristics of interest in the design space exploration of the tailsitter.

Criterion		Variable	Target/Limit	Units	Direction of Improvement
Cost Efficiency					
	Up-front Cost	Installed Power	100	hp	decrease
	Recurring Cost	Fuel Weight	100	lb	decrease
Noise		Tip Mach No.	0.75	N/A	decrease
		Shroud	N/A	N/A	N/A
Safe Customer Interface					
	Vehicle Control	Disk Loading	15	lb/sqft	decrease
	Rotating Parts	Shroud	N/A	N/A	N/A
	Foreign Object Damage	Shroud	15	lb/sqft	decrease
Security in Operation		N/A	N/A	N/A	increase
Compactness		Gross Weight	500	lb	decrease

Table 14 Feasibility Criteria

A Georgia Tech sizing code, GTARSP, was used to size the vehicles for this study. All vehicles were required to carry a 100 lb. payload 500 miles. GTARSP was modified to provide a sizing capability for modeling the tailsitter. Extensive changes were made to the rotor sizing routine, mission performance module, and parametric weight estimation. Also, a mission was developed that was based on the Atlanta area as well as the payload and range requirements that were previously identified in the economic analysis. A baseline vehicle was sized to see if it would be possible to meet all the stated goals with current technology. As it turned out, it was impossible to meet the goals with the baseline vehicle. Table 15 depicts relevant vehicle parameters for the AVSLA tailsitter, a SMR helicopter and a coaxial helicopter. The other configurations had to be sized in order to ensure that the calculations for the tailistter were reasonable. The SMR and coaxial helicopters were based on the Northrop Firescout and Sikorsky Mariner, there was sufficient data available to size both of these vehicles and they represent the current state of the art in VTOL UAVs.

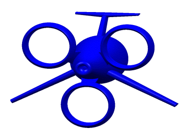
	Baseline	AVSLA variant	
Gross Weight:	2549	2342	
Mission Fuel Weight:	809	774	
Weight Empty:	1446	1348	
Installed Power:	400	428	
Gross Weight:	2449	2396	
Mission Fuel Weight:	563	808	
Weight Empty:	1498	1367	
Installed Power:	613	594	
Gross Weight:	2134	2134	
Mission Fuel Weight:	329	329	
Weight Empty:	1597	1597	
Installed Power:	318	318	

Table 15 Comparison of Sized UAVs

An investigation was conducted to see if it would be possible to meet the previously stated gross weight, power, and fuel weight target values without infusing technology but rather changing different vehicle parameters. Seven parameters were varied within specified ranges, these were: disc loading, rotor solidity, rotor angular velocity, the number of blades per rotor system, the twist in the blades, the wing aspect ratio, and finally the number of engines (Table 16). A face-centered central composite design was used to create the necessary combinations of variables that would allow for an adequate exploration of the design space. A total of 143 different combinations were sized to define the design space. A routine was added to GTARSP to automate this process.

		Bounds	
Name	Units	Lower	Upper
Range	stat. Miles	350	550
Service Radius	stat. Miles	100	259
No. Customers	--	400	1000
Time Constraint	minutes	430	600
Speed	miles per hour	115	200
Time Penalty	minutes	10	20
Refueling Time	minutes	15	30

Table 16 Variable Ranges for Design Space Exploration

Once all the data was collected, a response surface was regressed. The response was initially assumed to be second order with interactions between the variables. This is why the variables were initially varied over three levels rather than two. As it turned out, the initial assumption was correct, the response surfaces all had an adjusted correlation coefficient value greater than 99%. Additionally, the residuals were checked to ensure there was no apparent pattern to them. A random scattering of residuals suggests that the response surface model that was chosen was indeed appropriate. By making these checks, it was clear that the response surface generated for the tailsitter was appropriate.

After a response surface was computed and verified, a Monte Carlo simulation was used to fully explore the design space to examine whether or not the tailsitter could meet the system requirements without any technology infusion but rather through a manipulation of vehicle parameters. The Monte Carlo results appear in the appendix of this report. Another useful output of the response surface method that was used was the prediction profiler. This matrix shows the sensitivity of the responses with respect to the variables against which they were regressed (Figure 25).

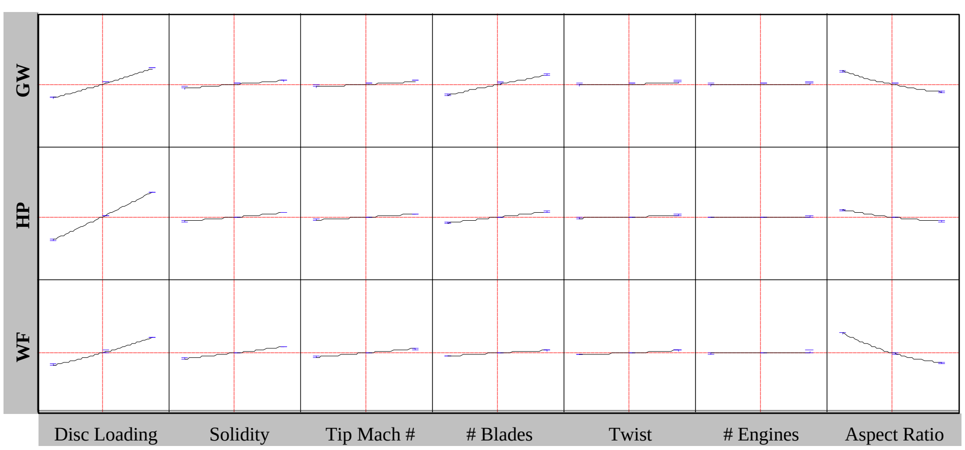


Figure 25 Sensitivity of GW, HPi, and WF to Seven Design Variables

By examining the prediction profiler, it is evident that the smallest vehicle, requiring the least amount of installed power and fuel can be obtained by setting all the variables, except the aspect ratio, at their lowest values. Doing so results in a tailsitter that weighs 1818 pounds, requires 225 horsepower installed, and consumes 233 pounds of fuel. This is a clear improvement over the baseline but the vehicle still falls far short of the targets. It is now clear that new technologies will be required. Also, these new technologies will be applied to the smaller tailsitter and not the baseline one.

3.3 Technology Identification, Evaluation and Selection

3.3.1 Identification of Propulsion Technologies

Advancements in propulsion technology will have a large impact on the three vehicle parameters that are being minimized. To model a propulsion system in GTASRP, three inputs are necessary. The first is the minimum specific fuel consumption (SFC) and the power setting at which this occurs, the second is the mass specific power (MSP) of the engine, and the third is the trend of SFC versus power setting. Of the three different propulsion systems that were modeled, the first two are combustion engines, the third was an electric engine. The efficiency of an electric engine is given by specific energy (SE) which is the amount of energy a battery or fuel cell stores per unit mass. In order to have a common variable, SE was converted to SFC. SFC is a direct measure of efficiency that is used with respect to hydrocarbon fuels.

The use of liquid hydrocarbons as a source of fuel for a fuel cell is currently technically feasible so it was felt that it is not unreasonable to make this conversion. The use of reformed hydrocarbon fuel has already been applied to polymer electrolyte membrane (PEM) cells by researchers working for the automotive industry [10], the future however may lie with direct fuel feed fuel cells that do not require reforming. This is the type of fuel cell that is assumed for this investigation, it is known as a direct methanol PEM fuel cell. Methanol is a good choice for a fuel source since it is 50% oxygen, 32.5% carbon, and 12.5% hydrogen by composition. Using forecasts published by the office of the Secretary of Defense, extrapolations on SFC and MSP for the combustion engines were made to 2025 [11]. Based on the available data (see Figure 26), notional piston and turboshaft engines were hypothesized.

