AUTONOMOUS VTOL SCALABLE LOGISTICS ARCHITECTURE

Phase I Final Report

EXECUTIVE SUMMARY

A study to define the characteristics of an Autonomous VTOL Scalable Logistics Architecture (AVSLA) was conducted under Universities Space Research Association (USRA) grant number 07600-056. This grant was awarded by the NASA Institute for Advanced Concepts (NIAC), a "virtual institute" that provides an independent, open forum for the external analysis and definition of space and aeronautics advanced concepts to complement the advanced concepts activities conducted within the NASA enterprises.

Design of the Automated VTOL Scalable Logistics Architecture (AVSLA) began with an in-depth analysis of the current products shipped in the United States, particularly in the Northeast Region. The results of this logistics analysis produced two shipment categories of interest. The first is a 0-100 pound shipment delivered up to 500 miles. The second category of shipments is in the 1,000-10,000 pound weight range with delivery up to 250 miles. Once types of shipments were defined, modeling was used to determine viability of replacing current transportation methods with a VTOL aircraft.

Modeling was performed using Vensim, a visual cause and effect software package. Data obtained from the trucking industry and FedEx was used to calibrate the model, and several different architectures, vehicle sizes, and delivery methods were used extensively to determine the efficiency of VTOL aircraft versus today's delivery standards. VTOL aircraft performed well in the 0-100 pound (Light Lift) category, consistently providing service under the FedEx cost and time tables. However, due to the low cost transport that the trucking industry provides, VTOL could compete on cost within the 1,000-10,000 pound (Heavy Lift) weight category. Therefore, the focus of the AVSLA architecture is primarily on the Light Lift vehicle, with a Heavy Lift vehicle analyzed for time-sensitive military and commercial cargo transport.

Before a Light Lift vehicle could be designed, expectations for the methods of control, routing, and scheduling needed to be determined. A point-to-point delivery system is most efficient when using a high-speed, single package delivery vehicle. This system provides timely service at a low cost to the consumer. In addition, the routing method also took into account the high-speed nature of a Light Lift VTOL aircraft. A recommendation is made for an unconstrained, "free flight," routing system, giving the automated aircraft the ability to choose and change its flight path as environmental condition changes. Finally, stand-alone control was determined to be the most cost-effective method of asset management. This type of management leaves most flight, routing and delivery choices to the automated aircraft.

After choosing to have a large portion of the control onboard each vehicle, system IT requirements were developed to asses the costs and viability of vehicle processing capabilities. In addition, safety and collision avoidance equipment necessary to provide safe air transport were defined. Onboard communications, radar, transponder, satellite positioning, computing needs, and automation controls were analyzed for use on the Light Lift and Heavy Lift vehicles. Specialized military equipment is also defined.

Once the system and IT requirements were determined, various vehicle platforms were analyzed for use in the Light Lift category. Elimination of vehicles based on performance, efficiency for this type of transport, and specific system metrics was performed. Vehicle choice was narrowed down to three types; a tilt-shroud vehicle, a tri-rotor design, and a 15-degree fixed

shroud. Sizing of these three vehicles was performed, with the resulting recommendation being the tilt-shroud design.

Finally, an economic analysis was performed to provide recurring and non-recurring costs for the architecture. It was determined that 185,000 vehicles could be produced at an overall cost of $4,000 per vehicle (constant year 2000 dollars). Operating costs are dominated by fuel and maintenance costs, but are reasonable for the benefits in time and cost the VTOL vehicles provide. System development costs would be minimal due to the low complexity of control by ground facilities. Therefore, the majority of the system cost is in the VTOL vehicles themselves, rather than the infrastructure that allows them to work together.

Overall, the AVSLA provides a low-cost delivery system that overcomes today's express delivery systems in both consumer cost and parcel delivery time. It is recommended that a Phase II study be performed to determine the effects of scaling from the Northeast Region to the entire United States. Further information is also needed from the FAA, mainframe manufacturing companies and military/specialized commercial transport officials to complete some of the Phase I analyses. Phase II funding would be sufficient to complete these analyses and bring AVSLA closer to reality.

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INTRODUCTION

During the 20th century, incredible advancements in computing technology brought science fiction to reality in many areas. Cellular phones allow people to communicate with anyone in the world in real-time; robotic arms and machines replace humans in automated factories; and personal computers access virtually unlimited information on the Internet and deliver e-mail to anywhere in the world. Partly enabled by long distance electronic communication, corporations position facilities in locales offering low capital and labor costs and market their products worldwide via the Internet. Traditional distribution channels are being supplanted by direct shipment of products and materials between companies and consumers. However, most physical goods still travel by road, in a car or truck, for some portion of their journey. As the population steadily increases, roadways that are already congested with commuters, delivery vehicles, and travelers become further crowded to the point that, in a few areas of the country, "rush hour" never ends. Since demand for transporting goods will probably continue to grow, either the road network must grow with it, or new technologies must be integrated into the transportation problem to reduce demand on the already strained road network. The U.S. Department of Transportation (DoT), in its "FY2000 Budget in Brief" has stated that

> Despite significant progress, a transportation system that serves a growing America still requires more capacity, better connections, and improved conditions and performance. The transportation solutions of the past – building more roads, bridges and airports – can no longer be our first choice to give Americans the mobility they need. It's too expensive and too damaging to our communities and our environment. Instead, our transportation system should be better managed to make more efficient use of our existing system, leaving new capacity as a solution only when other strategies fall short. A total of $39.8 billion is proposed for transportation mobility programs, 5 percent more than in FY 1999.[1]

This report presents one transportation alternative that could minimize public investment in the transportation infrastructure. The use of Vertical Take-Off and Landing (VTOL) aircraft to transport parcels that are currently transported on our nations highways offers an unique opportunity to reduce highway congestion and increase overall transportation system throughput without requiring extensive capital investments in the form of new airports and new roads to get to and from those airports. However, economic and societal limitations must be overcome before this vision can become a reality. For example, autonomous vehicles can substantially reduce crew costs. And once the vehicles themselves are autonomous, the dispatching system can also be made autonomous in order to reduce response times and to further drive down costs. This is the background that led to the creation of the Autonomous VTOL Scalable Logistics Architecture (AVSLA) concept.

In the AVSLA concept, small, autonomous, VTOL vehicles, capable of taking off and landing in virtually any area, deliver materials directly from the supplier to the buyer. An integrated dispatching system receives delivery orders from shippers while the parcel is still being prepared for transport. As the parcel is packaged and prepared, a small transport vehicle is already on its way to the pickup location. The air vehicle arrives "just in time," as the parcel completes its packaging process. Warehouses could shrink in size, eventually becoming unnecessary as "just in time" pickup and delivery are realized. Larger autonomous air vehicles

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[1] From *FY200 Budget in Brief.* U.S. Department of Transportation. 2000.

can accommodate larger, specialized deliveries (i.e., logs, military equipment, ammunition, water to extinguish fires, heavy equipment, etc.). A common architecture allows both vehicles types to use the same dispatch center, communication network, and on-board processing systems to provide "just in time" service as part of a new logistics architecture.

An in-depth understanding of what is being transported today, and what will be shipped in the future, is required to develop this new delivery system. This study analyzed the parcel industry to determine the market segments where an automated air delivery system could excel over the current transportation system. Based on this knowledge of the market, the market segments where an AVSLA could offer cost and time advantages were identified. Once the use of VTOL aircraft was determined to be beneficial in specific weight and distance categories, the delivery system was analyzed at the subsystem level. The subsystem tasks to be completed included air vehicle design and the definition of air vehicle Information Technology (IT) requirements, system level control and management structure, resulting system IT requirements based on control scheme selected, and method of implementation. In order to make comparisons between approaches within these tasks, system cost, ecological impact, safety, efficiency, and feasibility were chosen as key metrics.

The goal of this study was to establish the feasibility of an architecture that is faster and cheaper than the current scheme and one that promotes innovation within the shipping industry. The level of safety of the new architecture must exceed that of the current scheme. And, for long-term viability and community acceptance, the new system should be more ecologically friendly. Finally, while making extensive use of near-horizon technologies, such as nanotechnology and alternative fuels, this new delivery architecture must also promote further advancements in technology, as profits within the industry are directed back into research.

This report is broken into nine main sections: Logistics Analysis; Modeling and Simulation; Delivery Architecture; Vehicle Design; Cost Analysis; Control and Management Structure; System Information Technology Requirements; Economic Analysis; and Conclusions and Phase II Recommendations. Each section further defines the AVSLA and prepares for in-depth follow-up in Phase 2.

1 LOGISTICS ANALYSIS (NORTHEAST REGION)

In order to solve a problem, it is first necessary to understand the problem. Hence this study, which seeks to decide if an Autonomous VTOL Scalable Logistics Architecture (AVSLA) offers a new solution to the problem of transporting high-priority parcels, began with an analysis of the parcels being shipped in the area of interest. The densely populated Northeast United States Region was chosen for this analysis due to the assumption that a highly congested area would benefit most from airborne delivery. However, the highly concentrated population in this area could place many restrictions on automated air vehicle flight paths. The objective was to determine the type and amount of freight being transported in the region. This information was then used to pinpoint categories of freight that a new architecture would be carrying. Conclusions on parcel sizes and transportation distances are shown at the end of the section[2]. Also discussed are the potential system-level cost savings associated with deployment of an AVSLA.

1.1 Commodities Analysis

1,309,423,000 tons of freight was shipped in the NE region during 1997. This represents an average of 3,587,460 tons per day. Figure 1-1 depicts a distribution of the commodity types being shipped in the region, grouped by U.S. Government Standard Classification of Transported Goods (SCTG) and ranked by total tonnage.[3]

Commodity tonnage being transported in the region gives a broad view of transport activity. However, the insight it provides is insufficient for the development of the prospective AVSLA solution. Target commodities for the AVSLA solution will be those commodities that have higher value and lighter weight than average, since the aircraft solution will be less efficient per ton than the truck alternative for heavy, low value products. Therefore, commodities should be viewed using a more useful metric, the dollar value per unit ton. Figure 1-2 depicts and ranks the dollar value per ton ratio of commodities shipped in the Northeast.

The seven commodities that had a dollar value to ton ratio (V/T) of 10 dollars per pound ($/lb.) or more are listed in order of V/T in Table 1-1. Combined, these top seven commodities make up only 1.4% of the total tonnage shipped but over 35% of the total value shipped. Therefore, these top seven commodities encompass the most attractive market segments for the AVSLA.

Table 1-1: Top seven value/ton commodities.

SCTG Code	Description	V/T [$/lb.]	% Total Value Shipped	% Total Tons Shipped
38	Precision instruments and apparatus	68	3.3	0.0
21	Pharmaceutical products	35	6.0	0.2
35	Electronic, electrical equipment/components, office equipment	29	13.2	0.4
9	Tobacco products	18	0.6	0.0
30	Textiles, leather, and articles of textiles or leather	14	5.8	0.4

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[2] The primary source of statistical freight data was the US Department of Transportation/ Department of Commerce Commodity Flow Survey which quantifies all commodities being transported in the area by the US Government Standard Classification of Transported Goods (SCTG) descriptor, the mode of transportation, and the weight and value of shipments. The survey's statistics are derived from the 1997 and 1993 Economic Census. Transport data is separated by State and Census Regions: Northeast, South, Midwest, and West. The Northeast Region covers the majority of the area of interest (Maine, Vermont, New Hampshire, Massachusetts, Connecticut, Rhode Island, New Jersey, New York, and Pennsylvania), but excludes Maryland and Washington DC.

[3] *1997 Commodity Flow Survey, Northeast Region*, U.S. Department of Transportation / U.S. Department of Commerce, EC97TCF-REG(1), April 2000

37	Transportation equipment	14	1.2	0.0
34	Machinery	11	5.4	0.4
Total			**35.5**	**1.4**
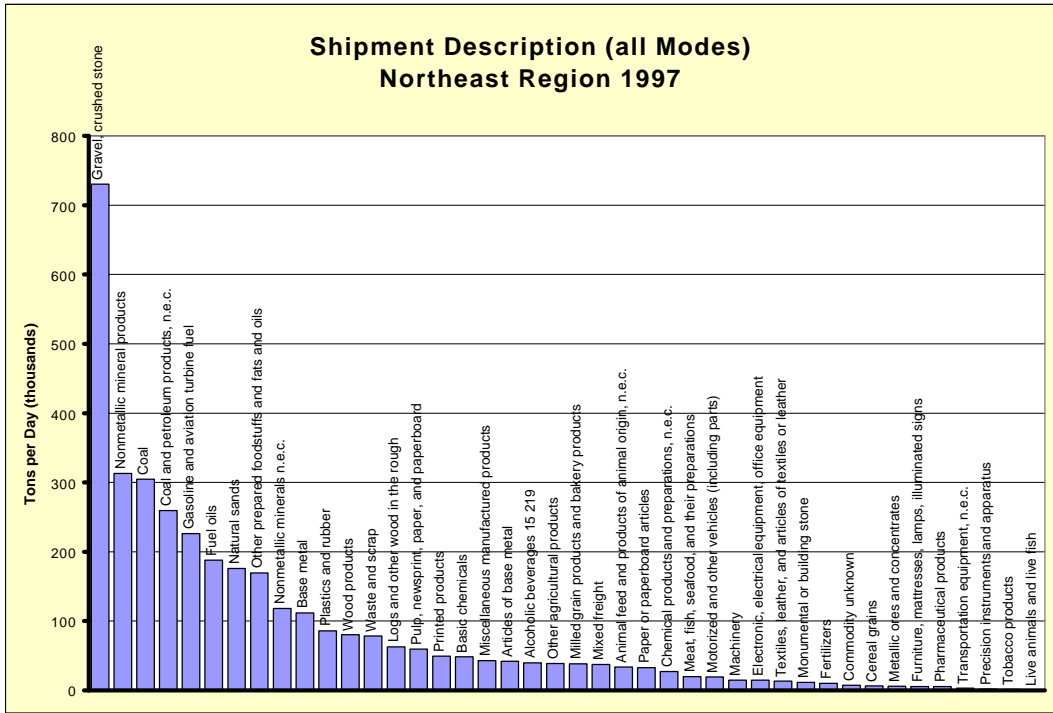
Figure 1-1: Tonnage shipped by commodity.
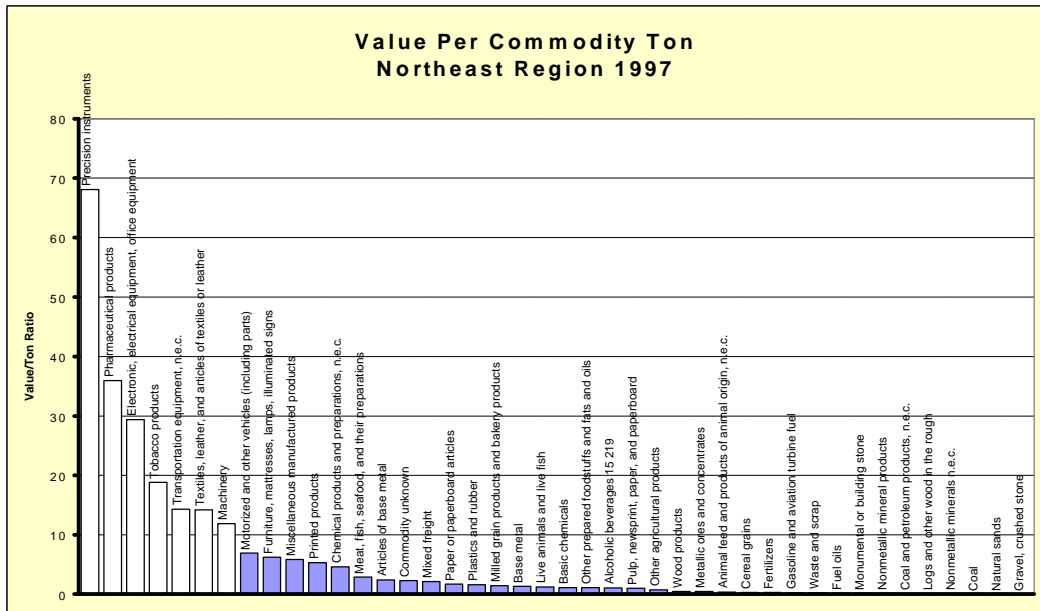
Figure 1-2: Value Per Commodity

**Top Seven Commodities
Broken out by Weight Category**
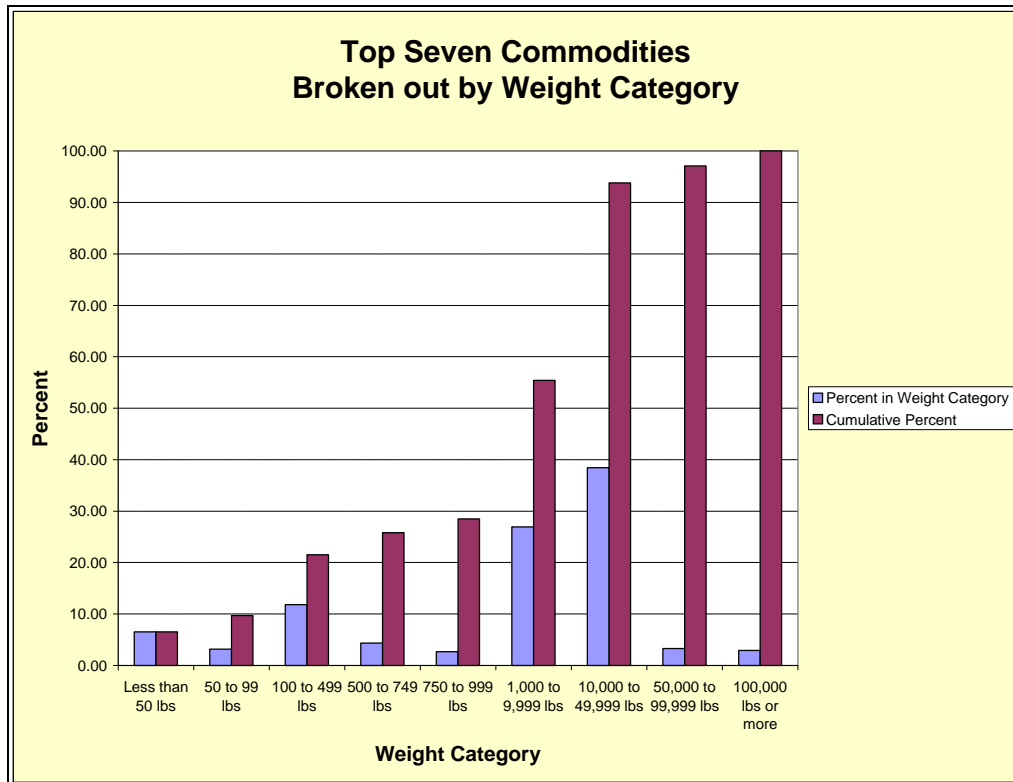
Figure 1-3: Top seven commodities broken-out by weight.