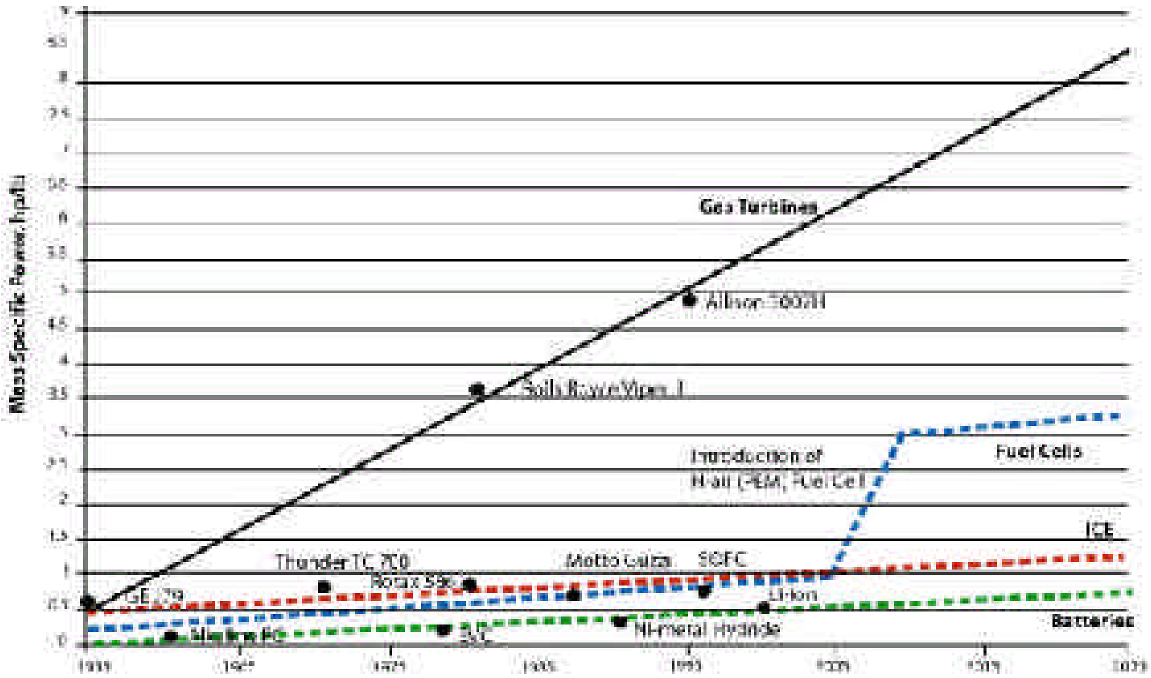


Figure 26 MSP Improvement up to 2025

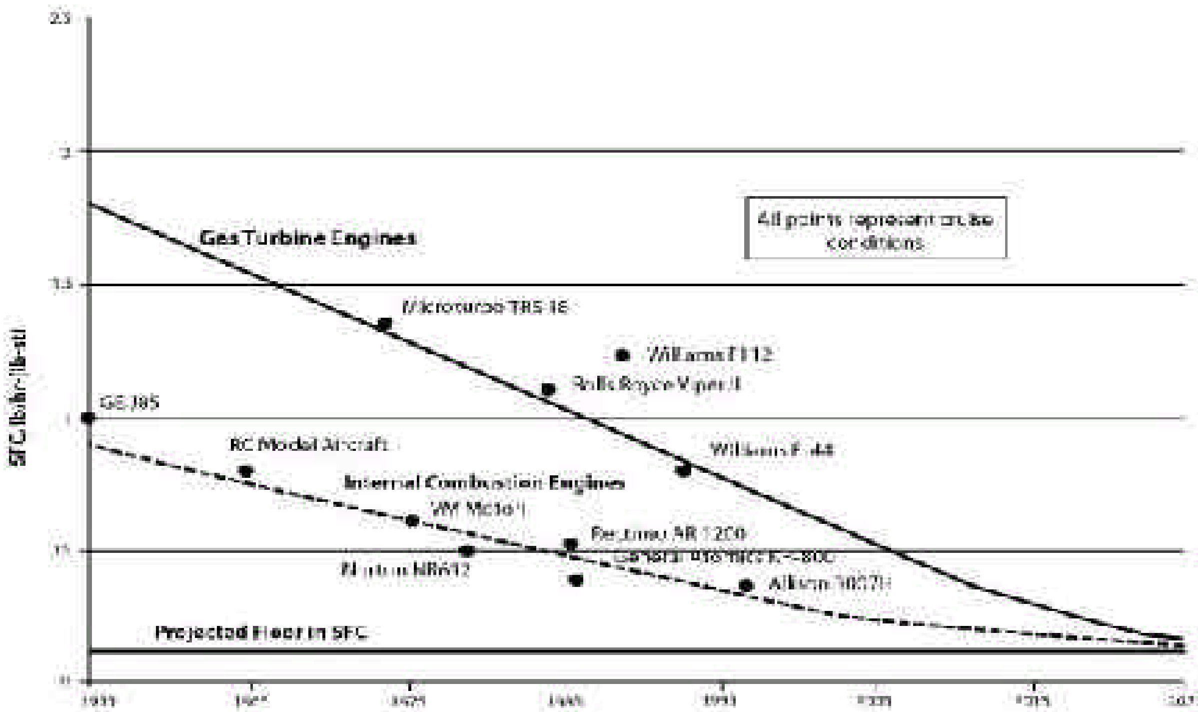


Figure 27 SFC Improvement up to 2025

Although a forecast for fuel cell MSP is presented in these figures, a forecast for an equivalent SFC does not appear. In order to calculate the SFC for the direct methanol fuel cell, data presented by DARPA was converted from the SE to SFC in the following manner. The SE, measured in watts-hr/kg, is converted to hp-hr/lb by multiplying the latter by 0.00134 to convert from watts to electric horsepower (basically equivalent to brake horsepower) and then by 2.204623 to convert from kilograms to pounds. Finally, the reciprocal of the number (in units of hp-hr/lb) is taken to arrive at the SFC value of the cell. The source for the fuel cell data was a DARPA presentation (Figure 28) that was downloaded from the web.

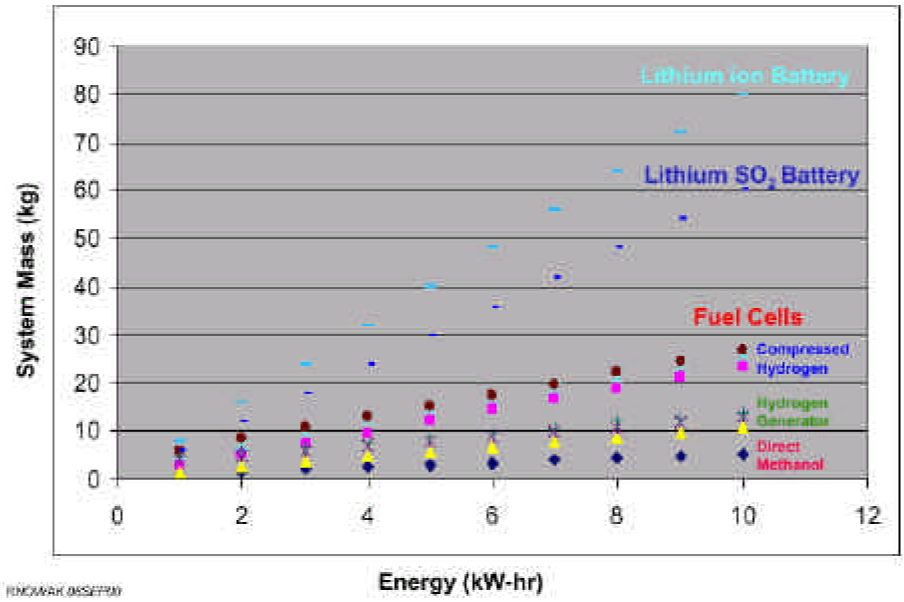


Figure 28 Power to Weight Relationship for Different Electric Power Sources

The data in the figure was tabulated for the direct methanol fuel cell. The type of cell was chosen for the following reasons: a large weight penalty is not incurred with increasing energy production; it has a relatively low operating temperature; it can use hydrocarbon fuel; and it is highly fuel efficient. Upon inspection of Table 17, it can be seen that even the smallest cells have remarkably low fuel consumption values.

FUEL CELL - DIRECT METHANOL

W-hr/kg	hp-hr/lb	"SFC (lb/hp/hr)"
1333	3.939	0.254
1333	3.939	0.254
1600	4.727	0.212
1667	4.924	0.203

Table 17 Tabulated SFC for Direct Methanol Fuel Cell

Being optimistic, the SFC at maximum power was chosen so that the minimum SFC (occurs at ~50% power) would be 0.203 lb/hr/hp. Although this is an optimistic estimate, fuel cells have the potential to make truly dramatic improvements in powerplant efficiency. A case study for an automotive system fuel cell showed that even with current technology, a fuel economy improvement of 14 miles per gallon (mpg) is possible for an SUV (from 20 mpg to 34.4 mpg). The fuel cell studied for that case was a 116 kW pure hydrogen stack [12].

The final characteristic that was addressed was the fuel consumption to power fraction relationship. This is important because SFC is not constant with respect to amount of power being drawn from the engine/fuel cell. The relationships (Figure 29) were used in modeling the three engines [11, 12].

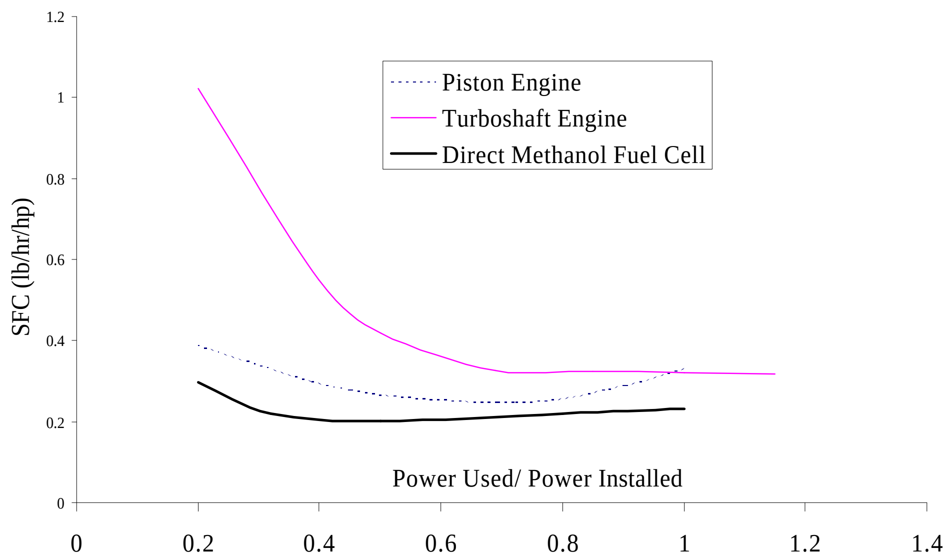


Figure 29 Power Output to System Efficiency Relationships

The characteristics of the hypothesized engines, three current turboshaft engines, and a lithium ion battery have been tabulated for comparison purposes. The battery was considered initially, but ultimately it was not modeled because it was clearly the worst choice in the group (Table 18).

Designation	Type	SFC (lb/hp/hr)	Weight (lb)	Power (hp)	NOTE
RRA 250-C20B	Combustion	0.65	161	420	Eagle Eye
WTS 117	Combustion	0.69	72	125	Guardian
CT63-M-5A	Combustion	0.65	139	317	Hughes 369
Direct Methanol	Electrical	0.203	100	320	Notional -2025
Advanced Piston Engine	Combustion	0.250	100	120	Notional -2025
Lithium-Ion Battery	Electrical	1.991	100	89	Notional -2025
Advanced Turboshaft	Combustion	0.312	100	652	Notional -2025

Table 18 Tabulated Engine Characteristics

3.3.2 Identification of Structural Material Technologies

Three different material types have been identified as potential structural materials for the fuselage and shroud of the AVSLA vehicle. They are in different stages of development currently but all are assumed to be available by 2025. The effects of these materials were applied to the modeling of the vehicle as multiplicative technology factors that were applied to the calculated fuselage and wing weights. A description of each material follows.

Fiber Metal Laminates

Fiber Metal Laminates (FML) [13] were developed at Delft University in the Netherlands during the last two decades as a family of new hybrid materials consisting of bonded thin metal sheets and fiber/adhesive layers. This laminated structure provides the material with very good fatigue, impact and damage tolerance characteristics and a low density. The most commonly used metal for an FML is aluminum; the fiber can be aramid or glass. The FML with glass fibers, called GLARE®, has the best properties for aircraft structures[9]. The bond lines between the layers of metal and prepreg act as barriers against corrosion and the laminate has an inherent high burn-through resistance as well as good damping and insulation properties. While the primary driver behind the development of this family of materials was a 20% weight reduction, it turns out that additional benefits like cost reduction and an improved safety level (superior flame retardation characteristics) make these materials even more attractive for aerospace applications. Airbus has taken the initiative for applying this technology to aerospace products, they will use GLARE as the skin material for the upper fuselage of the A380.

Structurally Amorphous Metals

Bulk Structural Amorphous Metals (SAM)[10] represent a new class of materials. They are produced at low cooling rates. This results in giving them a structure that, unlike conventional metals, is amorphous or "glassy." As a result of this novel microstructure, amorphous alloys exhibit unique combinations of properties, e.g., hardness, strength, damage tolerance and corrosion resistance. The SAM program will develop amorphous alloys that can be synthesized in bulk quantities and at low cooling rates. Furthermore, it will establish models and tools to predict their formation, and discover useful microstructures that are derived from the bulk amorphous state. Efforts will also be made to identify how to exploit their mechanisms of deformation and fracture.

SAMs of interest are those based on iron, aluminum, titanium, magnesium and refractory metals. There is a heavy emphasis on economy and thus the only processes of interest are those that offer the

[9] GLARE will be widely used in the upper fuselage of the A380 resulting in a weight saving of 800 kg (1770 lb.)

[10] http://www.darpa.mil/dso/thrust/md/str_8.htm

potential for economical production of bulk metallic glasses in the form of sheet, wrought products and castings. The SAM development program also intends to demonstrate the compelling advantages of SAM in military systems.

Specific DoD interests include corrosion-resistant, reduced magnetic mass hull materials; moderate temperature, lightweight alloys for aircraft and rocket propulsion; penetrators; and wear resistant machinery components for ground, marine and air vehicles. SAMs' are completely different from FMLs' and their development is also not nearly as far along as FML. The three types of SAMs' being developed (listed in order of most to least) are zirconium based refractory metals, ion based metals, and aluminum based metals. More time is required to investigate this class of materials[11] but the Air Force is actively pursuing this type of material for development, especially for application to UAVs. For the purpose of modeling the effect of this material type on the UAV in GTARSP, a 30 % weight reduction was applied to the structure for which it was intended [13]. The graph shown in Figure 30 shows the relative performance of amorphous aluminum with respect to other materials in terms of stiffness and strength.