Further analysis of these seven commodities indicates that over 90% are shipped in groupings of less than 50,000 lb. (Figure 1-3).[4] In addition, shipping distances follow a fairly uniform distribution ranging from < 50 miles to >2,000 miles.

1.2   Modal Analysis

With a subset of commodity types to focus on, shipping distances were analyzed to determine the required vehicle range for an effective AVSLA. Figure 1-4 depicts the distance freight is shipped in the region, grouped by mode of transportation.[5]

It can be seen from Figure 1-4 that the majority of shipments handled by modes that an AVSLA would replace (courier and truck) travel less than 1300 miles. A detailed examination of each mode of transport was necessary to determine the range requirements for AVSLA air vehicles.

Figures A-1 and A-2 (see Appendix A) depict the relative importance of the modes of freight transportation used in the Northeast. Trucking is the dominant transportation mode in the region. It carries 86% of the total tonnage moved in the region and accounts for 71% of the value of shipments in the region. The other relevant segment of the modal market is "Multiple Modes". [6] Of the $225,966 million shipped by multiple modes, $221,545 million (98%) was

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[4] *Ibid.*

[5] *Ibid.*

[6] "Multiple Modes" also has elements of trucking included in it. Multiple modes is defined as Parcel, U.S. Postal Service or courier shipments for which two or more of the following modes of transportation are used: private truck, truck for hire, rail, shallow draft vessel, deep draft vessel, pipeline

shipped by parcel, U.S. Postal Service (USPS) or courier.[7] Typically these shipments weigh less than 100 lb., and account for 19% of the value of commodities shipped (15% for the USPS). Shipments in this segment have an average V/T of 42 $/lb. Parcel, USPS, and courier freight offers a high V/T.
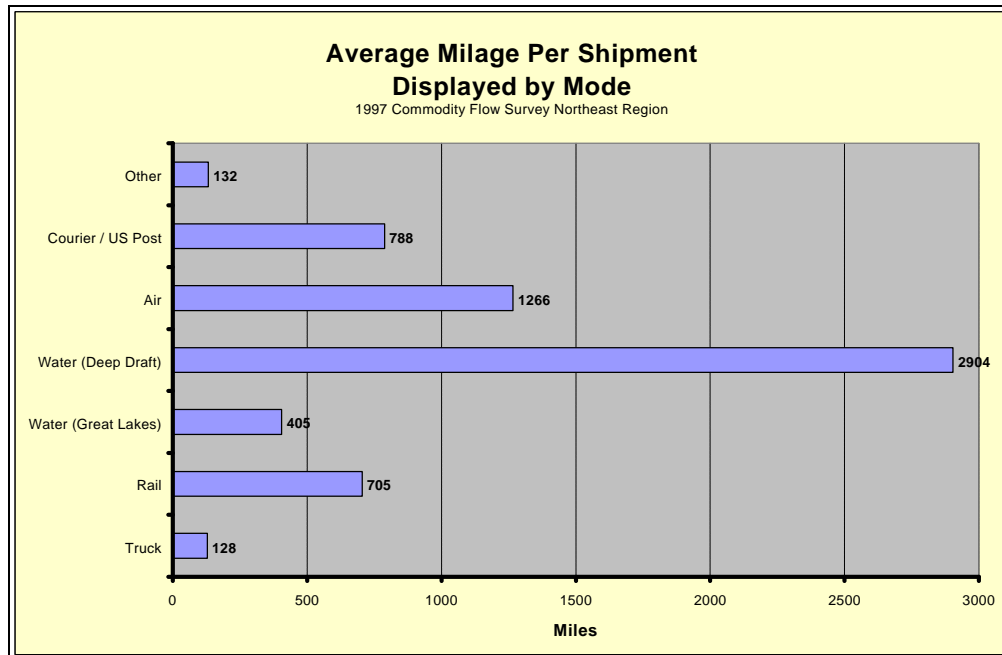
Figure 1-4: Average shipping distance grouped by mode of transportation.

Since high value/low weight commodities are typically shipped by either truck or USPS/courier service, a more detailed examination of these two transportation modes was warranted.

1.3   Truck Operations in the Northeast Region

Trucking dominates freight transportation in the region of interest; it accounts for 86% of the total tonnage and 71% of the total value of shipments. 10% of the *total* freight trucked in the region is below 10,000 lb. Almost 52% of the *total* freight weighs less than 50,000 lb.[8] Given the dominance of trucking in the Northeast, and that the *Commodity Flow Survey* only reports aggregate quantities that include *all* freight shipped (including grain, coal, logs, etc.) without specifying what portion of the high value/low weight commodities are trucked; it is assumed that the distribution by weight class of high V/T cargoes shipped by truck follows the same trend as the aggregate trends for all transportation modes shown in Figure 1-3. Then, as mentioned in the Commodities Analysis Section (1.1), approximately 90% of the high value/low weight commodities tonnage trucked in the region is shipped in quantities less than 50,000 lb., and about 55% of the tonnage trucked is composed of individual shipments of less than 10,000 lb.

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[7] *1997 Commodity Flow Survey, Northeast Region*, U.S. Department of Transportation / U.S. Department of Commerce, EC97TCF-REG(1), April 2000

[8] *1997 Commodity Flow Survey, Northeast Region*, U.S. Department of Transportation / U.S. Department of Commerce, EC97TCF-REG(1), April 2000

There is no data available on the unit weight of commodities trucked, only total tonnage trucked in specific weight brackets. A reasonable assumption, then, is that some of the commodities trucked in the 10,000-50,000 lb. range could be broken down to smaller shipments and trucked in the <10,000 lb. bracket; thus the estimate that 55% (by weight) of trucked shipments weigh less than 10,000 lb. represents a minimum estimate.

According to the Commodity Flow Survey, trucks carry relatively short-haul cargo in the region (see Figure 1-4).

- Average distance traveled: 128 miles
- 91% (by weight) of truck freight travels less than 250 miles
- 83% (by weight) of truck freight travels less than 100 miles

Based on the above data, a reasonable requirement for an AVSLA operating in the Northeastern United States is that at least some of the air vehicles in the system be capable of transporting 10,000 lb. of cargo a range of 250 statute miles. This is the basis of a Heavy Lift requirement for the AVSLA.

1.3.1   Truck Quantities in the NE Region

Department of Commerce data that defines the number of trucks in the U.S. and their usage[9] was used to asses the number of trucks which could be retired if an AVSLA was deployed in the Northeastern United States. The nationwide truck population totals 59,200,800 vehicles; roughly 22% (about 13 million) of these operate in the Northeast U.S. However, this figure includes pickups, minivans, wreckers, concrete mixers and various other body types that obviously are not factors for the AVSLA. The AVSLA study focused on a subset of this population – specifically the body types listed in Table 1-2 – associated with the manufacturing, wholesale, retail, and services industries.

Examining Table 1-2, it is clear that an operational AVSLA has the potential to reduce the total truck population in the Northeast region by 230,000 vehicles (1.76%) and move the associated freight using autonomous air vehicles.

Table 1-2: Target truck population, Northeast Region.

Body Type	Industry	(Data in Thousands - Nationwide)			
	Manufacturing	Wholesale trade	Retail trade	Services	Total
Multistop/Step van	19.3	72.1	85.4	49	225.8
Platform with added devices	12.4	16	26.4	25.8	80.6
Depressed Center/low boy	3.8	1.9	4.4	3.9	14
Basic platform	61.2	61.5	72	72	266.7
Insulated non-Refrigerated van	2.8	4.7	2.8	1.1	11.4
Insulated Refrigerated van	13.4	78.5	20.5	3.9	116.3
Drop Frame van	4.5	3.8	9.9	4.4	22.6
Open top van	1.6	1.5	.	1.2	4.3
Basic enclosed Van	78.5	100.7	82.5	40	301.7
Total	**197.5**	**340.7**	**303.9**	**201.3**	**1043.4**

	Nationwide	Northeast Region
Total Target Trucks	1,043,400	229,548

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[9] *Truck Inventory and Use Survey*, TC92-T-52, 1992 Census of Transportation, US Department of Commerce

1.4   USPS/Courier Operations in the Northeast Region

Although USPS and Courier Operations carry only 1% of the total regional tonnage, they account for 19% of the value of commodities shipped – making this mode of transport another ideal target market for an AVSLA.

The USPS identifies "Standard Mail (B)" as the standard class of service for mail weighing from 16 oz. to 70 lb. It accounts for 1% of USPS shipments but 15% of the weight shipped. The average package weight is 3.5 pounds and approximately 1.06 billion pieces of this category are shipped nationwide per year.[10] Conservatively, 235 million pieces of this type of mail is shipped in the Northeast Region each year.

In order to provide a complete analysis, package weights of up to 100 lb. were also included in this study. 60% of the total USPS/courier tonnage transported in the region was less than 100 lb.; data is not available on unit weight of these commodities, only total tonnage transported in specific weight brackets.[11] Again, a reasonable assumption is that some of the freight transported in the ">100 lb." range could be transported in the "<100 lb." bracket; thus, at a minimum, 60% of the tonnage transported consists of individual shipments weighing less than 100 lb.

In the Northeast region, the distance breakdown for freight under 100 lb. is slightly weighted towards shorter distances (see Figure 1-5).[12] Key points to note when examining this data are that

- almost 80% of all USPS and courier shipments travel less than 1,000 miles
- almost 60% travel less than 500 miles
- over 30% travel less than 100 miles

Based on the data presented in Figure 1-5, the ability to carry 100 lb. 500 miles is a reasonable mission profile for one class of vehicles in an AVSLA transporting the high V/T cargo classes currently being moved by the USPS and courier services. These high V/T cargo classes are listed in Table 1-3,[13] and vehicles designed to meet these payload and range requirements will be referred to as Light Lift vehicles.

Table 1-3: Top ten classes of cargo shipped via USPS Standard Mail (B) or Courier Service.

Commodity	Percent
Precision instruments	3.2
Chemical products and preparations	3.4
Machinery	3.8
Pharmaceutical products	4.7
Articles of base metal	4.9
Plastics and rubber	6.1
Electronic, electrical equipment, office equipment	9.3
Textiles, leather, and articles of textiles or leather	12.5
Miscellaneous manufactured products	16.4
Printed products	16.8
TOTAL	**81.1**

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[10] *Revenue Pieces and Weight Report, Fiscal Year 2000*, United States Postal Service
[11] *1997 Commodity Flow Survey, Northeast Region*, U.S. Department of Transportation / U.S. Department of Commerce, EC97TCF-REG(1), April 2000
[12] *1997 Commodity Flow Survey, Northeast Region*, U.S. Department of Transportation / U.S. Department of Commerce, EC97TCF-REG(1), April 2000
[13] *Ibid.*
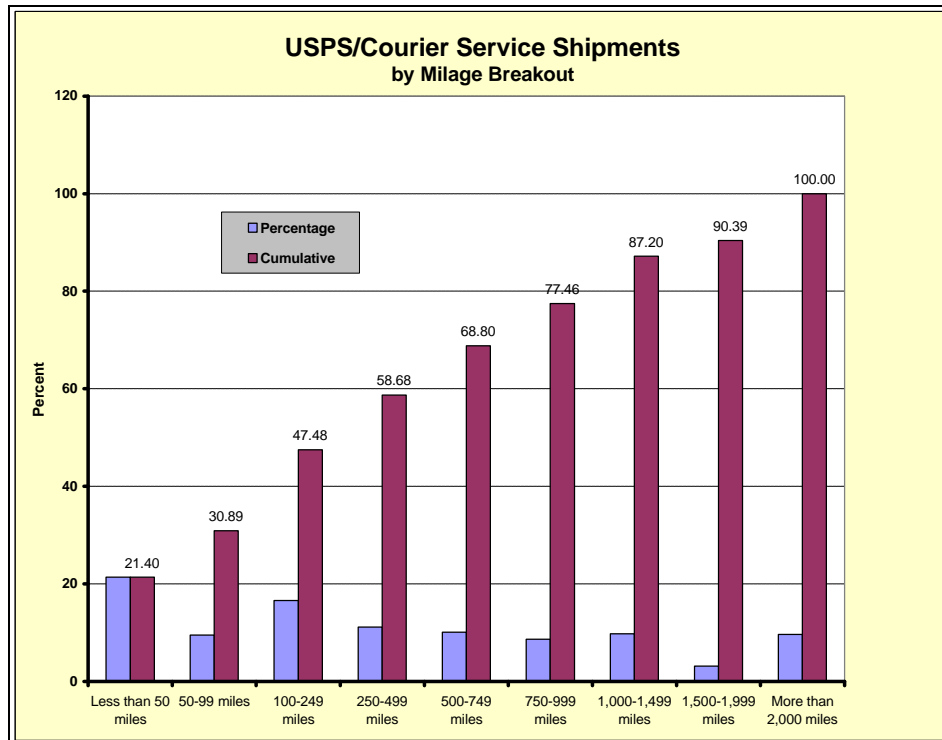
Figure 1-5: Shipping distance histogram for shipments in the Northeast U.S., weighing less than 100 lb., and being transported by USPS or by a Courier Service.

1.5 Total System Cost of Existing Architecture

Numerous attempts have been made to calculate the full public and private costs of the existing transportation system. There is a general recognition that the figures associated with some elements of the total system cost are very rough estimates. However, the total cost of the transportation system does play an important part in the motivation and necessity to move to a more modern and less costly system. Costs associated with the existing system can be categorized into either indirect costs or direct costs

1.5.1 Indirect Costs

Indirect costs are those costs that are not readily or specifically identified with a particular activity. In the case of the current (largely road-based) logistics network, there are three main categories of indirect costs: human costs, environmental costs, and other indirect costs. Human costs include the costs of lost productivity and happiness in the population and the loss of individual lives; human costs are difficult to quantify. The following are a few examples of the types of human costs attributed to the highway transportation system:

- Estimated 6,400 highway deaths per year are attributed to commercial trucks (approximately 11% of the total deaths on highways)[14]
- Estimated 50-19,000 cancer deaths per year attributed to carcinogens from vehicle emissions[15]

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[14] *Traffic Safety Facts 1997,* US Department of Transportation, national highway Traffic Safety Administration, DOT-HS 808 806, November 1998

[15] *Indicators of the Environmental Impacts of Transportation,* US Environmental Protection Agency, EPA-230-R-96-009, October 1996

- Estimated 852 million headaches annually from CO emissions associated with vehicle use[16]
- Estimated 40,000 premature deaths in the US per year from vehicle emissions[17]

Environmental costs represent societal costs of the damage done to the environment by the logistics architecture currently in use. Environmental costs are more measurable than human costs and include the following:

- Air pollution, generally considered the main environmental impact of freight movement, estimated to cost $40 billion per year[18]
- Greenhouse Gas Emissions, possibly as high as $47 billion per year[19]
  - Highway vehicles are responsible for 62% of Carbon Monoxide emissions, 32% of Nitrogen Oxides, and 26% of Volatile Organic Compounds according to EPA estimates[20]
  - Emissions from vehicle air conditioners
  - Tailpipe emissions
- Water Quality, estimated to be $39 billion per year[21]
  - Application of de-icing compounds (rock salt)
  - Polluted highway runoff
  - Wetlands and habitat reduction
- Noise, estimated to cost as much as $11.4 billion dollars per year[22]
- Tire, battery, antifreeze, and oil disposal. Estimated to cost $4.2 billion per year[23]

Other indirect costs not directly associated with health and the environment include

- Traffic congestion, estimated to cost as much as $181,635 million per year[24]
- Crash Costs, estimated to be as high as $839,463 million per year[25]

Trucks are responsible for as much as one third of this total.[26]

1.5.2 Direct Costs

Direct costs are those costs that are directly related or easily identifiable with a particular activity. The reliance on road-based logistics in the United States is clearly evidenced by the fact that local, state, and federal highway expenditure for the construction and maintenance of pavement and bridges is projected to total $125.3 billion annually.[27] Studies have shown that most pavement costs are directly related to damage caused by heavy vehicles.[28]

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[16] *Ibid.*

[17] *Ibid.*

[18] *Addendum to the 1997 Federal Highway Cost Allocation Study, Final Report*, US Department of Transportation, Federal Highway Administration, May 2000

[19] *Federal Highway Cost Allocation Study, Final Report*, US Department of Transportation, Federal Highway Administration, 1997

[20] *Ibid.*

[21] *Ibid.*

[22] *Ibid.*

[23] *Ibid.*

[24] *Ibid.*

[25] *Ibid.*

[26] *Ibid.*

[27] *Indicators of the Environmental Impacts of Transportation,* US Environmental Protection Agency, EPA-230-R-96-009, October 1996

[28] *Federal Highway Cost Allocation Study, Final Report*, US Department of Transportation, Federal Highway Administration, 1997

Other direct costs exist for a cargo carrier, including labor costs, fuel costs, and capital costs, but these are considered later as part of a comparison between an AVSLA and the current express package logistics architectures (see Section 2).

1.5.3 Total Costs

Costs associated with all Northeast highway transportation ($249B) and that specifically associated with trucking freight ($42B) are summarized in Table 1-5. The Northeast region costs shown represent worst case scenarios based on estimates of regional costs as a fraction of National figures.

As mentioned in section 1.3.1, adopting AVSLA could reduce the total truck population in the Northeast region by 230,000 vehicles (1.76%). This translates into a potential reduction of *$750 million per year* (as shown in Table 1-6) in highway transportation costs.

This $750 million annual reduction in total costs would be offset, to some degree, by the costs of operating the AVSLA architecture. However, the AVSLA concept has inherent transportation system savings (e.g. reduced congestion, crash, and direct highway costs). It would be designed with state of the art and environmentally friendly technologies, which, even if it operated at the relative costs indicated in Table 1-6, would still cost only *$40 million per year*. The net result of transitioning to AVSLA is, therefore, a potential saving of **$710 million, annually**.

1.6 Logistics Requirements Summary

AVSLA is best suited to transporting cargo with high value to weight (V/T) ratios. Two modes of transportation are currently used in the Northeast region to move these type commodities: trucking and USPS/courier service. Most trucking operations transporting high V/T cargo are shorter haul, medium weight; most USPS/courier operations are longer haul, lighter weight. Analysis of the high V/T freight being moved in the region suggests a two-tiered approach to air vehicle payload-range requirements (see Table 1-4). The first tier, referred to as "Light Lift" throughout this report, would consist of vehicles capable of carrying up to 100 lb. of cargo a range of 500 miles. The second tier of vehicles, called "Heavy Lift," would be capable of carrying up to 10,000 lb. of cargo a range of 250 miles. Implementing an AVSLA could reduce the roadway vehicle population in the Northeast by 230,000 vehicles, and save $710 million annually.

Table 1-4: Summary of AVSLA air vehicle payload-range requirements.

	Payload	Range
Light Lift	100 lb.	500 miles
Heavy Lift	10,000 lb.	250 miles

Table 1-5: Annual highway transportation costs for the Northeast U.S.

Estimated Costs of Highway Transportation for the Northeastern U.S.			
Factor	*Total Cost*	*Trucking Responsibility*	
Direct Costs (const. & maint.)	$27,566,000,000[29]	51.20%[30]	$14,113,792,000.00
Indirect Costs			
Air pollution	$8,897,460,000[31]	21.00%[32]	$1,868,466,600.00
Greenhouse Gases	$10,340,000,000[33]	20.00%[34]	$2,068,000,000.00
Water	$8,580,000,000[35]	10.00%[36]	$858,000,000.00
Noise	$2,518,120,000[37]	48.00%[38]	$1,208,697,600.00
Waste Disposal	$920,920,000[39]	10.00%[40]	$92,092,000.00
Congestion	$39,959,700,000[41]	14.00%[42]	$5,594,358,000.00
Crash Costs	$150,500,000,000[43]	11.20%[44]	$16,856,000,000.00
Total	*$249,282,200,000*		*$42,659,406,200.00*

Table 1-6: Annual total systemic cost of highway transportation.

Factor	Total Trucking Costs	AVSLA System Cost Savings (Replace 1.76% of trucks in region)	AVSLA System Costs	
Direct Costs (const. & maint.)	$14,113,792,000	$248,402,739	0.00%	$0
Indirect Costs				
Air pollution	$1,868,466,600	$32,885,012	50.00%	$16,442,506
Greenhouse Gases	$2,068,000,000	$36,396,800	25.00%	$9,099,200
Water	$858,000,000	$15,100,800	25.00%	$3,775,200
Noise	$1,208,697,600	$21,273,078	50.00%	$10,636,539
Waste Disposal	$92,092,000	$1,620,819	25.00%	$405,205
Congestion	$5,594,358,000	$98,460,701	0.00%	$0
Crash Costs	$16,856,000,000	$296,665,600	0.00%	$0
Total	*$42,659,406,200*	*$750,805,549*		*$40,358,650*

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[29] *Ibid.*

[30] *Addendum to the 1997 Federal Highway Cost Allocation Study, Final Report*, US Department of Transportation, Federal Highway Administration, May 2000

[31] *Ibid.*

[32] *Addendum to the 1997 Federal Highway Cost Allocation Study, Final Report*, US Department of Transportation, Federal Highway Administration, May 2000

[33] *Federal Highway Cost Allocation Study, Final Report*, US Department of Transportation, Federal Highway Administration, 1997

[34] Estimate

[35] *Federal Highway Cost Allocation Study, Final Report*, US Department of Transportation, Federal Highway Administration, 1997

[36] Estimate

[37] *Federal Highway Cost Allocation Study, Final Report*, US Department of Transportation, Federal Highway Administration, 1997

[38] *Ibid.*

[39] *Ibid.*

[40] Estimate

[41] *Federal Highway Cost Allocation Study, Final Report*, US Department of Transportation, Federal Highway Administration, 1997

[42] *Ibid.*

[43] *Ibid.*

[44] *Traffic Safety Facts 1997,* US Department of Transportation, national highway Traffic Safety Administration, DOT-HS 808 806, November 1998

2 MODELING AND SIMULATION

To better understand the variables that affect the cost and performance of an AVSLA, a cause and effect model was created using Vensim®, a visual modeling software package, designed by Ventana Systems, Inc. Within Vensim®, a dynamic system can be conceptualized, simulated, analyzed, and optimized. Using data gleaned from the logistics analysis, a Vensim® model was constructed to provide a quantitative cost and time analysis that then drove an economic competitiveness analysis within the Light Lift and Heavy Lift service bands described in Section 1.6.

The model simulated the constraints and actions of the three main parties in the shipping process – the requestor, supplier, and delivery agent. In the model, the requestor determines what product is needed, when it's needed, and where it should be delivered. This information is transferred to the supplier who can then create a quote of cost and delivery time based on both internal information (e.g. quantity in stock and production cost) and external information (such as the requestor's method of payment, delivery agent availability and cost predictions, exchange rates, etc.). Because the delivery agent participates in the ordering process, and is engaged prior to shipping time, the delivery agent can adapt its plans and prices to current market conditions. This is different from today's model in which the delivery agent picks up parcels according to prescribed routes and schedules and is unaware of the volume or weight of packages that will be received on a given day. Once the requestor has found a satisfactory product and price, an order is placed and the supplier begins the packaging and pre-shipping process. The supplier can estimate the time that the parcel will be ready for pick-up and the delivery agent can arrange to have a delivery vehicle present at that time to immediately accept the package and carry it to the requestor. Upon arrival at the requestor's site the delivery vehicle drops off the package and continues to the next pick-up. This operational concept requires some new technologies and some changes to the way that suppliers, requestors, and delivery agents interact. Foremost is the need to transmit, receive, and act upon a greater amount of data, and the need to ensure that data is secure throughout the entire process.

2.1 Evaluation Metrics

Two performance metrics have the greatest effect on the perceived value of a logistics system: total delivery time and cost. During this study, it was assumed that the total time from request generation to delivery must be the same as or shorter than the current logistics systems, and that total delivery cost must be less in order to provide an attractive substitute for the systems that are in place today. The VenSim® model was used to determine the factors that affect delivery time and cost. Pick-up time (which includes all time from when a parcel is ready for shipment until the package is en route to its destination) is based on vehicle availability and the method of pick-up at the particular supplier. En route travel time is then based on delivery distance, vehicle speed, and transfer factors, if the cargo is moved from one vehicle to another during shipping. Finally, the drop-off system at the requestor's delivery site is a factor that determines the time taken to drop-off the package. Cost is affected by the vehicles' total hourly operating costs, total delivery time, fixed costs, and overhead.

2.2 Model Details

The actual Vensim® model is shown in Figure 2-1. The model consists of variables representing the characteristics of each component of the triad. These variables are linked via directional arrows that show causal relationships. Color-coding is used to help distinguish

between links from the three components of the triad. Blue arrows represent requestor outputs, green arrows show supplier outputs, maroon arrows represent delivery agent outputs, and red arrows show the links between the two main outputs (system cost and overall delivery time) and the rest of the model. Note that this model is independent of the logistics architecture used – some architectures take full advantage of certain information routes while others ignore those communication avenues.
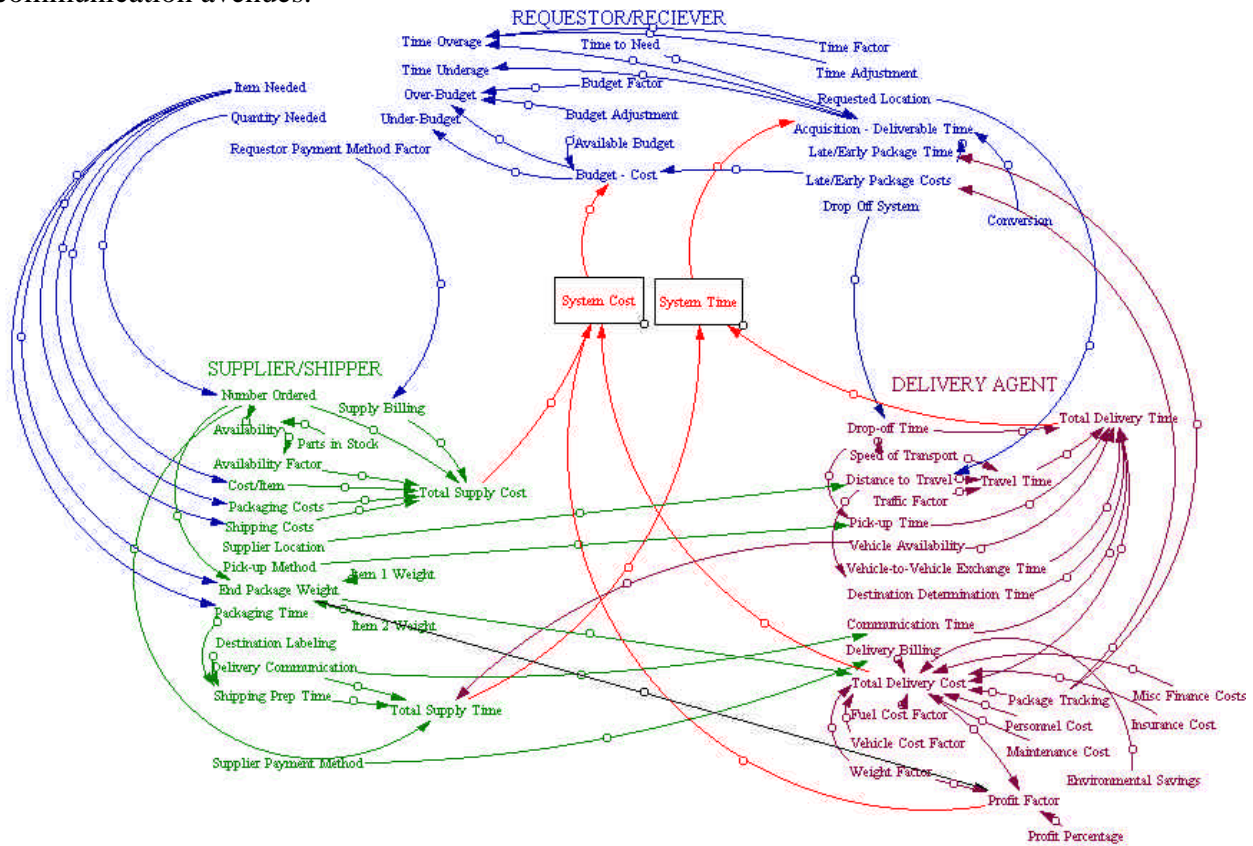
Figure 2-1: Vensim® model of the requestor/supplier/delivery agent triad.

Once a model is created, any factor within the model can be isolated and its causal relationships can be viewed (as well as its downstream effect relationships). Figure 2-2 is a sample of a causal chain for system cost.

In addition to generating cause and effect trees, the Vensim® model was used to generate quantitative estimates of delivery cost and time for the parcel categories that aligned with the AVSLA vehicle tiers. These parcel categories were termed "light transport" for parcels weighing less than 100 lb. and "heavy transport" for parcels weighing between 1,000 lb. and 10,000 lb. Due to the fundamental nature of the triad model, it can efficiently simulate any parcel size or logistics architecture. The analysis for each parcel category includes a comparison of the current transportation architecture and vehicle with the proposed architecture and vehicle. For the light transport category, the logistics architecture currently used by express package industry companies (such as UPS or FedEx) was compared to an AVSLA using small VTOL aircraft in a point-to-point delivery scheme. The heavy transport analysis made a comparison between the current trucking industry and an AVSLA using medium lift autonomous VTOL aircraft in a point-to-point delivery scheme. Due to the similarity in the payload and range requirements for commercial heavy transport vehicles identified in this study and typical military

transport requirements, the values obtained for the heavy transport system are deemed applicable to a military logistics architecture.
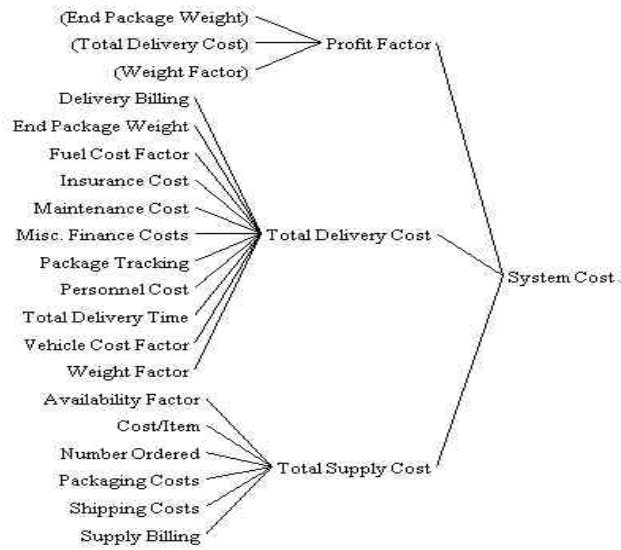
Figure 2-2: Causal tree for system cost generated by the Vensim® model.

3   DELIVERY ARCHITECTURE

The architecture of a delivery system is largely defined by three key factors – the delivery network topology, the vehicle routing methodology, and the scheduling process. Consider a trip by car from New York to Los Angeles as an analogy. In this case, a highway map, such as the one in Figure 3-1, describes the network topology. By selecting a specific set of roads from the large set available to follow in order to reach Los Angeles, a vehicle routing task is performed, and the scheduling process consists of deciding when to leave – it could be based on what time a traveling companion finishes work.
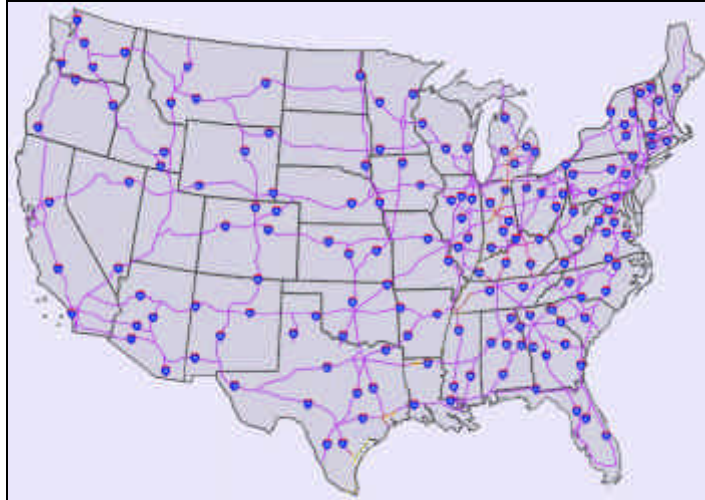
Figure 3-1: A map of the interstate system in the United States. The interstate system is essentially a U.S. government logistics network topology.

A large factor to consider in designing a new delivery system is the system's delivery network topology, that is, the "shape" of the paths that packages follow while traveling from origin to destination. Vehicle requirements (for both size and distance), system requirements (including transfer stations and communication hubs), and required intermediary equipment all depend on the topology of the delivery network. Many different delivery network topologies are used today, depending on the type of transport. The systems analyzed in this report include distributed, hub and spoke, flattened hub and spoke, point-to-point, and a hybrid distributed architecture.

Other factors that define the operation of a logistics system are the vehicle routing, which asks what specific route each vehicle follows, and service scheduling, which determines when pick-ups and deliveries will occur. Another aspect of the operational architecture is the form of vehicle routing and scheduling used. Vehicle routing is dependent on the restrictions placed upon the system. Variations include a prescribed routing plan, a constrained routing method, and a complete decision-based unconstrained system. The choice of what routing method to use is heavily impacted by government regulations, especially for UAVs. Scheduling is much more difficult to define. Package delivery services tend to use scheduled service and priority-based service, and trucking companies often use a posture-based or asset-based service. However, advanced computing technologies have the use of a predictive-adaptive service scheduling a realistic possibility.

The impacts of each of the different aspects of the operational architecture are analyzed further in the following sections. A point-to-point system with asset-based scheduling and unconstrained flight paths is finally selected in the conclusion of this section.

3.1 Network Topology

The network topology is a fundamental attribute of a delivery system. Much time and effort is put into the design of the most efficient system based on delivery style, needs and package statistics. The following analysis of common systems is a preliminary look at the best solution for the new architecture design; however, further analysis will be necessary in Phase II to completely define the system to be used.