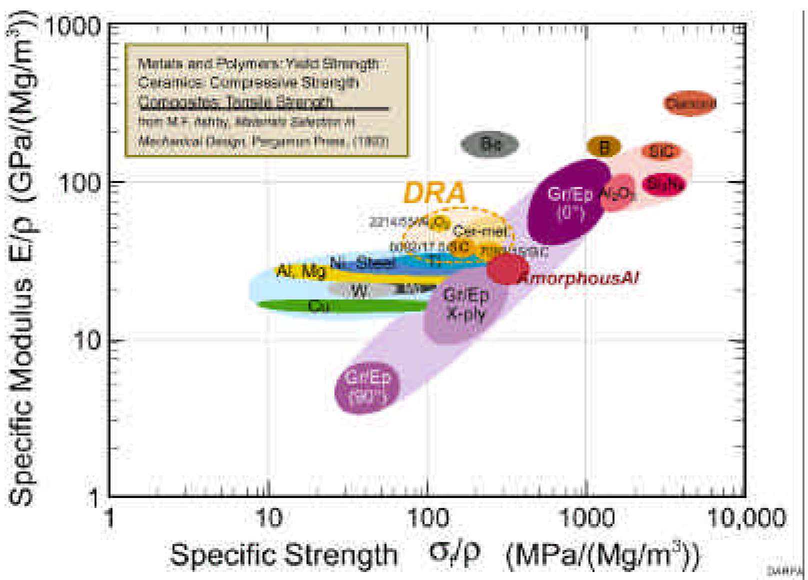


Figure 30 Stiffness and Strength of Amorphous Aluminum Relative to other Materials

In addition to the performance benefits, there should also be a cost benefit to using this material type. The cost mainly comes from the reduction of waste material in the manufacturing process, i.e. a reduction in the buy to fly ratio. The relative affordability (cost divided for a given performance) for amorphous aluminum (projected by the Air Force) is shown in Figure 31. The projections for both

[11] POC at DARPA: Dr. Christodoulou

affordability and performance indicate that amorphous aluminum shows great promise over standard 2024 aluminum.

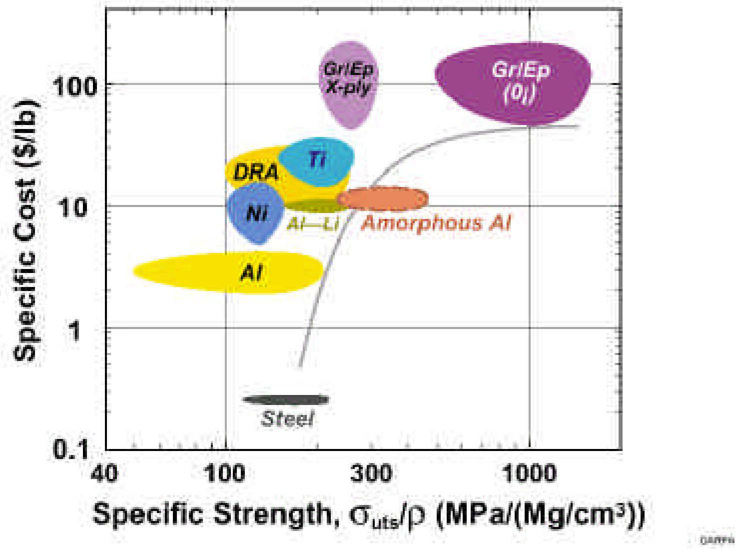


Figure 31 Affordability of Amorphous Al Relative to Other Materials

Metal Foams

The Defense Advanced Research Projects Agency (DARPA) is investigating ways to develop a new class of low-cost, ultra-lightweight structural materials[12] that can replace current materials used in aircraft and missile construction; metal foams. The candidate foams, aluminum and titanium, will result in weight savings of 50% relative to solid aluminum and titanium but cost no more than current materials. This 50% weight reduction was the impact modeled in GTARSP.

Metal foams are already available on the market, they can be formed in both open cell (like a stiff sponge) or closed cell (strong Styrofoam) configurations depending on their application. These materials do not exhibit any type of decay relative to their monolithic metal counterparts and offer tremendous weight savings and multi-functionality, perhaps as heat sinks/dissipaters and noise absorbers while simultaneously providing structure. Shown in Figure 32 below is the sound absorbing potential of aluminum foam (open cell) relative to standard, solid aluminum. Note the relationship between the pore size and the frequency of the best noise absorption. Different pore sizes may potentially be used in different parts of the vehicle in order to eliminate various noises at their source.

[12] http://www.darpa.mil/dso/thrust/md/str_6.htm

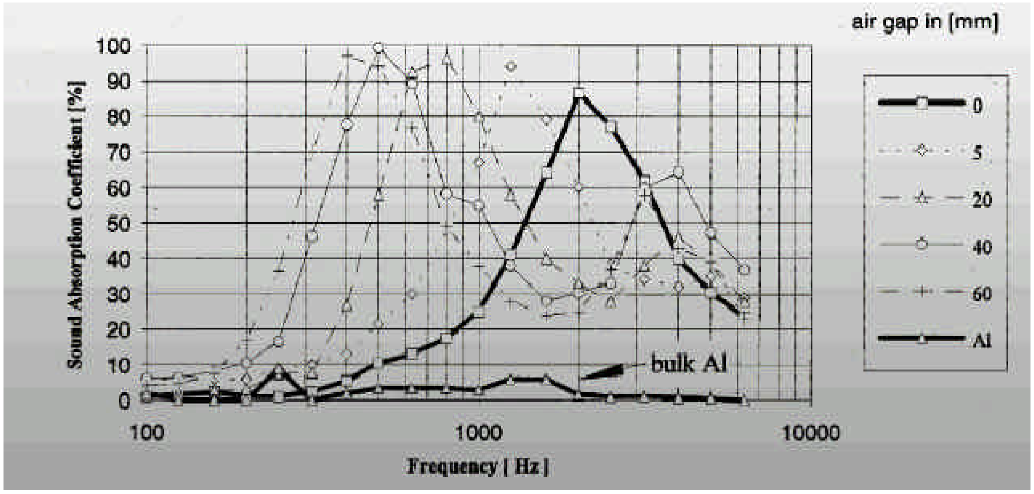


Figure 32 Performance of Aluminum Foam in Noise Absorption

The multifunctional character of metallic foams makes them particularly strong candidates for a number of military and commercial applications. These materials are particularly useful for aerospace applications and other weight-limited applications where high strength-to-density ratio, high stiffness, and relatively low cost are important. Other applications exist in the automobile and defense industry where metal foams have proven their value as effective isotropic crash/blast absorbing materials, vibration absorbing materials, and heat/fluid transport or storage media.

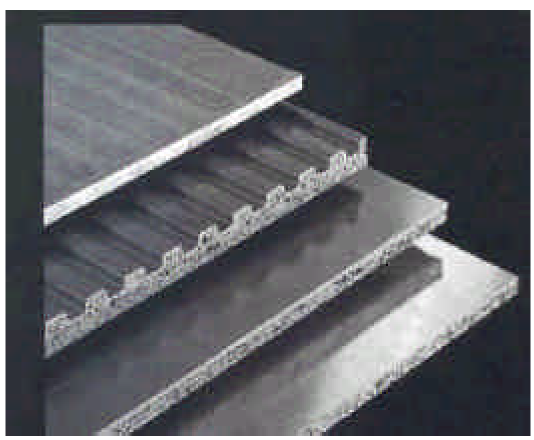


Figure 33 Panels of AluLight (Aluminum Based Metallic Foam)

3.3.3 Technology Evaluation

The technologies identified were evaluated through the use of technology "k" factors that were mapped onto variables used by GTARSP. A Technology Impact Matrix (TIM) was populated in order to assign benefits and drawbacks to the technologies that were identified and also to identify what vehicle parameters are being impacted.