3.1.1 Hub and Spoke

The Hub and Spoke topology is commonly used by light package handling services, such as UPS and FedEx. This type of topology gains efficiency by consolidating packages with relatively close origins and destinations into a single shipment prior to making large movements. This method provides economy of scale during long-range movements, but often adds inter-vehicle and inter-modal transit times as packages are shifted from one vehicle or mode of transit to another. At each step of consolidation, the packages are transferred to larger and larger vehicles. The typical scenario is that a package is collected and transported by small delivery vehicle to a local hub. This package then is transferred to a larger vehicle along with other packages leaving the region that are then carried to a facility where a long-distance vehicle is loaded with packages destined for locations greater than approximately 500 miles. Once the long-distance vehicle arrives at the destination hub, packages are dispersed in stages that reverse the consolidation process until the package reaches its final destination. Figure 3-2 depicts the Hub and Spoke topology graphically. This topology was analyzed in the Vensim® model by including vehicle-to-vehicle transfer time, which models the transfer of packages at each hub.
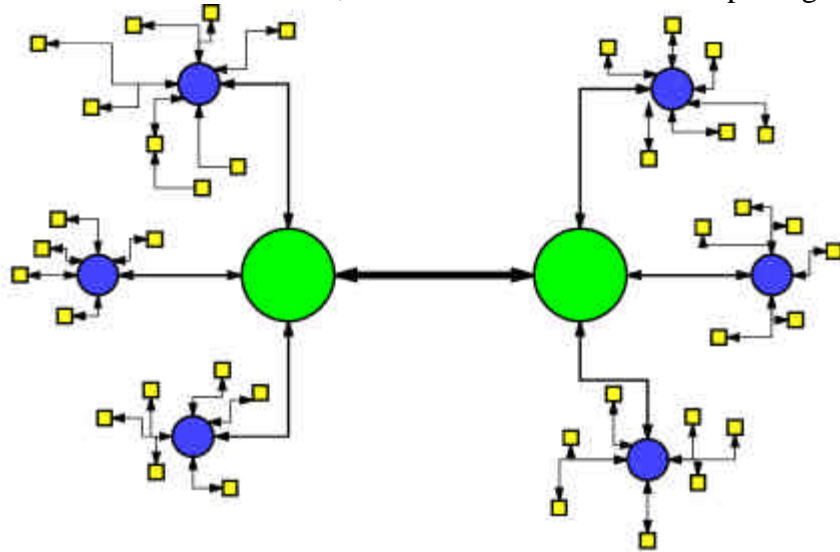
Figure 3-2:Illustration of the Hub and Spoke routing concept. Note there may be only one top-level hub.

As implemented by most companies in the express package industry, this topology works well by using ground transportation for local transport and air vehicles for long-distance transport. The system is dependent on a combination of low cost, large capacity ground vehicles and small aircraft for transport between the local and long-distance hubs. After viewing the

operation cost comparison between the average 10,000-lb. capacity truck and a similar VTOL, it's apparent that a VTOL replacement is not as efficient as a truck. However, the drawback to keeping a ground truck in the system is the time required for transfer of packages between lighter vehicles and the large trucks and the time taken to transport packages from the local hub to the long-distance hub. Additionally, in practice, this concept can result in as many as 8 mode changes, adding considerable time and cost to the delivery of a single package.

3.1.2 Flattened Hub and Spoke

Similar to the standard Hub and Spoke topology, the Flattened Hub and Spoke topology uses regional or local hubs to consolidate long-distance packages. These packages are then directly transferred from local hub to local hub without the use of a long-distance hub. This system is illustrated in Figure 3-3.

The disadvantage of the Flattened Hub and Spoke topology is that the hub spacing is more varied, requiring the vehicle that travels between hubs be capable of traveling distances anywhere between 100 and 3,000 miles. Two options are available to provide those vehicle capabilities. The first is to design a single vehicle type to transport a payloads up to 3,000 miles, which is then underutilized on shorter routes. The second is to size two vehicles, one designed for shorter distances and the other for 3,000 miles. Having two vehicle types is similar to the standard Spoke and Hub method. The difference lies in the increased number of transfer points for this system, which is likely to increase the number of vehicles required; as the number of vehicles increases, so do maintenance costs and system complexity.

The advantage to the Flattened Hub and Spoke topology is that only two transfers of packages, from one vehicle to another, are made. By reducing inter-vehicle (and perhaps inter-modal) transfer times, total delivery time is shorter than for the standard Hub and Spoke, so long as the vehicles themselves are as efficient, or as fast, as those used in the standard Hub and Spoke.
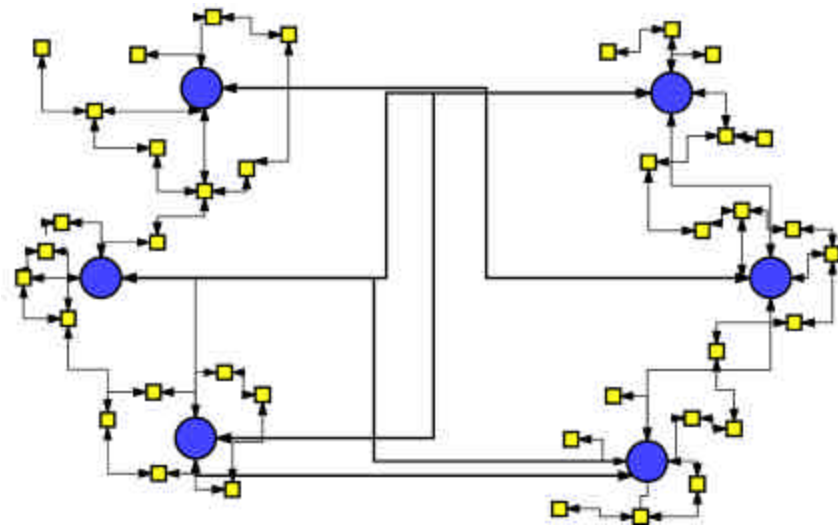
Figure 3-3: Illustration of the Flattened Hub and Spoke routing concept.

3.1.3 Distributed (Point-to-Point)

The Distributed topology is much different. In this system, packages are delivered by one vehicle that travels completely from origin to destination. In the diagram below, the squares can represent either a package origin or a package destination. Whenever a vehicle drops off a

package, it is dispatched to receive the closest package that is awaiting pick-up in order to minimize asset latency.
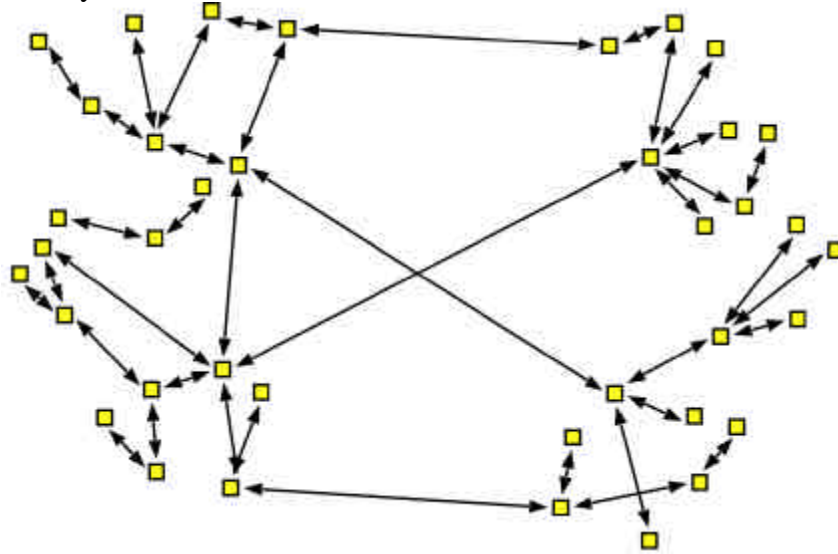
Figure 3-4: Illustration of the Distributed (Point-to-Point) routing concept.

The greatest disadvantage to this topology, like those already discussed, is the need for one vehicle with the range to travel short or long distances. In order to hold enough fuel to travel the width of the country, for example, a vehicle would need to have a large gross weight, due to fuel capacity. In addition, without the use of hubs, as vehicles drop-off their payload, the effective use of vehicle assets drops to zero until a new shipment is found and picked up.

There are two major advantages to this topology – customer perceived delivery speed and flexibility. Because packages can be delivered door to door by one vehicle with no transfers, package recipients can receive their packages more quickly than any other system using comparable vehicles. Additionally, since this topology does not force the shipping company to invest heavily in package routing hubs, the topology is fundamentally more flexible, that is the topology can change with daily package volume or long-term shipping trends. Figure 3-4 is an illustration of what a distributed network might look like. For shorter distances, this method is the most effective and requires less manpower or machine-power to operate. At a regional level, the value of this approach depends on the average shipping distance.

3.1.4   Hybrid Distributed

In order to provide the most effective system, a derivative of the Distributed topology, referred to as a Hybrid Distributed (HD) topology, is analyzed and will be an area of focus during Phase II. Due to cost, time, and the design of light-lift air vehicles, it may be more feasible to use an HD topology for widely dispersed markets with long average shipping distances. This system maximizes the benefit of using light-lift VTOL aircraft, which can carry a 100-lb. package, 400 miles in just over 3 hours. However, because Phase I only analyzes the system for use in the Northeast corridor, where the longest high package volume shipping route is about 400 miles (Boston to Washington D.C.), the HD topology is only discussed here because it may prove useful for larger scale applications. During Phase II, scaling of an AVSLA to a national level will be analyzed in which a form of the HD topology will be included that would presumably include use of an airport hub scenario similar to Figure 3-5. A trade study between transferring long distance packages to another vehicle, transferring a package through a series of

light vehicles, or using a light vehicle with multiple refueling stops to get the package to its destination will have to be performed. Using a light vehicle could take up to 15 transfers (or 15 refuelings) to go from the East Coast to West Coast. The HD topology offers the flexibility and delivery time advantages of a distributed topology locally and regionally, and the economy and volume capability of a hub and spoke topology at the national and global levels.
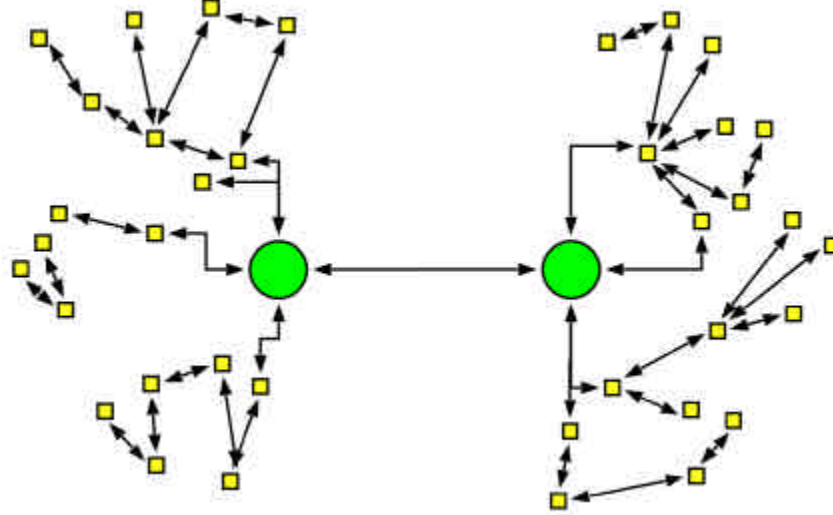
Figure 3-5: Illustration of the Modified Distributed routing concept.

3.2   Vehicle Routing

Although the delivery network topology determines how all elements of a delivery network are connected, it does not determine the specific route that a package takes while travelling from its origin to its destination. Additionally, unlike the car travel analogy presented at the beginning of this section, air routes are three-dimensional and can change in response to weather, traffic patterns, and other influences.

Today, the flight paths of autonomous vehicles are constrained by government regulation to areas that are unpopulated or over water; it is difficult to guess at where the government and the public will allow unmanned aircraft to fly in the future. Because it is impossible to forecast the exact nature of future regulations, the routing preference for an entirely automated system is difficult to define. The FAA will make many decisions in the next ten to twenty years regarding UAVs that will greatly effect the outcome of this architecture. In order to promote an automated airborne package delivery system, the FAA must be convinced to reduce restrictions on UAV use, especially if they are proven safe. In order to enable AVSLAs, it is important to dedicate resources to proving the safety of UAVs and to educating the public and the regulatory community about these efforts. However, UAVs may continue to be forbidden to fly over populated areas for some time. This type of restriction would change the viability of using UAVs to deliver personal packages or commercial packages within the heavily populated areas where congestion on the ground infrastructure is worst. Restrictions as minor as keeping UAVs from entering airspace around central transportation hubs, like airports and heliports, are more likely and can be overcome without too much negative impact on the AVSLA. Since much depends on the outcome of the FAA's decision, various routing structures are analyzed based on an open airway system with minimal restrictions; further study during Phase II would look at creating a relationship with the FAA to influence the development of future UAV regulations.

3.2.1 Prescribed Routing

Prescribed routing is typically implemented along with fixed scheduling, and is the routing most used by UPS, FedEx, the USPS, and other carriers for small parcels. In a prescribed route system, vehicles follow specified routes during the transport of a package. The benefit of such a system is that travel times are very consistent and can be predicted in advance. Being able to determine where a vehicle will be at any point in time is also beneficial for tracking packages and handling vehicle malfunctions. In addition, routes can be planned to avoid the most populated areas, minimizing damage in the event of an accident. The drawback to this type of routing is that vehicles are constrained to particular routes even during high traffic times and/or adverse weather conditions. This type of constraint could cause large delays in delivery times, making the system less attractive to users. Recent advances in logistics planning and analysis have created the ability to modify the routes that are prescribed for each vehicle on a daily basis. The limit to this technology, however, is that many parcel delivery services have specified pickup locations that must be visited at specified times each day. No information about the parcels waiting at those pickup locations is available until a vehicle visits them.

3.2.2 Constrained Routing

Constrained routing provides restricted areas and 'no-fly' zones, but allows for routing choices to be made and changed at any point, as long as the flight path doesn't cross a restricted area. Constrained routing is much more lenient than prescribed routing and allows for deviations from the standard route. Adding deviation capability removes the disadvantage of not being able to avoid adverse weather or heavy traffic areas. In addition, a vehicle can compute the fastest route given the conditions on multiple routes. Generally, by allowing a vehicle or control center to choose the best route based on current conditions at each moment in time, the system, as a whole, becomes more efficient. Constraints may include no-fly zones in which a vehicle would need to avoid military areas, airports, high traffic areas, etc.

3.2.3 Unconstrained

The unconstrained system is similar to the "free flight" concept in that a flight path can be chosen and changed at anytime; information is readily available regarding heavy traffic areas, such as airports and heliports, but the user is not restricted from these areas.[45] Although this method is a new concept, many of the researched air transport systems are leaning towards a "free flight" system. In general, the heavy-lift UAVs will typically be oriented away from city centers and heavy traffic areas; however, the light-lift vehicles are envisioned to operate in these areas. This means that, in order to enable an unconstrained system, the light-lift UAVs will need to either choose to avoid airports and other highly congested areas or be able to maneuver easily through such an area. Allowing "free flight" enables the vehicles to operate at their most efficient level, maximizing time savings. Some restrictions to the system may need to be added for national security issues, which would bring the unconstrained system closer to being a constrained routing system.

3.3 Scheduling

An analysis of the types of scheduling available was completed and shows that scheduling is directly related to the vehicle capabilities within the architecture. For instance, most parcel delivery services are based on a regularly scheduled service due to the cost effectiveness of having a delivery van as full as possible. However, a partially loaded van can

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[45] http://www.faa.gov/freeflight

still be profitable. The trucking industry is more asset based, because it's very inefficient to move empty or partially loaded trucks. Each of these industries provides priority service, if needed; however, there is a large cost to the customer for using that service. The added cost is due to the need to send an empty vehicle from its current location to the priority pick-up. The longer the truck or van remains empty, the larger the cost passed on to the priority customer. The optimum service would be one that could predict or know of deliveries in advance, so that vehicles could be positioned to react to a delivery as it becomes available.

In addition to establishing relationships with large customers, other technologies could aid in efficient vehicle scheduling. For instance, if a shipper knows the destination, weight, and size of a parcel in advance, the shipper could provide a real-time quote on the price to ship that package based on the current status of the network. The shipper could also realize, and offer as an option to the customer, that, by slightly delaying the parcel pick-up to allow another pick-up and delivery to occur, a delivery vehicle could travel less distance without a package in it, and therefore operate more cheaply, reducing the cost to the customer. One technology that could enable this is a smart pickup facility capable of determining package destination and weight and transmitting that information to a central scheduling and routing system. Then, for instance, a mailbox would not be visited for its regularly scheduled pickup if it were known in advance that it was empty.

3.3.1   Standard Scheduled Service

Although a standard scheduled service is basically self-explanatory, it should be noted that this 'tried-and-true' method is used for public transportation, parcel delivery service, air transport, and the standard work schedule of the majority of Americans. Changes to this basic system have been gradually accepted, but are slow in coming; the use of this type of scheduling by the UAV light-lift or heavy-lift architectures would be very inefficient. For the light-lift system, if packages weighing close to 100 pounds were pooled together for pick-up at a specified time a UAV for each package would be needed for delivery, due to the low payload capacity of each vehicle. A large time loss would be incurred as vehicles waited in line for loading. For the heavy-lift system, it has already been shown that these vehicles are not cost effective for regular delivery. Therefore, with an on demand type system, regular scheduling would not be appropriate, as it would be unknown when the vehicles would be in use or unneeded.

3.3.2   Posture-Based Service

Posture-based service is a method of scheduling that determines where vehicles are sent based on their current location. This system minimizes the distance vehicles travel empty or unloaded. Pick-up locations depend on where current vehicle assets are located. For example, if a vehicle were delivering a package to a suburb of New York City, then the next scheduled package pick-up for that vehicle would be expected to also be in or around New York City. The largest drawback to this type of system is that pick-ups and deliveries to remote locations are scheduled last, due to the inefficiency of moving an empty vehicle. This can be avoided by having vehicles that can quickly reach any destination in the area without incurring large expenses for traveling empty.

3.3.3   Priority-Based Service

Priority-based service schedules packages in order of importance or priority. Typically customers pay more to have their package designated priority. A useful analogy is found in hospitals, where triage is used to determine the severity of a patient's condition, and hence the priority of treating that patient. A patient in critical condition is cared for prior to a patient with

minor wounds even if the request to care for the patient in critical condition was made after that of the patient with minor wounds. By the current delivery standards, a customer who needs to have a package delivered quickly pays an additional charge for priority service. That priority package goes through a separate handling process, which costs the delivery agent more to provide than the standard service.

If an entire architecture were set-up on a priority-based service, the charge for delivering a priority package might fall quickly. Package pick-ups and deliveries could be scheduled by priority. The charge for priority service becomes a trade-off between the location of the nearest available vehicle and the number of packages to be delivered in the area that aren't priority. Since the priority package takes precedence over the non-priority packages, the customer would have to compensate for their preferred order. As the system becomes more efficient, the cost difference between priority and non-priority shipment could decrease.

3.3.4   Predictive-Adaptive Service

Due to the advanced technologies used in the computer industry, many architecture related systems have been designed around computer capabilities to be more time and cost efficient. One of these architectures relates directly to the package shipping industry. Predictive-adaptive service is one in which the dispatch system reviews the history of previous shipments to determine where shipments are likely to occur. This type of system is perfect for handling repetitive mass delivery situations, such as just before Christmas, and lulls in shipping, such as the week after Christmas. In addition, if specific customers often ship at specified times of day or year, more vehicles can be prepared for upcoming deliveries from that customer. The greatest benefit to this architecture is that it can be combined with any of the previous architectures. For instance, a bus company may have a set schedule, but on expected heavy days they may send two buses instead of one. A similar scheduling methodology can work with UAV package delivery.

The heavy-lift transport also benefits from predictive-adaptive scheduling. A fire-fighting network could use fire probability prediction models to prepare fire-fighting UAVs to be in locations most likely to have forest fires. In terms of military use, during battle the system can predict periods of ammunition needs based on the last rate of usage or a history of previously requested deliveries during similar battles.

For either transport type, the predictive-adaptive methodology may incur errors at times; however, it provides an effective use of vehicle assets a large percentage of the time. As the system becomes experienced and develops more history, the adaptation becomes more effective and time and cost is lowered throughout the delivery system. Of course, a predictive-adaptive scheduling system risks adversely affecting the system if a sudden change in patterns occur.

3.4   Architecture Conclusion

As determined in the Cost Analysis section, it is apparent that using an airborne replacement for the tractor-trailer trucks used by current delivery agents is not cost effective. By including transition time into the Vensim® model, it was shown that it also isn't time effective to transfer packages from an air vehicle to a truck in the Flattened Hub and Spoke system. With the ability to travel up to 400 miles in approximately 3 hours (and with a maximum vehicle range of 500 miles), the point-to-point system or distributed service derivative had the best overall cost and time results and is the recommended approach for the delivery architecture.

As mentioned, the routing choice depends greatly on FAA restrictions for UAVs; using the assumption that the FAA will eventually settle on fairly minimal flight restrictions for UAVs,

an unconstrained "free flight" system is recommended. Determining the FAA's stand on this issue will be necessary in Phase II of the AVSLA in order to provide substantiating evidence that UAV restrictions will be lenient.

In determining the scheduling method, it is important to realize that the vehicle design allows for quick transport from any location within a region to any other location within the region in 3 hours. Given this ability, it's logical that a service that is similar to the asset-based system would be the most cost and time effective. Minor alterations to the system can include a predictive-adaptive model that optimizes the use of vehicle resources. In addition, the architecture would work with customers that implement the "just in time" form of shipping. This would allow customers to call before an item is ready for shipment. By the time a vehicle arrived the shipment would be ready, bypassing any need for warehousing. Coincidentally, the shipment could be dropped off "just in time" to be used or consumed by the receiver. Overall, the architecture is optimized to improve delivery time, lower cost, and lower storage charges that incur from shipping quantities exceeding the current need.

4 VEHICLE DESIGN

Once the system and basic vehicle requirements were identified (i.e., Light Lift: 100 lb. payload for 500 miles, and Heavy Lift: 10,000 lb. payload for 250 miles), the vehicle design stage was initiated. Multiple designs were brainstormed for both the Heavy Lift and Light Lift vehicles and a Sikorsky sizing program (called VTM+) was used to pinpoint the advantages and disadvantages of each design. From a large number of configurations, three designs were down-selected for the Light Lift category and two vehicles for the Heavy Lift based on a relative ranking, by expert opinion, of the expected performance of each vehicle configuration in key performance areas. Next, the vehicles were modeled in CATIA® to provide a visual representation of each concept. Ultimately, one design was recommended for each category – these vehicles are summarized at the end of this section.

4.1 Light Lift Vehicle Sizing

Due to constraints on size and weight, the Light Lift vehicle proved to be the most difficult to model. In order to maneuver within local neighborhoods, the vehicle should be light and small (less than 10 ft x 6 ft x 3 ft), allowing it to easily fit easily within a driveway or parking space. Additionally, the vehicle is required to hover with a 100-lb. payload and have sufficient redundancy to fly safely over populated areas. Table 4-1 lists vehicle types sized for the Light Lift category and corresponding advantages and disadvantages.

The advantages and disadvantages were weighed between the designs and six vehicle types were chosen for further consideration and sizing. After sizing the six vehicles, they were compared using a weighted average of safety, initial design cost, operating cost, difficulty of control, overall weight, and fuel consumption metrics. A group of design experts assigned scores in each category for each vehicle based on sizing results and past experience. Table 4-2 shows the results of this comparison. The two designs with the highest scores (the tilt shroud and the shrouded fixed-angle side-by-side, referred to simply as the angled shroud) were chosen for further analysis. Table 4-3 presents a summary of the attributes of each design. The sizing results in Table 4-3 include weight reductions due to nanotechnology based materials, and current technology in rotary engines. [46] Because the NIAC mandate is to focus on systems that will exist 20-40 years in the future, an estimate of the impact of future technologies on the vehicle designs was made. Researching possible advancements showed that the most useful benefits derive from nanotechnology. According to the National Nanotechnology Initiative[47], nanotechnology efforts expect to "Develop materials that are 10 times stronger than steel, but at a fraction of the weight…" and improve "…computer speed and efficiency of minuscule transistors and memory chips by factors of millions making today's Pentium IIIs seem slow." Additionally, the high funding level for nanotechnology research indicates that some of this new technology may be available, as touted, by the year 2020. This technology is most critical for the Light Lift vehicle design. In order to represent the effects of nanotechnology in the sizing software, a structural weight technology factor of 0.2 (20%) was used for all body, wing and rotor components, a factor of 0.4 (40%) for engine and fuel system components, and a 0.6 (60%) factor for drive systems and flight controls. These factors are multiplied by parametric estimates

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[46] New rotary engine technology founded by Freedom Motors; Davis, CA (www.freedom-motors.com)
[47] *National Nanotechnology Initiative: Leading to the Next Industrial Revolution* part of the president's FY 2001 budget NSTC/IWGN report.

of system weights based on today's technology to estimate system weights using 2040 technology. A 10% increase in fuel efficiency is also assumed.

Table 4-1: Advantages and disadvantages of vehicle concepts considered for Light Lift service.

Vehicle Type	Advantages	Disadvantages
Standard Helicopter	Known dynamics, previous assembly knowledge, existing vehicles of required size (tried and true method)	Heavy vehicle w/ large fuel consumption rates, load would need to be external or connected to the structure (like the skycrane), external load handling would require extensive additional control logic. Safety issue with open bladed rotor and open bladed
Co-axial Rotor Helicopter	No tail rotor needed, increased power from engine(s) due to lack of tail rotor, dynamics and design are similar to standard helicopter.	Heaviest of vehicle designs analyzed, addition of wing to decrease rotor dependency during forward flight isn't feasible, and safety issues with open rotor design.
Tilt Wing	Stable high-speed forward flight, aerodynamic in hover and forward flight, fuselage is more accessible to store load while maintaining aerodynamics, wing adds to lift lowering fuel costs, and smaller proprotors for some added safety.	Control difficulties in hover and transition, "Barn door" effect caused by wing in transition, ailerons change from roll in forward flight to yaw in hover adding to control difficulty, and safety is still an issue on open proprotor design. Wing tilting mechanism adds complexity.
Tilt Rotor	Stable high-speed forward flight, aerodynamic in forward flight, accessible fuselage for load, ease of control, wing adds to lift lowering fuel consumption in forward flight, and smaller proprotors for limited added safety.	Safety issue with open proprotor design. High disk loading increases hover power requirements. Extra motors or mechanics required to tilt rotors.
Shrouded Rotor	Enclosed rotor adds to vehicle safety, shrouding or ducting the rotor adds some efficiencies during hover, and control vanes within the shroud adds to control ability. Ability to add wing adds to lift in forward flight, reducing reliance on rotors.	Less efficient than open rotor design in forward flight, rotor placement critical for maximum payload size (i.e., inefficient to place in fuselage), larger engine size required to meet forward flight speed requirement.
Angled Shaft Shrouded Rotor	Enclosed rotor adds to vehicle safety, angled shaft maintains hovering efficiencies and increases forward flight efficiencies, control vanes within the shroud adds to control ability, and ability to add wing reduces rotor reliance and reduces fuel costs i	Balance of more efficient duct-type rotor with forward flight inefficiencies is difficult to obtain, rotor placement critical for maximum payload size.
Shrouded Rotor w/ Rear Prop	Rear prop overcomes forward flight inefficiency, enclosed rotor adds to vehicle safety, ability to add wing reduces rotor reliance and fuel forward flight fuel costs, and veining within the shroud adds to control.	Adding the rear propeller increases vehicle weight, and rotor placement remains critical for maximum payload size.
Shrouded Tilt Rotor	Shrouded rotor efficiencies are kept for hover and forward flight, enclosed rotor design adds to vehicle safety, ability to add wing decreases fuel costs, and vehicle is stable at all speeds.	Addition of shrouds to wing ends adds to overall wingspan (i.e., length requirements are an issue). Tilting motors required to move ducted rotors from hover to forward flight.
Shrouded Fixed-Angle Side-by-Side (Angled Shroud)	Shrouded rotor efficiencies are kept for hover and forward flight, enclosed rotor design adds to vehicle safety, ability to add wing decreases fuel costs, reduced complexity due to lack of rotor tilting mechanism.	Reduced forward flight efficiency due to relatively large momentum drag (flow turning). Shrouds may increase weight and vehicle size.

Table 4-2: A weighted comparison of the six top vehicle types.

		Helicopter		Co-axial		Tilt Shroud		Tilt Rotor		Angled Shroud		Tri-rotor	
	multiplier	score	total	score	total	score	total	score	total	score	total	score	total
Safety	5	2	10	2	10	5	25	1	5	5	25	5	25
Design Cost	1	5	5	4	4	3	3	4	4	3	3	3	3
Operating Cost	5	3	15	3	15	4	20	4	20	5	25	4	20
Ease of Control	4	2	8	4	16	5	20	5	20	5	20	5	20
Gross Weight	4	1	4	1	4	5	20	5	20	5	20	3	12
Fuel Mileage	1	3	3	3	3	5	5	5	5	5	5	5	5
Total Score (max = 100):			**45**		**52**		**93**		**74**		**98**		**85**

Table 4-3: Summary of design attributes for the two vehicles suggested for the Light Lift mission.

	Tilt Shroud		Angled Shroud	
Design GW	314	lbs	369	lbs
Payload	100	lbs	100	lbs
Empty Weight	142	lbs	171	lbs
Weight Empty Fraction	45	%	46	%
Fuel Weight	72	lbs	95	lbs
Fuel Capacity	11.1	gal	14.6	gal
HP Installed	88	shp	120	shp
GW/Arotor(s)	20	lbs/sqft	25	lbs/sqft
Rotor Radius	1.58	ft	1.53	ft
Equiv Blade Chord	0.18	ft	0.22	ft
AR Blade	8.9		7.1	
Tip Speed	700	ft/s	700	ft/s
RPM Rotor	4229	RPM	4363	RPM
# Blades/rotor	3		3	
# Rotors	2		2	
Wing Loading	20	lb/sqft	20	lb/sqft
Wing Aspect Ratio	3.0		3.0	
Wing Area	15.7	sqft	18.4	sqft
Wing Span	6.86	ft	7.44	ft
Inbd Root Chord	3.05	ft	3.31	ft
Inbd Tip Chord	1.53	ft	1.65	ft

Figure 4-1 shows a conceptual rendering of the tilt shroud Light Lift aircraft in forward flight mode. In forward flight, this aircraft measures approximately 15.5 feet across and 8 feet long. Figure 4-2 shows a conceptual rendering of the angled shroud Light Lift aircraft, which has approximately the same dimensions. Both of these concepts have all-moving horizontal tails which are also part of the landing gear system. When in vertical flight and landing, the horizontal tail is rotated into a vertical orientation as shown in Figure 4-3. This reduces the ground spotting to about 6.5 feet from nose to tail, enabling the aircraft to fit within any area that can accommodate a typical delivery truck. Additionally, using the horizontal tail in this way reduces complexity by eliminating the need for additional landing gear actuators. Note that neither aircraft has a vertical tail. Yaw control will be accomplished using differential thrust from the proprotors and differential drag on the wings.

Based on the sizing results shown in Table 4-3, the tilt shroud concept was selected as the best for a Light Lift AVSLA vehicle. This is mainly due to the increased cruise performance of the tilt shroud, which is sufficient to offset the weight penalty of the tilting mechanism. Of course, this conclusion is only valid if the aggressive technology improvements that were

assumed in generating these numbers are realized. Phase II will further investigate the impact of technology maturity assumptions.
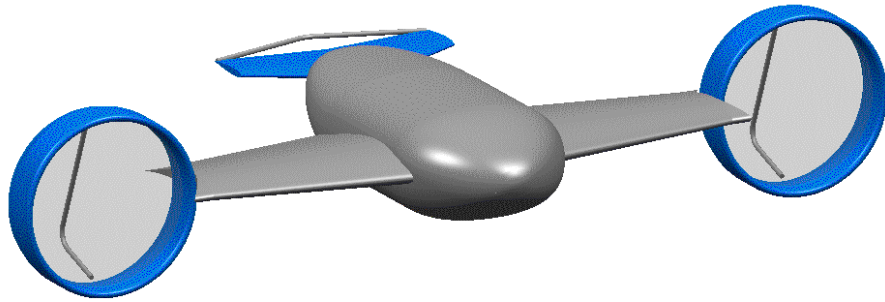
Figure 4-1: Rendering of the tilt shroud light vehicle concept.
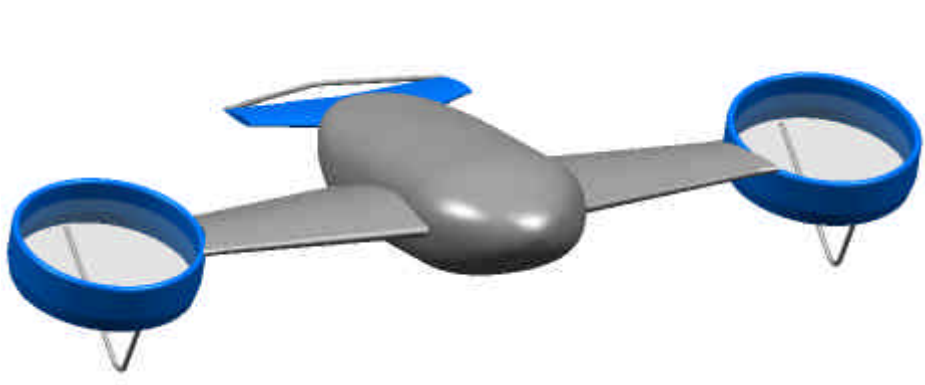
Figure 4-2: Rendering of the angled shroud light vehicle concept.
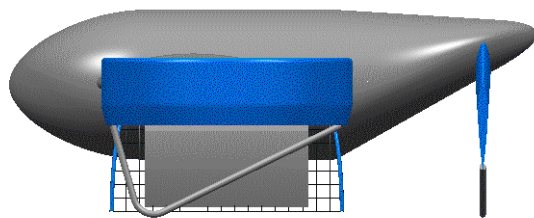
Figure 4-3: Tilt shroud light vehicle concept in landing configuration. Note how the horizontal tail becomes part of the landing gear.

4.2   Heavy Lift Vehicle Sizing

Because size constraints are relaxed, safety, cost, and efficiency drive the Heavy Lift vehicle design. As already noted, the cost to operate the large vehicles makes them most suitable for high-risk or cost insensitive applications. Therefore, the design had a goal of providing as many cost saving opportunities as possible, which coincidentally created a more efficient vehicle as well. As always, safety is the foremost concern. An emerging technology is put under

rigorous scrutiny and must have a near flawless record to become an integral part of the system as a whole.

To create the most cost effective design two alternatives were analyzed. The first design eliminates the initial research, design and production costs of a all-new aircraft by integrating an automated control system with an existing Heavy Lift vehicle. Additions to the vehicle would include the required Information Technology (IT) items (i.e., flight sensors and processors, communications devices, and military requirements) and additional or upgraded actuation servos. Many of the IT requirements can be met with existing equipment on military and civilian helicopters. Weight savings could be achieved by removing non-essential equipment and furnishings from the vehicle. However, if needed, the vehicle could be set-up to be interchangeable from a human piloted vehicle to a UAV. The major trade-off with this type of vehicle is the high operational costs vs. low development costs. If further studies show that only a small number of vehicles will be needed, this is the likely means of creating them.

The other option is to create a new vehicle that is designed from the outset as a UAV, and therefore does not make any concessions for the needs of human occupants, such as the cockpit and cabin. By eliminating extraneous fuselage and internal equipment, the gross weight of the final product is lowered considerably. Ultimately, a lower gross weight leads to lower operating costs (fuel, maintenance, price, insurance, etc.) The trade-off with this type of design is the higher development costs vs. lower operational costs.

The requirement defined in the logistics analysis is that the heavy vehicle would be able to carry a 10,000 lb. payload 250 miles. This requirement is similar to the current military utility aircraft capabilities and matches requirements for a design study performed by Sikorsky in 1998. The minimum threshold requirements for the 1998 design were that the vehicle could travel autonomously at 145 knots for 2.5 hours with an internal payload of 10,000 lb. If the load were carried externally, the speed and endurance would decrease; however, at 145 knots the total distance traveled in 2.5 hours is 417 miles. Therefore, even with decreased performance, the vehicle should easily be able to perform the required 250-mile mission.