	Technology Impact Matrix														
		Fiber Laminate Shroud	Fiber Laminate Fuselage	Metallic Foam Shroud	Metallic Foam Fuselage	SAM Shroud	SAM Fuselage	H-air Fuel Cell	Adv. Piston Engine	Adv. Small T-Shaft	Fly-by-light	Fly-by-wire	Wireless		
		T1	T2	T3	T4	T5	T6	T9	T10	T11	T12	T13	T14	Min	Max
K Factor Elements	Fuselage Weight		-20%		-50%		-30%							-50%	0%
	Wing Weight		-20%		-50%		-30%							-50%	0%
	Electrical Weight							20%			-20%	-10%	-25%	-25%	20%
	Flight Controls Weight	-2%		-2%		-2%								-2%	0%
	Transmission Weight							-10%						-10%	0%
	Engine Power to Weight							97%	54%	300%				0%	300%
	Flat Plate Drag			3%	10%	1%	-3%							-3%	10%
	Specific Fuel Consumption							-69%	-62%	-52%				-69%	0%
	Fuel Tankage Ratio							35%						0%	35%
	Transmission Efficiency							3%						0%	3%
	Contingency Rating							-60%	-40%	20%				-60%	20%

Table 19 Technology Impact Matrix

The technology impact factors then had to be normalized to fit in a scale between –1 and 1 because the response surface for the tailsitter was regressed against normalized variables. The effect of this normalization can be seen in the Technology Mapping Matrix (TMM Table 20).

		Variable	Baseline Value	*3-Level Non-Dimensional Baseline Value	Dimensional Impact Min	Dimensional Impact Max	Min (%)	Max (%)
Technical Metric K Factors	Fuselage Weight	K8	1	1	0.5	1	-50%	0%
	Wing Weight	K5	1	1	0.5	1	-50%	0%
	Electrical Weight	K20	1	0.111111111	0.75	1.2	-25%	20%
	Flight Controls Weight	K17	1	1	0.98	1	-2%	0%
	Transmission Weight	K14	1	1	0.9	1	-10%	0%
	Engine Power to Weight	NA	1.63	-1	1.63	6.50	0%	300%
	Flat Plate Drag	f COEFF	0.035	-0.538461538	0.03395	0.0385	-3%	10%
	Specific Fuel Consumption	SFCo	0.65	1	0.20345	0.65	-69%	0%
	Fuel Tankage Ratio	K	0.06	-1	0.06	0.081	0%	35%
	Transmission Efficiency	XMSNEFF	0.95	-1	95%	98%	0%	3%
	Contingency Rating	CONT	10%	0.5	4%	12%	-60%	20%

Table 20 Technology Mapping Matrix

The technology factors are then mapped onto the second order response that was assumed earlier. Analytically this could be written as,

$$R = b_O + \sum_{i=1}^{k} b_i k_i + \sum_{i=1}^{k} b_{ii} k_i^2 + \sum_{i}^{k-1} \sum_{j=i+1}^{k} b_{ij} k_i k_j$$

Equation 2 Response Surface with Mapped K Factors

A full factorial design was created in JMP to model the design space. The technologies were evaluated in a two-level design space, hence the technologies were assumed to either be on or off. Since there were eleven technologies, 2048 possible combinations had to be evaluated. The response surface coefficients for GW, HP, and WF, from the three level design space exploration (when system feasibility was being evaluated), were entered into an EXCEL spreadsheet program. A full factorial design space generated using JMP was also then input. Following modifications to the sheet required for the AVSLA study, the 2048 cases were run and the results for GW, HP, and WF were then imported into JMP to create a prediction profiler. The prediction profiler represents a virtual design space based on the regressed response surface with the mapped technology factors. By looking at the different possible technology combinations, by turning them on and off in the prediction profiler, it is possible to see what technologies must be infused to reach the gross weight, power, and mission fuel weight targets.

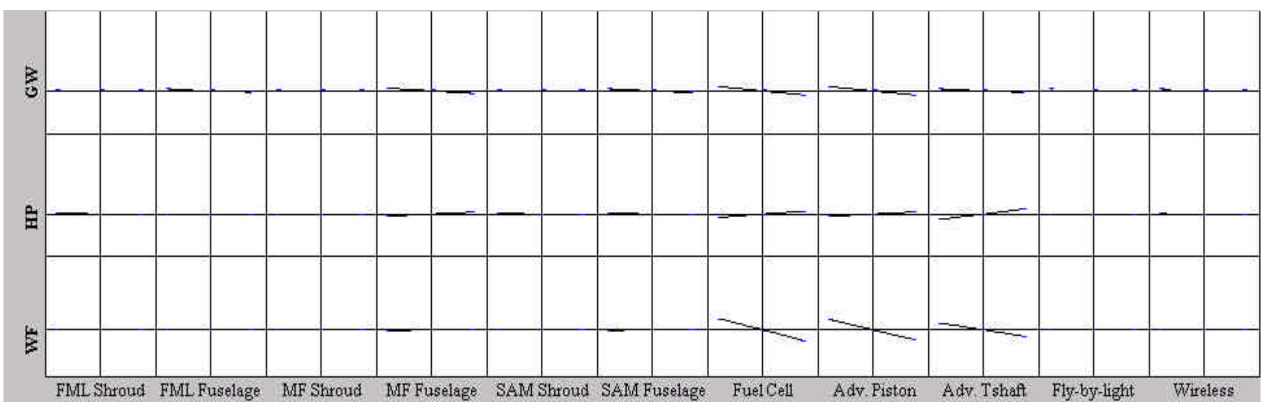


Figure 34 Prediction Profiler for "k" Factors

The prediction profiler shows that the choice of propulsion system has the largest effect on the response variables. This is as should be, thus the prediction profiler in some ways validates GTARSP. The topic of the next section will be which combination of technologies is the most effective in changing the values of the response variables.

3.3.4 Technology Selection

The **T**echnique for **O**rder **P**reference based on **S**imilarity to the **I**deal **S**olution (TOPSIS) was used to evaluate all of the feasible technology combinations. Of the 2048 cases "sized" using the response surface equations for gross weight, horsepower, and mission fuel weight, only 195 represented feasible combinations. These 195 "concepts" were evaluated by determining how similar they were to the ideal solution. The ideal solution was based on the minimum calculated gross weight, power, and fuel weight values. These did not come from one specific vehicle but rather from the entire pool of feasible concepts. A weighting factor was applied to each response metric and ten different weighting scenarios were evaluated. These weighting scenarios ranged from ones favoring extremely high mission performance to those favoring economic performance. For the mission performance, the largest weight was applied towards minimizing gross weight. For the economic performance evaluation, the largest TOPSIS weighting factor was applied to the installed power. Researchers at NASA Ames have concluded that rotorcraft purchase price is most sensitive to the installed power [8]. The second largest TOPSIS weighting was applied to the mission fuel weight in an attempt to factor in operating costs. Thus the only part of the life cycle cost not emphasized in the TOPSIS evaluation is the RDTE cost. This cost however falls out of the scope of this investigation. Shown next are a table of the weighting factor scenarios (Table 21), followed by a table that ranked the best 25 concepts for the different scenarios.