Therefore, two options are available for further study in Phase II. The first option is a vehicle designed specifically for autonomous use as a Heavy Lift autonomous vehicle for both commercial and military use. This option has high development costs, but the vehicle can be optimized for cargo transport and lower operating costs. The second option is a control system designed to be integrated into an existing helicopter, allowing for conversion of both medium and Heavy Lift vehicles that can alternate between manned and unmanned operation. The benefit to the control system option is a large decrease in development costs; however, the vehicle design would not be optimized for autonomous cargo transport. Therefore, a detailed analysis will need to be performed in Phase II that looks at customer needs and budgets in the Heavy Lift commercial and military platform. If there is a need for having both manned and unmanned cargo transport, the conversion control system may be more appealing, yet having a dedicated autonomous cargo transport may eliminate the need for manned VTOL, altogether.

4.3   Vehicle Design Conclusion

Safety and utility were the greatest concerns in creating both the light and heavy vehicle designs. Although there are many other factors that go into the designs, the resulting vehicles must have room for redundant systems, multiple engines in the event of engine failure, and shrouding to protect from rotor strikes in the case of the Light Lift vehicle.

The Light Lift AVSLA vehicle recommended is the Tilt Shroud vehicle, due to its low weight and fuel consumption. Although both vehicles examined in detail for the application are

very competitive, the enhanced cruise performance of the Tilt Shroud offsets the additional weight of the tilting mechanism, provided that the technology levels assumed while generating this data are reached.

The Heavy Lift AVSLA vehicle recommendation is much more difficult to pinpoint, so two design options are left for Phase II study. The conversion control system, a system that can be inserted into virtually any VTOL design, and the strictly autonomous cargo vehicle, previously designed by Sikorsky. Both design options meet the requirements stated in the logistics analysis; however, as mentioned the tradeoff between development cost and transport optimization needs to be further researched. During Phase II, information will need to be gleaned from future customers in the military and commercial arenas to determine if a single design that allows for manned and unmanned use is beneficial. If the need exists for manned and unmanned use, and the historically lower utilization of Heavy Lift VTOL aircraft continues, a conversion system would be more efficient. However, if the utilization of the Heavy Lift vehicles in a commercial system approaches the assumed level of the Light Lift vehicles (2,600 flight hours annually), a new design UAV may prove a better option.

5 COST ANALYSIS

5.1 Light Transport Analysis

  The input data used to represent the logistics architectures of today's express package industry largely came from the 1999 FDX Corporation (the parent corporation of FedEx Express) annual report[48], which lists operational cost data that make up a large portion of the total system cost in the model. The equations and data used appear in Appendix B. Since the proposed architecture is a new, untested system, data for the model had to be approximated using various sources. Many aspects of the delivery agent costs were modeled using data from Sikorsky's Dragon Warrior® Unmanned Autonomous Vehicle (UAV) project. The Dragon Warrior® vehicle (see Figure 5-1) is a small (6 ft in length, 2.25 ft high, 10 ft wingspan), 206 lb., autonomous vehicle capable of speeds up to 125 knots and a range of 150 nm. Data used for the analysis included vehicle speed, fuel costs (dollars per pound of fuel consumed and pounds of fuel consumed per hour of operation), and maintenance costs. Vehicle cost per package was determined as shown in Table 5-1; the per-vehicle cost of the point-to-point VTOL vehicles is estimated to be $4,000. This value was determined using cost estimation software referenced in the Economic Analysis section of this report (Section 8). The large production volumes mandated by the point-to-point AVSLA concept will help distribute development and fixed costs, reducing unit costs to levels that may be competitive with the system currently in use. Vehicle cost and life cycle for the FedEx type van is approximated.
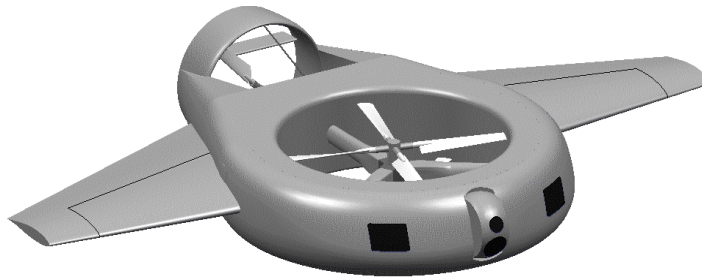
Figure 5-1: Sikorsky's Dragon Warrior®.

Table 5-1: Calculation table for vehicle cost of VTOL and FedEx type vehicles.

Basic Comparison of Vehicle Cost (Excluding Financing Costs)		
	1-Package VTOL	Current Trucks
Packages per Day	1,500,000	1,500,000
Packages per Hour	187,500	187,500
Vehicle Cost (each)	$4,000.00	$50,000.00
# of Vehicles Needed	187,500	8,600
Total Cost of All Vehicles	$750,000,000.00	$430,000,000.00
Vehicle Life (years)	8	12
Vehicle Cost per Year	$93,750,000.00	$35,833,333.33
Vehicle Cost per Day	$360,576.92	$137,820.51
Vehicle Cost per Package	$0.24	$0.09

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[48] FDX Corporation 1999 Annual Report

The data in Table 5-1 on packages per day data is derived from an independent report that shows the average number of packages delivered in the US by FedEx on a daily basis using 8,600 trucks. Since the data excluded UPS and the US Postal Service, the number of packages and trucks was approximated as being sufficient to represent the Northeastern United States, considering that the population in the northeast represents roughly one-third that of the US as a whole.

Once enough data was gathered to build the numerical portion of the Vensim® model, many different transportation scenarios were simulated to compare various architectures. Before running comparisons of current systems and the point-to-point AVSLA, data from FedEx was used to calibrate the model to match FedEx Express rates. Once calibrated, data for the point-to-point AVSLA was input into the model. The analysis showed that, with the technology assumptions that were made, a point-to-point AVSLA could operate profitably with rates lower than those charged by FedEx for First Overnight® service (FedEx First Overnight® guarantees next morning delivery, which most closely resembles the timing of point-to-point delivery). The main cost results of the comparison are shown for 100-miles and 200-miles shipping distances in Figure 5-2.

Although many of the data inputs are based on assumptions, the results favor the point-to-point system over the current delivery van system from a cost point of view. The system time results are just as favorable, as expected, given the speed advantage and direct routing inherent in VTOL aircraft.
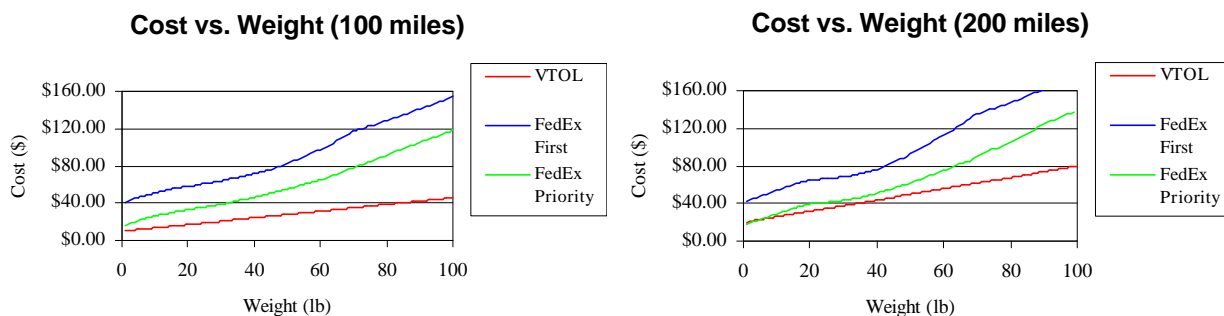
Figure 5-2: Cost vs. Weight comparison between two Fed-Ex delivery options and the predicted point-to-point AVSLA price structure (labeled "VTOL" in the charts).

5.2 Heavy Transport Analysis

Similar to the light package transport analysis, the heavy transport analysis involves many assumptions based on currently available data. Since trucks serve most of the heavy transport market segment, data was compiled from trucking industry reports to provide fuel, personnel, maintenance, vehicle, and road usage costs. Details of the data found and calculations can be found in Appendix B.

Characteristics for the larger VTOL were approximated using the VTM+ sizing software, available at Sikorsky Aircraft. Assumptions were made on the number of vehicles needed by taking a portion of the currently used trucks. Data was found that shows 192,000 trucks were purchased in 1999[49]. The market analysis of the target shipping items shows that the largest value shipments make up 34% of the total shipping value, but only 1.76% of total trucks are

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[49] Truckinfo.net (statistics compiled from several governmental sources; US-DOT, ICC, NHD, BTS, etc.)

replaced by the AVSLA. So, multiplying 192,000 trucks by 1.76% leads to 3,379 trucks nationwide that currently move the items of interest. Again, since nearly 1/3 of the population resides in the Northeast corridor, it has been assumed that 1/3 of the 3,379 trucks operate in the northeast corridor. Therefore, 1126 trucks are analyzed and the replacement number of VTOL vehicles is set at 600. This calculation is generated based on the ability of a VTOL aircraft to deliver a package in just under one-half the time of a truck. Sizing of the VTOL results in the following approximations: a gross vehicle weight (GVW) of 36,000 lb., fuel costs of $354.76 per flight hour (FH), maintenance of $1,303.40 per FH, insurance cost of $417.71 per FH, and personnel cost of zero dollars for a total of $2,075.87. The insurance cost includes a multiplying factor of 1.5 to account for the increased liability costs of not having a human operator.

Rate comparisons of the proposed Heavy Lift AVLSA transport and trucking industry rates are shown in Table 5-2 and in Table 5-3[50]. The current trucking analysis matches the rates currently available from local trucking companies. Cost reductions of the AVSLA due to possible governmental contributions for the reduced air pollution, highway traffic, and overall transportation congestion are converted into an hourly cost and subtracted from the system costs of Table 5-2 to provide system costs in the Table 5-3.

Table 5-2: System cost comparison between current and point-to-point delivery systems for 1,000 lb. to 10,000 lb. parcels, excluding pollution costs.

	System Cost								
Weight (lb)	1000	2000	3000	4000	5000	6000	7000	9000	10000
Trucking	$411.51	$611.51	$811.51	$1,011.00	$1,211.00	$1,411.00	$1,611.00	$2,011.00	$2,210.00
VTOL AVSLA	$7,244.00	$7,288.00	$7,332.00	$7,376.00	$7,420.00	$7,464.00	$7,508.00	$7,596.00	$7,640.00

Table 5-3: System cost comparison between current and point-to-point delivery systems for 1,000 lb. to 10,000 lb. parcels, including pollution costs.

	System Cost w/ Environmental Credit								
Weight (lb)	1000	2000	3000	4000	5000	6000	7000	9000	10000
Trucking	$411.51	$611.51	$811.51	$1,011.00	$1,211.00	$1,411.00	$1,611.00	$2,011.00	$2,210.00
VTOL AVSLA	$5,780.00	$5,824.00	$5,868.00	$5,912.00	$5,956.00	$6,000.00	$6,044.00	$6,132.00	$6,176.00

Both comparisons show that the feasibility of replacing the current trucking industry with air vehicles is financially restricted. There is still a niche for this type of automated Heavy Lift vehicle. Large, heavy-lift UAVs can be used in military applications where human life is at risk (i.e., ammunition delivery to front line operations), hazardous areas (i.e., nuclear accidents, biochemical spills, large forest fires, etc.), and as a replacement for repetitive manned helicopter operations (logging, helicopter transport of heavy equipment, etc.). Therefore, there is still a place for these large UAVs; however, operational costs keep them from being a solution to the payload transport in the 1,000 to 10,000 lb. range.

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[50] Shipping rates were compiled from FreightQuote.com (http://www.freightquote.com)

6 CONTROL AND MANAGEMENT STRUCTURE

The greatest impact on the system architecture is based on the decision structure of the system. Many different structures were analyzed to find the most cost effective, efficient, and safe method of control. The methods have been likened to governmental structures for clarity. The systems considered consist of Central Control (a dictatorship), Regional Control (an oligarchy, Stand-alone Control (a democracy), and distributed control (a commune). Each of these decision structures is analyzed in depth below. Stan-alone control is shown to be most advantageous for the AVSLA.

6.1 Central Control

As mentioned above, the Central Control method is similar to a dictatorship. With this method, there would be one centrally located computing facility that would make all vehicle decisions. More specifically, each vehicle would be controlled from pick-up to drop-off by the central control computer. Routing, flight control, and package manipulation would all be controlled by the mainframe. The mainframe itself would have multiple external environmental inputs, such as weather, traffic, and incoming delivery requests to aid in choosing appropriate flight paths. In addition, a link to each vehicle would provide vehicle data, such as location, speed, heading, altitude, and nearby obstructions. Closed-loop flight controls would be handled locally by the vehicle for the sake of stability and safety, but the majority of the flight decisions would be made by the mainframe. Figure 6-1 is a cartoon of the Central Control structure. Figure 6-2 is a representation of this structure in a form similar to a Data Flow Diagram (DFD).

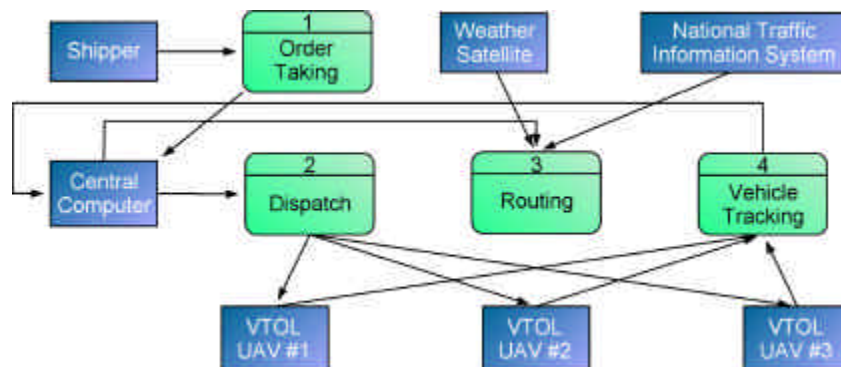**Figure 6-1: A cartoon of the central control scheme.**

Figure 6-2: A representation of the Central Control Structure using symbology similar to Data Flow Diagrams.

This control scheme offers the advantages of a centrally accessible comprehensive knowledge of system asset locations at all times, secure data storage, and a single location for system updates.

There are, however, many disadvantages to a centrally controlled system. The central computing facility would require a huge amount of processing power to make decisions for a large number of vehicles. Because of the rate of change in local conditions, and the number of vehicles that would be flying simultaneously, timesharing the central processing power would be ineffective. Instead, the central processing center would have to rely on massively parallel processing. The greatest disadvantages are security and safety. Since the vehicle relies heavily on the Central Control facility for instruction, a loss of communication with the Facility would be disastrous. It would be possible to have an emergency processor on each vehicle in the event that it is disconnected from Central Control; however, many different events could cause control to be transferred from Central Control to onboard control. In addition, the flight control required to bring the vehicle to the ground safely would require enough processor power to perform normal flight. Therefore, the system would have the added cost of having an available decision control processor onboard and still having the central processing facility costs. Finally, due to the need for constant communication, a constant information flow would be required to and from the satellite. Maintaining a constant, high bandwidth connection to the central processing facility would increase communication costs and increases the ability for intentional and non-intentional tampering with the communication links to vehicles.

6.2 Regional Control

The Regional Control method is similar to the Central Control method, but the vehicles are allowed to make more autonomous decisions. In addition, the Central Control facility is replaced by multiple regional control facilities. This system is likened to an Oligarchy because the regional control centers would work together to make control and dispatching decisions that cross regional boundaries. Nominally, each regional center would control vehicles within its local area; regional processors would need to work together to "hand off" vehicles passing from one region to another. For the same number of vehicles, each regional facility would require less processing power than a Central Control facility. Rather than control the entire flight of a vehicle, the regional control facilities would control all flight path decisions. For example, a vehicle could be told to 'fly from point A to point B and await instruction'. The vehicle would decide how to travel between the points. In the event of a communication loss or error the vehicle wouldn't become a hazard. Figure 6-3 depicts the Regional Control system. If a regional center were lost, the remaining centers would have enough processing power to expand and redistribute their regions of influence to accommodate the entire network of vehicles. This demonstrates a key point of this system: the regions are not geographically fixed, they are based on the distribution of vehicles and traffic in a given area. The physical size of all regions enlarges and contracts as necessary to ensure that no regional center is overloaded.
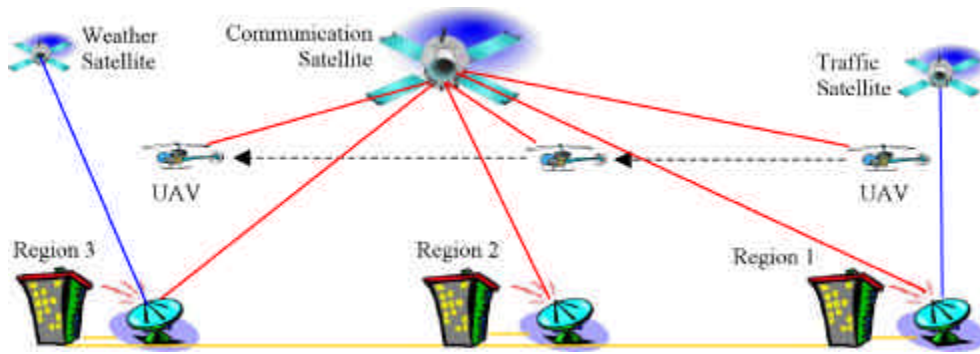
Figure 6-3: A cartoon of the Regional control structure

By adding flight control to the vehicle itself, an advantage is gained by creating a stable system in the event of communication collapse. Since the regional control centers send only flight path instruction to each vehicle, communication bandwidth is significantly reduced and vehicles are still able to make flight decisions while awaiting further instruction if communications with the control center are cut off. Therefore, this method is inherently safer. Another advantage to this system is the reduced facility processing load. In the Central Control model, the processor is in charge of asset awareness, dispatch, flight, flight path, and pick-up/drop-off functions. The Directional Control method removes the need for flight control and the number of vehicles under control is lessened. Although extra computing facilities are required for each region, the relationship between cost and computing power is exponential, so the savings in the processor size could alleviate a large portion of the facility costs. A cost savings benefit is also available due to the change in communication structure. Rather than a continuous communication stream, bursts of information can be sent every time further flight path instruction is needed. Communication time and bandwidth are reduced, decreasing cost.

The disadvantages to this method are similar to the Central Control drawbacks. Although the system is less susceptible to flight problems due to loss of communication, extended down time of the satellite link would create a problem with both delivery delays and fuel consumption. Without communications, the vehicle will loiter, burning fuel. If fuel levels became critically low, the vehicle would need to perform an emergency landing. A further disadvantage to this method is the need for more satellite uplinks. Two methods for connecting to a facility uplink are available and can be compared as locations for each region are chosen. The first method is to have one uplink with cable connecting each facility to the uplink. The other method is to locate the regional facilities near regional uplinks, so that each facility has its own uplink. Finally, due to the added processing power on the vehicle, overall costs are increased proportional to the number of vehicles used.

6.3   Stand-alone Control

Stand-alone Control removes the control facility entirely and transfers individual vehicle decisions to the vehicle itself. Without a control facility to provide weather and traffic data, the vehicle also would need the ability to check weather and traffic servers for its particular flight path. This method is likened to a democracy because there would still be a technical hierarchy involved that distributes knowledge to make it available to each vehicle. Dispatch of available deliveries would be similar to systems used by independent taxi operators. Each new delivery would be listed and made available for all vehicles. A vehicle that would be able to meet the transit time requirements of that delivery would then request that particular delivery and the delivery would no longer be available. Each vehicle would have sufficient computing power to

allow flight control, flight path decisions, pick-up and drop-off control, refueling, emergency procedures, and environmental interpretation (weather, traffic, and obstacles). As technological advances in computing progress, the size, power consumption, and cost of the processing equipment will decrease. Figure 6-4 depicts the Stand-alone system.

The advantages of the Stand-alone Control system are mainly in safety and efficiency. Since the vehicle performs all of the decision-making, the only drawback to a communication lapse is not being able to dispatch new deliveries (minor efficiency problems are created with a loss of communication between weather/traffic servers and the vehicle). In addition, since control is not communicated, results of inadvertent tampering are benign. In addition, the only intentional tampering available is through the dispatch signal, which can be encrypted for security because of its short length. The Stand-alone method also eliminates the need for a control facility. A small dispatch center would still need to be located near a satellite uplink; however, such a system could be placed in a small office. The processing power needed for dispatch would be much lower than Central Control and would decrease the overall cost of the system. By allowing the vehicle to choose its own flight path and make on-the-fly changes, delivery times can be optimized to provide the most efficient delivery available. In addition, while concluding a delivery, a vehicle can choose from a list of available parcels for its next delivery. This scheme would help to minimize idle time.
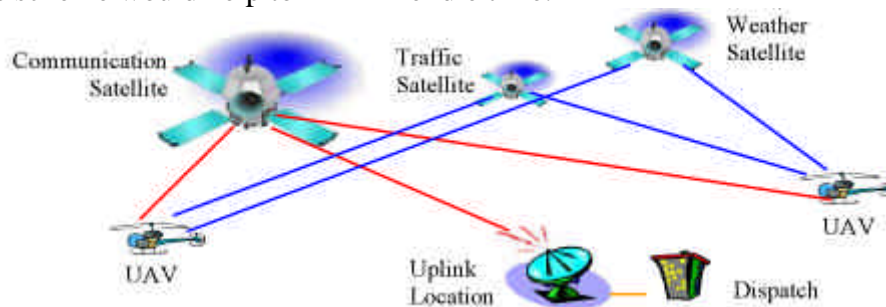
Figure 6-4: A cartoon of the Stand-Alone control system.

Disadvantages to the Stand-alone Control method involve the cost of processing power and the lack of administrative control of the vehicles. By putting such an arsenal of computing power on the vehicle, the cost per vehicle rises considerably. A tradeoff must be made between a parallel processing system capable of controlling 185,000 complex vehicles, simultaneously, for Central Control and approximately 50,000 for Regional Control versus the cost of having 185,000 smaller processors capable of controlling one vehicle each. An economic analysis will need to be completed during Phase II, when a mainframe or computing manufacturer can be contracted to determine the expected costs of both systems.

6.4　Distributed Control

Distributed control is the functional equivalent of a commune in which all decisions are made with the input of any interested party. The only centralized component of this scheme is the order taking processor provided to centralize customer interface. In this scheme, each vehicle has enough processing power to fully control its flight and to contribute to decisions making for the network as a whole. Each vehicle essentially becomes a node in a massively parallel computer. Routing and dispatch decisions are made through negotiation among the vehicles affected. Centralized resources are minimized. Figure 6-5 is a cartoon of how this system would be structured; Figure 6-6 presents something similar to a data flow diagram for the system. The major advantages of this system include portability, adaptability, and

maintainability; the major disadvantages include security, traceability, massive communications, and the requirement to reach critical mass.

Because this scheme requires relatively few fixed assets, the entire architecture can be transported to any location and still work effectively. Under this scheme, the architecture could easily respond to changing demand and traffic patterns. Because each vehicle is a node in the processing system, the processing system can be maintained and upgraded one node at a time without degrading overall system performance. Additionally, if a node is lost for any reason, it can simply be replaced.
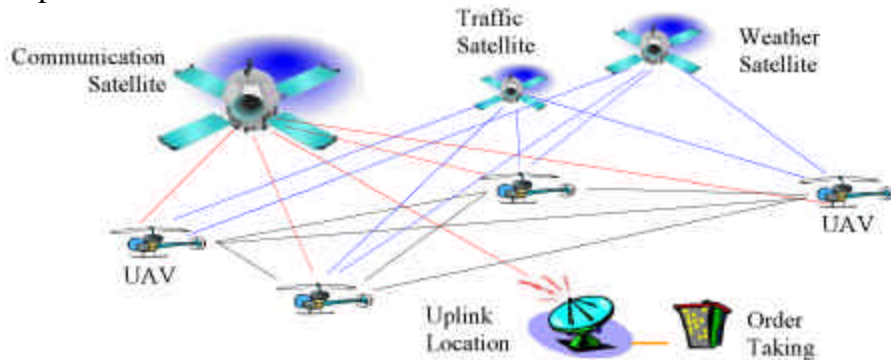
Figure 6-5: **A cartoon of a Distributed Control Structure.** **Note that the communications and coordination requirements are increased, but less ground infrastructure is required and the system is more flexible.**
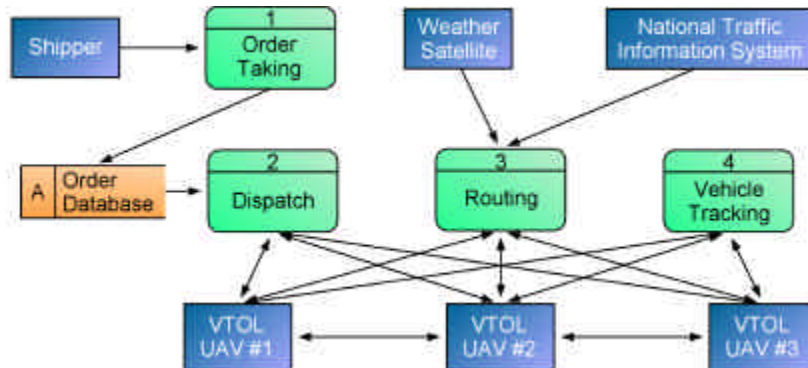
Figure 6-6: A representation of the Distributed Control Structure using symbology similar to DFDs.

This communal decision-making scheme poses many problems, most notably with system security. Because each vehicle can be directly involved in making decisions, each vehicle has access to the knowledge of the entire system. This means that, by controlling a single vehicle, an outsider can gain access to the entire system, influencing decisions and gaining information on operations. And because decisions are being made in a massively parallel way, it is difficult to trace the source of influence when bad decisions are being made. Adding to this difficulty is the massive amount of data being transmitted and shared among the vehicles. This massive data traffic also increases system expenses. Finally, in order for this scheme to work, a minimum number (or critical mass) of vehicles must be in operation. Optimizing the number of vehicles in the system and the excess processing power each can dedicate to the decision-making process will be a difficult task.

6.5   Control Conclusion

As can be seen from Sections 6.1 through 6.4, there are many advantages and disadvantages each of the four proposed decision structures. However, some guidelines must be used to choose the most appropriate control method. Table 6-1 provides a comparison of the four alternatives using common metrics. The metrics were created based on the expectations of the system as a whole (i.e., safety, efficiency, cost, reliability, etc.).   Weighting, or multiplication, factors were chosen to differentiate metrics by their importance to the AVSLA system. Although the weighting factors are subjective in nature, they were chosen based on the assumption that safety, reliability, and operating costs are the dominating features of a new architecture. Due to the fact that development costs are non-recurring, and can be spread out over the operational period, these costs were given the lowest weighting.   System shutdown refers to the time taken to bring the whole system down in the event of a catastrophe (i.e., terrorist threat, war, extreme weather, system failure, etc.). Finally, An overall score is tallied to depict the system that most fulfills the necessary expectations.

Table 6-1: Method for comparing decision-making schemes.

	multiplier	Central Control score	Central Control total	Regional Control score	Regional Control total	Stand-alone Control score	Stand-alone Control total	Distributed Control score	Distributed Control total
Safety	5	3	15	4	20	5	25	5	25
Efficiency	3	4	12	4	12	5	15	5	15
Reliability	4	3	12	4	16	5	20	5	20
Operating Cost	4	2	8	3	12	4	16	2	8
System Shutdown	3	5	15	4	12	3	9	2	6
Development Cost	1	2	2	2	2	3	3	2	2
Total (max=100):			**64**		**74**		**88**		**76**

The individual scores were based on the analyses already presented. The scores for safety, efficiency and reliability are taken directly from the advantage/disadvantage outcomes. However, an extensive look was taken to determine how the operating , system shutdown, and development costs compared. Operating costs were found to be lowest for the Stand-alone Control, due to the less complex nature of the computing system required. Although the quantity of processors is high, the overall complexity and parts cost for those systems is low comparative to the Central and Regional Control systems, and the Distributed Control scheme required more power in each processor and much greater communication requirements. Property costs for the Distributed Control scheme and the Stand-alone Control scheme are similar and much lower than for Central Control or Regional Control, since the only facility needed is a small dispatch center (see the Economic Analysis in Section 8 for costs on maintenance and storage facilities). Since vehicle costs are similar for all systems and only vary based on efficiency (i.e. fewer wasteful flight hours result in lower vehicle costs), operational costs are largely related to the computing complexity needed for each system.

Similarly, development costs are proportional to the complexity of computing power. Both the Central Control and Regional Control schemes are based on mainframes that don't currently exist. Therefore, research and development must be undertaken to put together a workable system that is also scalable to a national level for Phase II. Stand-alone Control and Distributed Control can be achieved with processors available today, but systems integration costs could be on the same order as for Central Control and Regional Control. The result for development costs is based on the assumption that development of a large, parallel processing

mainframe control system will be more expensive than integrating the small processors on board each vehicle. As mentioned, this analysis will be left for Phase II, since a mainframe or computing manufacturer will need to be contracted to determine costs for the Central and Regional mainframes.

Finally, the system shutdown scores are proportional to the level of direct vehicle control. With Central Control, the mainframe can immediately bring vehicles down for a safe landing when instructed. Regional Control requires that an update to each vehicles flight path be sent, informing the vehicles to make an emergency landing. The Stand-alone control system would require that a message be sent to all vehicles to start emergency landing procedures, at which time the vehicles would be responsible for making the decision on where to land and return a message to dispatch that confirms the landing is complete. And the Distributed Control system would require a shutdown message be propagated throughout the system. The actual time difference between each system's landing will most likely be counted in minutes; however, to show that there is a difference the scores are proportioned to show the various responses of each system.

Assuming that the computing cost analysis in Phase II doesn't cause a large change in the above score, the Stand-alone Control scheme was chosen for implementation. System shutdown is the only metric where this scheme scored lower than any other system. This is due to the lag in communicating to each vehicle to stop, find a safe landing place, and power down. Obviously, the time lag is relative to the two more centrally controlled methods and is still reasonable enough to be acceptable.

7 SYSTEM INFORMATION TECHNOLOGY REQUIREMENTS

Having already chosen the Stand-alone Control chosen, system Information Technology (IT) requirements were only fully detailed for that scheme; however, information is provided for all three control schemes in case Phase II cost analyses leads to a different control conclusion. The IT requirements are broken down by vehicle, dispatch office, satellite communication, and security. Initially, the maintenance and fueling aspects of the system will be assumed to be manned operations.

7.1 Vehicle Information Technology Requirements

Vehicle IT assets were broken down into two main classes: basic and control scheme specific. Basic assets are those that will be required by the vehicle regardless of the control scheme selected. Basic assets include those required by regulations – such as a Traffic Alert and Collision Avoidance System (TCAS) – and those that are required for effective vehicle operation – such as diagnostics and closed-loop stability algorithms. Control scheme specific assets are those assets that the vehicle may or may not require, depending on which control scheme is being used. These assets could include routing algorithms and communal decision making protocols. The amount of control scheme specific assets will largely be driven by the amount of decision-making power the air vehicles will have in the system.
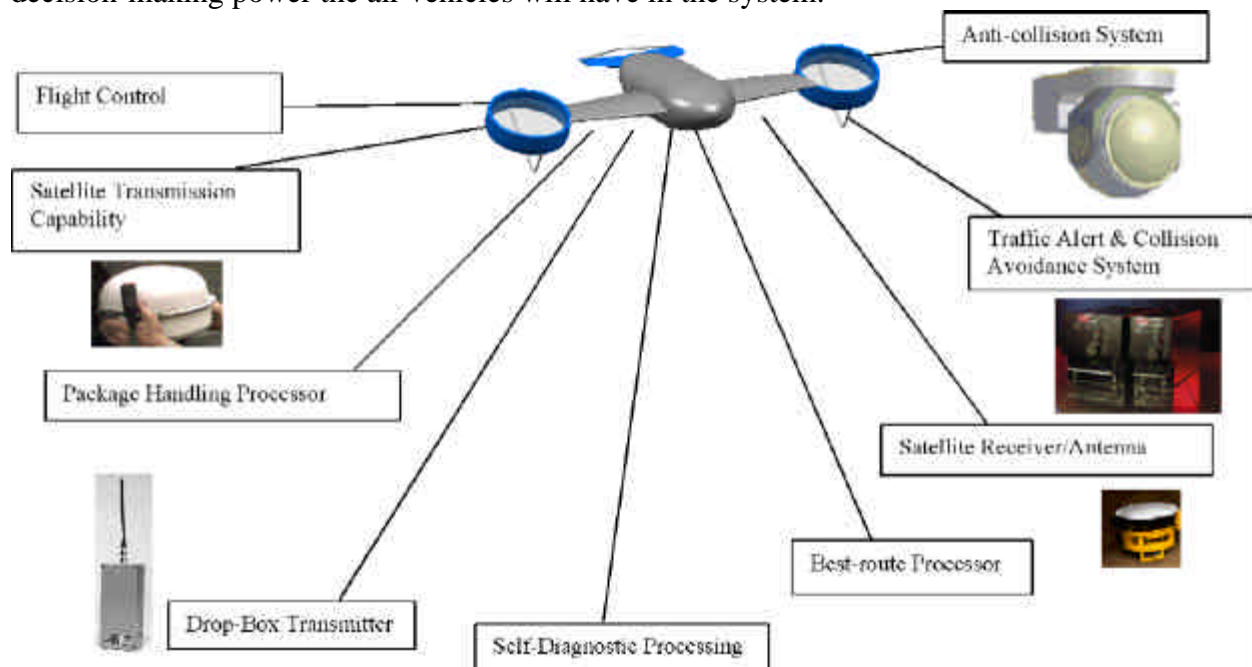
Figure 7-1: Full IT package, assuming full decision control by the autonomous vehicle.

Basic IT assets will allow the vehicle to perceive its surroundings (including collision threats and terrain) and provide local, closed-loop stability and control functionality. The extent of the other functions, including communication, processing, and flight control, depend on the amount of control delegated to the air vehicle. Figure 7-1 shows a fully integrated IT package, assuming full authority decision making is carried out by the air vehicle (details of each IT subsystem are provided in Sections 7.1.2 through 7.4). Specific control scenarios are discussed below that limit the necessary amount of electronics. Additionally, the military version of the

Heavy Lift UAV will require military specific IT equipment. These items are discussed in detail in section 7.1.6.

7.1.1   Flight Control

The most basic of the IT requirements involves the ability of the vehicle to remain stable in flight. Although it's possible to design a vehicle that would be remotely controlled by a human operator, the complicated nature of the delivery system, the large number of vehicles, and the high bandwidth required in this project makes remote piloting an expensive and difficult solution. Therefore, the vehicle must be able to control its own flight with the possibility of switching to remote pilot control if necessary. The basic flight system would require sensors to monitor altitude, roll, pitch, yaw and airspeed. All of the sensor output would then feed into a processor that could compute the necessary input to the flight controls. Table 7-1 shows an example of an inexpensive sensor array (under $150) and processor suite that could perform basic flight functions.

Table 7-1: Example sensor array with controller.

Flight Control	Sensor
Pitch	3-axis magnetic sensor
Roll	3-axis magnetic sensor
Yaw	3-axis magnetic sensor
Altitude	pressure transducer
Airspeed	thermal anemometer
Processor	PIC-type control

7.1.2   Location

Although the vehicle can now fly autonomously, the ability to control where the vehicle travels requires self-knowledge of location. With the deployment of the Global Positioning Satellite (GPS) system, determining location anywhere in the world is much easier than before. Due to the small size of the delivery targets for Light Lift packages, the locating system must be fairly accurate. Therefore, a Differential GPS (DGPS) system would be used to provide more accurate location than standard GPS. Additional ground units could also be used to provide even more precision. Of course, precision delivery of Heavy Lift packages would also benefit from a DGPS system, and use of highly accurate position determination methods will allow the system to operate in highly constrained urban environments. Obviously, location data would be used by the vehicle itself, and propagated throughout the system. In addition, a Mode C Transponder[51] would be added to the vehicle to provide location and altitude to other air traffic. Due to the large number of light vehicles proposed, the transponder signal should contain differentiating information that would allow air traffic controllers to 'hide' the vehicle data from air traffic radar. The larger, Heavy Lift AVSLA vehicles should probably have a transponder signal similar to that of manned craft, since its maneuvering capabilities would also be similar to the capabilities of manned vehicles.