	Weighting Scenario									
	1	2	3	4	5	6	7	8	9	10
Gross Weight	0.9	0.8	0.7	0.6	0.6	0.5	0.5	0.4	0.33333	0.1
Installed Power	0.05	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.33333	0.5
Fuel Weight	0.05	0.1	0.2	0.3	0.2	0.4	0.3	0.5	0.33334	0.4

Table 21 Weighting Scenarios for TOPSIS

	Performance				Top 25 Alternatives					Economics
Ranking	1	2	3	4	5	6	7	8	9	10
1	1148	1148	1148	1148	1148	1148	1148	1148	1148	1148
2	1994	282	1994	1361	282	1994	1361	282	1150	1419
3	282	1994	1361	282	1994	1361	282	1994	381	1344
4	1361	1361	282	1994	1361	282	1994	1150	914	381
5	1987	1987	1987	1359	145	323	993	1361	1994	914
6	69	1913	1351	1987	1359	145	323	993	282	1271
7	1913	1351	1359	145	323	993	1150	381	1987	1351
8	1525	508	69	1186	741	1525	1839	15	1258	1987
9	1351	1359	145	323	1525	1351	1351	299	1885	1133
10	1271	165	1271	44	1566	972	1677	1351	29	746
11	1677	220	135	1935	1561	1772	1259	704	69	220
12	145	267	2020	1259	1838	597	1758	554	1300	1264
13	508	69	323	1525	1772	1259	704	1838	54	1150
14	567	1525	1133	97	1702	44	236	567	323	494
15	135	1677	1837	1300	1550	1083	1548	1279	129	1935
16	1359	145	1186	741	993	1150	381	914	1264	1994
17	165	1271	44	1561	972	1677	299	1300	982	1758
18	1000	567	182	1548	760	267	269	1124	1966	1595
19	220	135	1935	1566	1351	1839	15	953	494	982
20	893	893	704	1150	955	1271	265	1901	135	98
21	1471	1471	1617	941	1471	1419	746	98	145	1756
22	2020	1000	1419	1839	538	165	1672	538	1628	1885
23	267	2020	1259	1838	597	1758	554	217	659	54
24	597	597	1181	299	660	2020	1641	1525	880	787
25	1935	741	1901	893	55	98	1844	44	1677	659

Table 22 Top 25 Technology Combinations for the Given Weighting Scenarios

The values appearing in the top 25 table represent the case that was run to get the response metric results. Based on the TOPSIS investigation, interestingly enough, the combination represented by case number 1148 was the best in every scenario. This counterintuitive result is probably due to the fact that this investigation was very "top-level". Nonetheless, case 1148 is the clear favorite for further investigations. The following table summarizes the response metric values and technology combination for case 1148. Notice that the fuel weight and installed power goals are met with a significant margin but the gross weight is still too high (Table 23).

Technology Combination		Response Metric Values		
Shroud Material	Fiber Metal Laminate	Gross Weight	570	lb
Fuselage Material	Metalic Foam	Installed Power	73	hp
Propulsion System	Direct Methanol PEM		53.7	kW
Flight Control System	Wireless	Mission Fuel Weight Required	35	lb

Table 23 Technology Combination and Response Metric Values for Case 1148

These results were computed using the regression surface calculated using JMP. Therefore, GTASRP was used to re-size this configuration, with these technologies, and this was done for two reasons.

The first is to validate the RSM approach, the second is to learn more about the sized configuration. The rotor sizes, performance, and component weights must be checked to ensure that something was not lost in the translation between the original analysis tool and the metamodel created using JMP. The performance results from GTASRP follow but the group weight statement appears in the appendix.

Performance Characteristics

Name	Value	Units	Notes
Flat Plate Drag Area	2.75	sqft	
Figure of Merit	0.66,0.62	coax,trad	
RFR	0.0599		
HP hover	67	hp	(43.2 F +ISA, 1200 ft, payload pickup)
HP cruise	50	hp	(43.2 F + ISA , 4089 ft)
HP climb	82	hp	(300 fpm)
Cruise Speed	145	kts	
Disc Loading	9	lb/sqft	
Tip Mach No.	0.71		
Required Fuel Weight	34.3	lb	at roughly 2.15 lb/gall, 34.3 lbs => 16 gallons

Table 24 Case 1148 Tailsitter GTASRP Performance Results

The GTASRP outputs were similar to the values predicted by the regression surface, especially for the gross weight and fuel weight; the installed power however was not predicted as accurately (80 from GTASRP vs. 73 from the RSE). This is most likely the result of one or both of two reasons. The first is that the metamodel did not include all of the factors responsible for predicting installed power. The second may be the result of the tolerances in GTASRP being too relaxed in the generation of the RSE data, they were set to 1e-3 (relative tolerance) for the automated DOE runs. This could have produced some scatter in the data points. The most probable reason for the prediction error is a combination of the two reasons with reason #1 carrying the greater influence.

An interesting result from the GTARSP sizing was that the empty weight fraction of the tailsitter was over 0.938. The reasons for this non-intuitive result are primarily twofold. The fuel weight is incredibly low, only 16 gallons (~34 lbs) of methanol were required to travel 447 nm. Secondly, the mission was designed such that the vehicle would travel unloaded to pick up the package, pick it up midway and then drop it off at a location before refueling. The reason for this was that an assumption used for designing the mission was that the agents would operate in a manner similar to a taxi service. This manner of delivery helped minimize the size of the vehicle.

3.4 Integration with the Environment

Sikorsky Aircraft Corp. sponsored a helicopter design laboratory at the Rhode Island School of Design (RISD) during the Fall 2001 semester. The 13-week laboratory had 15 students majoring in Industrial Design and Interiors. All of the students spent one third of the semester working on concepts for the AVSLA.

The RISD students were asked to craft a narrative about how a single package would be delivered by the AVSLA system. They were able to provide unique perspectives on how the AVSLA will interface with the natural and the built environment as well as how individual people would use the AVSLA. In addition, they provided vehicle designs influenced by the world around them. The RISD students provided a great deal of "out of the box" thinking, something that is essential to any attempt to develop a system with a 20 to 40 year incubation time.

One of the most valuable insights the RISD students provided was a glimpse into what the built environment of the future may look like. This is especially important because it can aid the development of an AVSLA system that is trying to hit a moving target to gain public acceptance in the world of the future. Some of the RISD concepts are presented in the following figures.

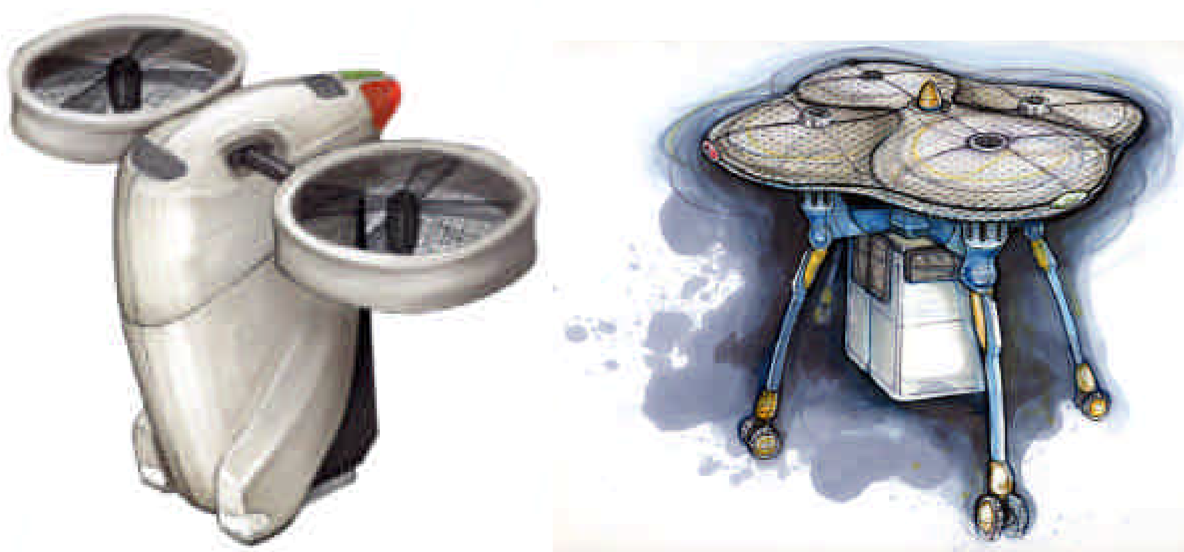


Figure 35 Two vehicle concepts developed by students at the Rhode Island School of Design.

3.5 Technology Roadmap

A technology roadmap is presented, this will provide the basis for structuring future work. The advancements that are forecast are largely based on the proposed progress is various DoD initiatives that are being, or will be, pursued specifically for the improvement of the state-of-the-art in UAVs.

A simple, four-phase system development chronology is proposed. A key assumption is that a seven-year certification period will be required, this used because it is a conservative estimate. Integration of UAVs into the civil airspace will eventually happen but it is still too soon to say what protocols will be in place and which will have to be developed.

The most critical elements for developing AVSLA are those related to the infrastructure, UAV autonomous capability, and UAV performance. The infrastructure development forecasts are based in large part to FAA program timelines that are associated with the implementation of “Free Flight” as well as the rest of the national airspace system redesign.

UAV autonomous capability will have a big impact on both the infrastructure, and its associated protocols, and the vehicle performance. Currently, vehicles such as Global Hawk and Predator only have the capability to report their system status and in-flight conditions. However, with the introduction of new vehicles the autonomous capabilities of UAVs are expected to grow by leaps and bounds; they may potentially operate as fully autonomous swarms [11], perhaps soon after 2025.

The mission performance of the AVSLA agents will be closely tied to the propulsion system, i.e. how much power for a given engine weight and the fuel consumption. Three powerplants were considered for this study, and although the fuel cell is recommended, milestones for all three are presented in the roadmap.

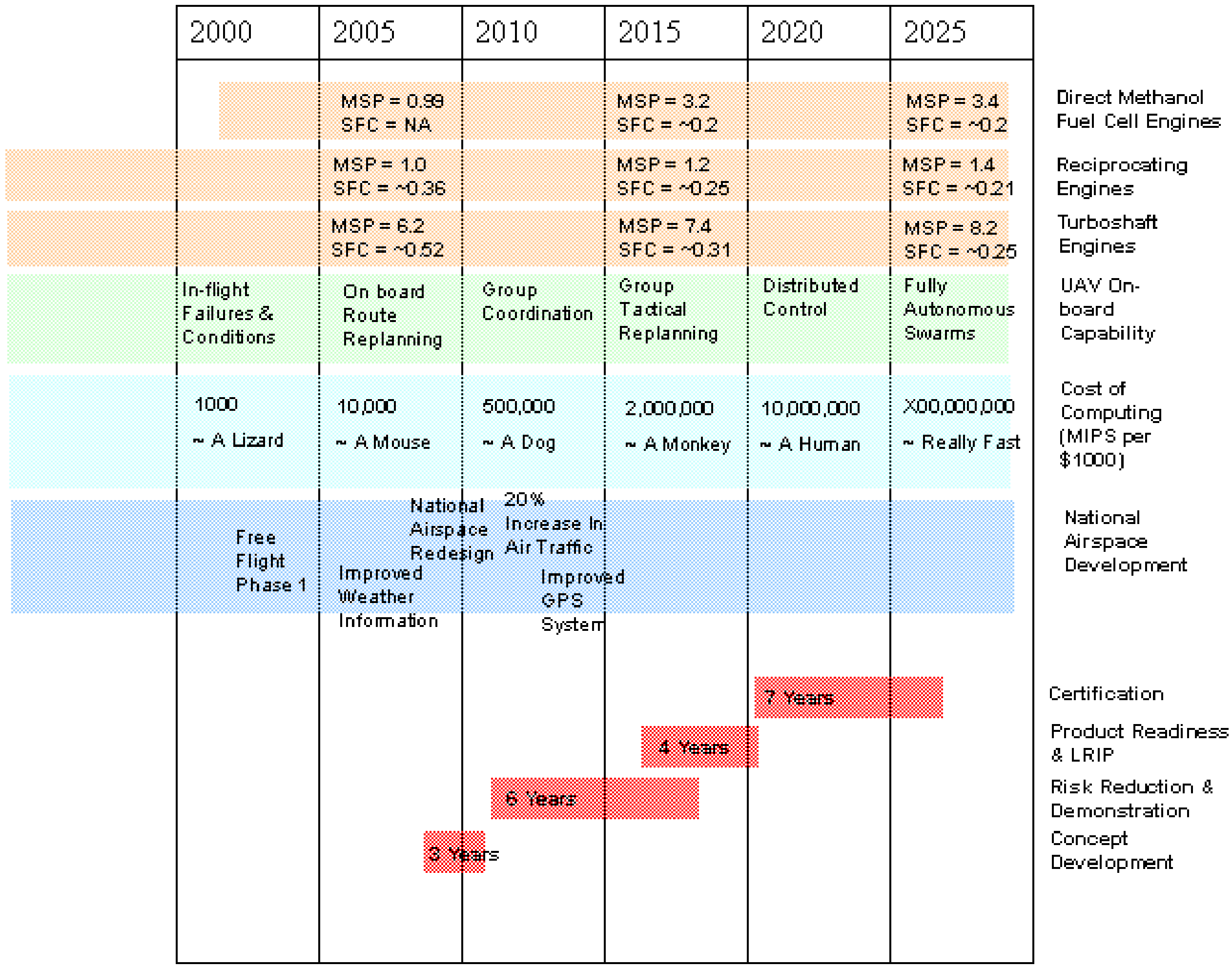


Figure 36 Technology Roadmap

The graphs that appear next served as the basis for making some the assumptions for the development of the roadmap. These charts forecast improvements in the relative cost of computing and UAV autonomous capability. The basis for making the other assumptions can be found earlier in the report (Sect 3.3.1, 2.5.6).

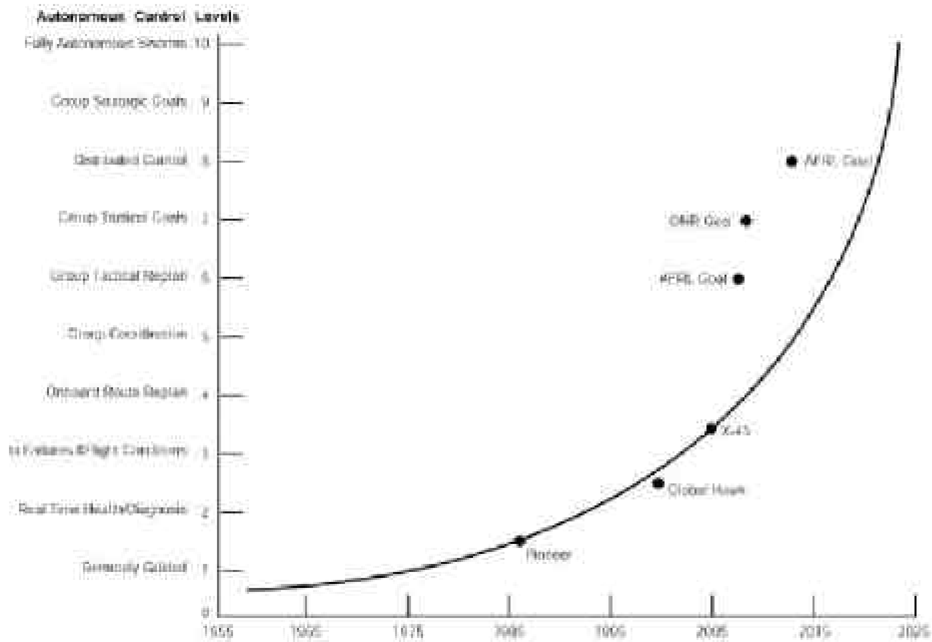


Figure 37 UAV Autonomous Ability Forecast

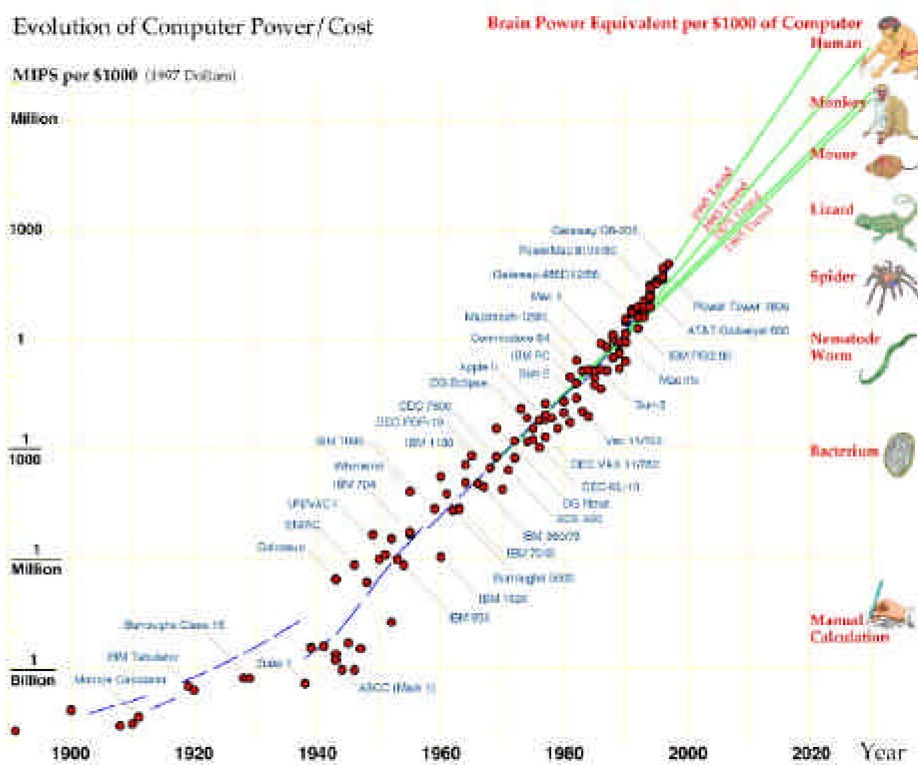


Figure 38 Evolution of Computer Power Vs Cost

3.6 Leveraging U.S. Army Technology Investments

The US Army technology community has instigated a number of UAV technology programs that could be relevant to the AVSLA program. The Small Affordable Turbine Engine (SATE) program is designed to reduce fuel burn 20%, cost 30%, and weight 50% over current technology engines. The UAV drive system program is designed to reduce both operating and support and production costs by 20% over current technology. The Autonomous Rotorcraft Project is designed to flight demonstrate autonomy architectures in a realistic and demanding rotorcraft UAV mission environment.

The US Army, in combination with DARPA, is beginning a Unmanned Combat Attack Rotorcraft competition. According to press releases (www.darpa.mil/tto/programs/ucar) the program will "design, develop, integrate, and demonstrate the enabling technologies" for mobile, autonomous attack on targets. The program will work on a number of technologies, including command and control, sensors, communications, and air vehicle design which would be relevant to the AVSLA program.

4. Summary and Recommendations

In summary, the AVSLA system-of-systems modeling and subsequent analytical results to date indicate that there is a region of the design/requirements space that could result in a feasible and economically viable package delivery concept. However, this is only true if certain technology hurdles (in the VTOL vehicle itself as well as the air traffic management approach) are overcome *and* the appropriate business model (e.g. target population, delivery distance, region, etc.) is selected. It is likely that, although government funded research is needed to mature AVSLA technologies (see the technology roadmap above), whether such a system ever enters service will depend on whether a private business enterprise can combine the technologies with the right business plan to form a *profitable, adaptable concept*. This realization was a guiding factor in how the team completed this Phase II work. It is hoped that this report has demonstrated how the AVSLA system dynamics model can be used both as an engineering tool and as a business development tool.

Along the lines of this latter item, the team sought and obtained input from United Parcel Service (UPS) on the operational realism and likely economic viability of AVSLA. Unfortunately, the relationship ended prematurely due to the dissolution of the *e-Ventures* group at the company. Clearly, helping our team on this project became a quite low priority for their organization. Although certainly not the news we were hoping for, the developments with *e-Ventures* did bring to light the fact that robustness to uncertain economic conditions must be of paramount concern in any business enterprise. This is especially so for a cutting-edge technology program which might be operating on slim margins.

4.1 Recommendations for Phase II Option work

In the original Phase II proposal, the team outlined several areas that at the time appeared fruitful for additional research through a one year extension. These initial thoughts have now been reviewed in light of the completion of the main Phase II research, and it is the team's view that the general themes proposed for the option research remain valid. Primary among these, and mentioned frequently throughout this report, is the need for more in-depth analysis of the various system modules within the overall environment. These include primarily the VTOL vehicle model, the network model, and the interjection of more refined air traffic constraints and bounds.

4.2 Recommendations for NASA Program Planning

A detailed technology investment roadmap was presented in Section 3 above, focused on the VTOL vehicle system. Without a doubt, however, NASA investment in this area and the larger architecture design should be closely coordinated with ongoing related programs. In particular, the AVSTAR project at NASA Ames Research Center and the Revolutionary Aerospace System Concepts (RASC) project out of the Office of Aerospace Technology enterprise (and located primarily at NASA Langley Research Center) are most relevant.

As significant amount of work is resident in the AVSTAR program that will hopefully expand from its current commercial aviation traffic management focus to issues relevant to AVSLA such as the operation of UAVs in controlled airspace, traffic management automation technologies, aviation system simulation (a point very key as we have outlined here). An additional recent development of note is that the incoming NASA administrator has indicated a desire to foster a greater collaboration between basic aeronautics R&D at NASA and similar efforts at the Department of Defense (DoD). There is likely no better example of the need for this than UAV vehicle and autonomous system-of-systems research. The number of references in this final report from various DARPA programs, for example, is one indication of the tremendous leverage that NASA could gain by coordinating future work with DoD.

The RASC project, like AVSTAR, offers a possible home for research directed towards advancing the critical path technologies needed for a economically viable AVSLA. In fact, one of the early studies under RASC involved a national level look at automated package delivery. The study, performed by the Logistics Management Institute (LMI), found that it was difficult to envision a national scale system that would be viable any time soon. This dovetails well with the present study, which appears to indicate that a regional system may be an excellent candidate at first, both from an economic perspective and from the viewpoint of "crawling before walking" from a technology standpoint.

What is proposed, then, is a coordination of continued AVSLA research with these two existing programs as well as a tie in, where possible, to efforts in UAV technology at DARPA and the DoD in general. The team would be pleased to begin to initiate such collaborations as part of the Optional phase under NIAC.

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