7.1.3   Collision Avoidance Systems

Able to autonomously travel and self-aware of location, the aircraft must next have the ability to avoid stationary and moving objects in its path. The FAA currently requires all commercial aircraft to be equipped with a Traffic Alert & Collision Avoidance System

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[51] Transponder information provided by *Avionics,* by J.M. Ferrara, Volume 1

(TCAS).[52] TCAS monitors the area surrounding the aircraft up to 80 nm in all directions. As other aircraft enter the monitored area, their transponder information provides altitude and location back to the TCAS. This information is used to determine if a collision is likely. On today's aircraft the pilot is responsible for maneuvering the aircraft once he/she is made aware of the collision threat. For the Light Lift AVSLA vehicles, a differentiated transponder signal could be used that would provoke a mitigated response on larger aircrafts' TCAS systems. The avoidance maneuver would be up to the smaller, more agile, autonomous craft. The autonomous vehicles would use onboard processors to determine the best course of action given a collision warning. Data on a Honeywell TCAS system offered is shown in Table 7-2.

Table 7-2: Honeywell TCAS 2000 specifications.

Function	Specification
Range	80 nm
Maximum Aircraft Tracks	50
Maximum Closing Speed	1200 knots
Temperature Range	-55 to 70 C
Processor	4 MCUs
Weight	16 lb

Table 7-3: OASys object and obstacle detection system specifications.

Functions	Specifications
Operating Voltage	28 VDC
Power	100 watts
Operating Temperature	-40 to 70 C
Interface	RS422, Ethernet, ARINC 429, LVDS, Discrete
Radar Range	4 nm in obstacle mode 40 nm in weather mode
Safety Zone	Adaptive up to 1 nm
Antenna	11" Ka-band (Very low side lobe)
Scan Rate	Up to 120°/sec. @ ± 90° coverage
Stabilization	Up to ± 30° combined pitch and roll @ 0.1° elevation accuracy
Tilt Control	Adjustable tilt offset
Angular Range	+/- 90 deg in azimuth +30 deg and - 80 deg in elevation
Unique Features	Built in LWx Weather Radar
	Acts as (Ground Proximity Warning System) GPWS

In addition to the TCAS system, which only monitors air traffic, the autonomous vehicle would need to see ground and miscellaneous air obstacles. These obstacles vary in size, orientation, and movement and can consist of buildings, towers, wires, birds, etc. An object avoidance radar system, called OASys, is available specifically for VTOL craft.[53] The system detects and monitors objects up to 4 nm away from the vehicle; objects with a 1 m^2 cross-section are consistently detected at a distance of 1 nm from the vehicle in any direction. Power lines, a traditional hazard for VTOL aircraft, can be detected at 2 km with visibility at 125 meters. In addition, the system can monitor immediate weather conditions up to 40 nm away. The antenna

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[52] Details on the Traffic Alert & Collision Avoidance System provided by Honeywell Corporation
[53] OASys Radar information provided by Amphitech; Blainville, Quebec, Canada

portion of the system, without the pilot interface, weighs 40 lb; however, as antenna technology is advanced the overall weight should decrease. OASys specifications are shown in Table 7-3.

7.1.4   Communication and Processing

Able to fly autonomously and avoid collisions, the aircraft must also be provided with decision making capabilities. Communication requirements very significantly with the level of air vehicle autonomy. In this section, the four control structures presented earlier are analyzed for both processing and communication needs. A Central Control system would rely primarily on constant communication and very little vehicle processing power, and is the first system analyzed. Next, a Regional Control system, which would rely on large communication bursts and a mildly complex vehicle processing system. Then, a Stand-Alone vehicle control system is analyzed, which makes use of short communication bursts and a highly complex vehicle processing system. Finally, a Distributed control scheme is examined, in which complex vehicle processing capabilities and high-speed, constant communication serve to minimize ground assets and increase system portability.

7.1.4.1   Central Control

From Section 6.1, the Central Control system treats the AVSLA vehicle like a pawn controlled completely by a control facility. Processors from the facility control all vehicle movement, flight-path, package pick-up and drop-off routines, etc. through a direct satellite link. The satellite link would be fairly complex and each vehicle would require a high-bandwidth link to the central processing center[54]. Five to ten vehicles can be linked through one satellite transponder (based on an information transfer of 1.5 Mbps); however, to cover the northeast region between 15 and 40 thousand frequencies would be needed. Another method of communication may be necessary. The central control system would allow vehicle costs to be the lowest, though. Sensor arrays, collision avoidance equipment, and communication equipment would be necessary; however, all processing and controllers could conceivably be contained at one central location. An exception, may be a small emergency processor that would control the vehicle in the event of severed communication. Therefore, this method balances the cost of a central control facility and a communication link with the savings of reduced vehicle processing power.

7.1.4.2   Regional Control

A more direct look at the Regional Control method from a system IT viewpoint provides minimal requirements for the architecture. The Regional Control method gives the autonomous vehicle control over flight, using an onboard processor to interpret sensor output. However, flight path decisions (i.e., waypoints) are made by a regionally located facility. The advantage of this is that, with reduced data transmission requirements, more vehicles could share the same frequency than in the Central Control scheme. Processing costs are added to the vehicle, yet subtracted from the central facility, since Regional control entails moderate processing power on the vehicle and similar processing at a central control facility. However, because multiple ground facilities must be built, total ground asset cost could increase relative to the Central Control scheme. In this system, flight control is performed on-board the vehicle and the flight processor is capable enough to eliminate the need for a separate emergency processor. There is also no longer as much of a concern during limited communication loss, while the vehicle is traveling between separate instructions.

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[54] Satellite communication details provided by the engineering department of Columbia Communications Corporation; Bethesda, Maryland

7.1.4.3 Stand-alone Control

Stand-alone control is the closest to a "Free-flight" system, where all flight and flight-path control is given to the vehicle. The need for a large central facility is eliminated; however, much more processing power is required on each vehicle. Outside information is now needed by the vehicles to make important flight-path decisions. However, common information can be sent to all vehicles on a single frequency to be used by each vehicle locally in its decision making. This type of common information includes weather, traffic, and changing no-fly zones between proposed pick-up and drop-off locations. The vehicle will require an advanced communication system that retrieves information from multiple sources and communicates back to various locations. Therefore, the largest cost factor for stand-alone control is the advanced nature of each self-controlled vehicle.

7.1.4.4 Distributed Control

Distributed Control essentially imposes the same autonomous flight capability requirements upon the air vehicles as Stand-along Control. However, Distributed Control also imposes other requirements upon the vehicle's information technology; namely, high-speed multiple party communications and communications relay, and additional processing power that can be dedicated to the "communal mind" to assist in making system-level decisions. Based solely on IT requirements, vehicle and communications infrastructure costs would rise. This must be evaluated in light of the reduced ground asset costs and the operational flexibility that is afforded by having no fixed base of operations.

7.1.4.5 Information Technology Influence on Control Scheme Conclusions

In Section 6.5, it was concluded that further study of the computing costs of each control structure would need to be completed in Phase II. This is still a worthwhile effort, but if Central Control, Regional Control, or Distributed Control becomes the preferred system, new communication technologies will need to be developed to handle the massive amounts of data and large number of nodes. Attempting to maintain direct communication with aircraft via satellite requires too many frequencies to be a feasible method of sending data. Therefore, the system IT analysis provides more reason for preferring the Stand-alone Control scheme.

7.1.5 Miscellaneous Systems

In addition to the other main systems utilized by the autonomous vehicle, several low complexity subsystems are needed to make the vehicle useable as a package/shipment deliverer. Some form of equipment is needed to allow the light vehicles to autonomously load and drop off packages. The Heavy Lift vehicles could use an external cargo hook type system similar to what is used on today's cargo helicopters, but some autonomous connection and disconnection procedures would have to be developed. On both types of vehicles, a communication system should be available to communicate with automated equipment at pick-up/drop-off locations, customer confirmation networks, and emergency response systems in the event of a failure. A diagnostic suite of sensors should also be available to keep malfunctions at a minimum. Each of these mission systems is reviewed in more depth below.

7.1.5.1 Package Handling

During air vehicle detail design, package-handling mechanisms will need to be devised to handle various internal and external loads of different sizes, shapes and weights for both vehicle classes. However, for the information technology portion of the project, control of the package handling mechanics can be assumed to be fairly simple. The requirements of such a system can then be analyzed in advance, with detailed specifications to follow after completing the

mechanical design of the system. Different systems will most likely need to be designed for the light vehicle and heavy vehicle. The light vehicle is likely have an internal package carrying system, due to flights in adverse weather conditions. One mechanical design is likened to a framed cargo net (see Figure 7-2). One motor would be responsible for lowering and raising the frame. A second motor tightens a cord, closing the framed net around the package. Pressure sensors can be used to determine that the net securely captures the package. Activation of the two motors and interpreting pressure sensor input can be accomplished using a small Programmable Interface Controller (PIC).[55] PIC controllers are perfect for a redundant system due to their low cost and small size. In addition, most PICs have numerous input and output pins allowing for multiple sensor input. The power required is very minimal (less than 2.5 mA at 5 V or 12.5 mW) and would cause very little drain on the power system of the vehicle. Processing speed is near 10 MHz, which is sufficient for interpretation of the sensor and servo control. The heavy vehicle would have a simple cargo hook type system, similar to those already designed and in use on many manned helicopters.
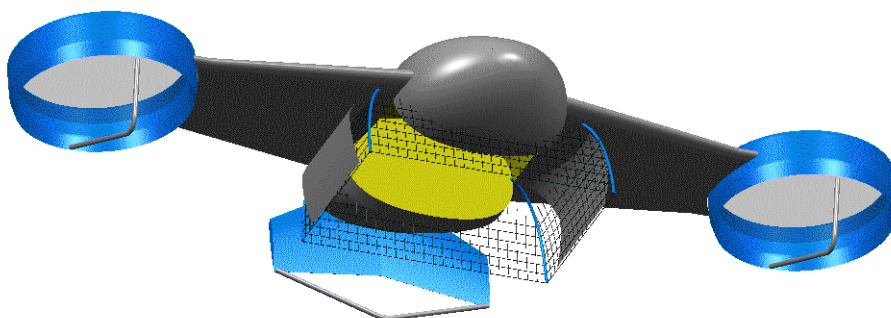
Figure 7-2: A view of a notional autonomous cargo handling system.

7.1.5.2   External Communication Device

Depending on the pick-up and drop-off procedures chosen for the system, various means of communicating to nearby external systems may be necessary. For instance, if packages are to be dropped off at some type of drop-box in the area of the package receiver, there must be a means of letting the drop box know that the vehicle is ready to place the package in the box (i.e., to open the box). One can imagine a system similar to a garage door opener. A signal is sent from the vehicle to the box, and the box could inform the vehicle when it is ready. Another scenario could be that the customer has requested to be notified when the package has arrived or is arriving. Once the package is near delivery, the vehicle can send a message back to dispatch to arrange a customer call, or a cellular transmission can be made originating from the vehicle with a pre-recorded message that the package has arrived.

Emergency transmissions during a malfunction also impact communication system requirements. There must be some type of communication link that can be used in the event a vehicle has a critical failure. Ideally, communication would be sent through a satellite link or line of sight radio, since this would immediately provide the maximum amount of information to the delivery system. An alternative, in the event of a primary communication system failure,

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[55] PIC details are in reference to a PIC16F84, produced by Microchip Technology, Inc. (a very common and inexpensive model at less than $10).

would be setting the transponder frequency to 7700, as private and commercial air traffic currently does to indicate an emergency.[56] This method would provide the nearest Air Traffic Control Tower with emergency information. The correct authorities could then be notified by Air Traffic Control.

7.1.5.3 Diagnostic Sensors

In order to keep the delivery system failsafe, precautions must be taken to prevent serious vehicle malfunction. Other than regular maintenance, precautions can be taken during flight to determine vehicle problems before they result in a system failure. Four main sensors would provide a wide variety of information to the vehicle or control center that could predict future failures. These sensors include a fluid level indicator for fuel level, a motor/main-rotor rpm indicator to monitor rotor speed, a thermocouple to monitor engine temperature, and an EEMS exhaust monitoring system. The four-sensor diagnostic suite would provide a minimum range of diagnostics information. A trade-off is made between a full diagnostic suite, which would provide a complete array of vehicle information for a high cost, versus the minimal diagnostics, which provide basic vital information at a low cost. To keep vehicle costs down the minimal sensor array is recommended. Experimental testing with prototypes, once available, should provide more useful data as to the efficiency of the 4 sensor suite. Parallel development or advanced Health and Usage Monitoring Systems (HUMS) could also provide a lightweight, low cost solution to this requirement.

7.1.6 *Military Vehicle Information Technology*

Although the majority of the vehicle systems are identical on both the Light Lift AVSLA vehicle and the Heavy Lift vehicle, the military version of the Heavy Lift vehicle does have additional IT requirements. To cover the possibility of personnel carriage, additional IT requirements are included. An Interrogator Friend or Foe (IFF) system will be installed to help the vehicle determine hostile targets. As an added security feature, a KY58 secure communications device would also be integrated onboard to make communications hard to intercept. Finally, since the army uses a different standard for location (other than latitude/longitude), location programming would need to be able to convert latitude/longitude from/to Universal Transverse Mercator (UTM). At some point it may be feasible to add armament to the UAV, to increase its abilities from a cargo delivery unit to an ordinance delivery, armed escort, or combat vehicle. Adding armament capability could greatly increase the IT requirements for the vehicle, by including target acquisition, weapons control, and other combat related systems. Although it is important to be aware of potential future needs, armed roles are beyond the scope of this study.

7.2   Dispatch System

The requirements for the dispatch system are fairly simple and are very similar to systems available today. A server would be set up that could handle a large volume of incoming data (i.e., similar to the Internet retail sites). Software for the server is already available and in use by many taxi services and trucking companies. This software could be easily modified to fit the delivery model and include data encryption. In addition, enough communication lines would need to be installed to alleviate any possibility of system lock-up or overloaded communication lines. Due to the simplicity of the dispatch system, it would be easy to install a redundant back up, to preclude the possibility of a server failure. Overall, the entire system could be housed in a

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[56] A transponder frequency of 7700 is commonly referred to as the Emergency Code.

small office, allowing space for one or two technicians to oversee operation during the initial start-up of the system.

The dispatch system is similar to a delivery service between the shipping party and the pick-up vehicle. A shipper sends information about a delivery, perhaps using the Internet. The data is then stored on a database for billing and tracking and delivered to the local satellite uplink. Information sent by the uplink is communicated via satellite to all vehicles. The first responding vehicle is recorded as the delivery agent for that load, and dispatch accordingly informs the entire system that the delivery has been accepted with the accepting vehicle's ID number as a confirmation to that vehicle. This process is repeated for each new delivery.

7.3   Satellite Communication

Due to the versatility of the vehicles, a communication system that can always maintain a connection to the vehicle at any point in time is necessary. The two apparent options are line-of-sight radio and satellite communications. Although radio is comparatively inexpensive, radio transmissions are more likely to be interrupted by weather, terrain, and both intentional and non-intentional interference. Hence, a satellite system was selected. Although many different applications use satellites as a communication link, it is still fairly complicated and expensive (though the development of low-cost launch vehicles may reduce satellite communication expense). A ground line must be laid between the originating data site (the dispatch center in this system) and a local uplink site. The communications company that owns the uplink charges a monthly service fee for use of the ground cable and for the amount of data per unit time sent to the satellite. In addition, a receiver and transmitter must be placed on each vehicle that has enough power to transmit data back to the satellite. With the influx of cellular phones, the technology required to create a low power transceiver has advanced considerably. These advances can be assumed to progress even further in the next ten to twenty years, further lowering the cost and size of the required equipment.

The satellites that seem most appropriate for tracking and dispatch communication are NASA's Tracking and Data Relay Satellite System (TDRSS) satellites. These satellites maintain constant coverage over the northeastern corridor of the United States, which is necessary for the delivery system to work. Communication with FAA weather satellites and a proposed traffic information satellite would also be required. Development and sponsorship of the traffic information satellite is another aspect of the Phase II proposal. Due to the use of many different satellites, the transceiver on the AVSLA vehicle will need to accept data from various satellites.

7.4   Security

The versatility and maneuverability of the delivery vehicles makes them attractive for many different uses. In addition, the payload and equipment carried by the vehicles makes them attractive for theft. Hence, a thorough security system must be employed to ensure that the vehicles are not hijacked, vandalized, or manipulated. Onboard vehicle control provides some security by eliminating the need for continuous datalinks to the vehicle. Short burst communication can be more difficult to decipher and imitate if good encryption software is used. Therefore, a complex encryption system would need to be implemented for both the vehicle and dispatch center's communication output.

In addition, programming routines that determine vehicle actions during idle landing, emergency landing, refueling, and pick-up and drop-off operations would need to provide a means of locating secure sites for landing. Despite these provisions, the vehicle should still be

able to provide tracking information in the unlikely event of a theft. Authorities could then follow the signal to re-secure the UAV.

Vandalizing of vehicles should be minimized. Similar to UPS and FedEx trucks in use today, AVSLA air vehicles would be in almost constant use during delivery hours. After completing the day's deliveries, the vehicles could assemble at a secured location(s) for the evening. Secure refueling sites would also be necessary to keep vandalism at a minimum during delivery hours. These sites will initially be manned sites but could be automated in the future.

Data security of the dispatch database must also be considered. Since billing information, that could include credit card data or other private customer information, could be stored in the database, it's crucial that this data be secured. In today's Internet retail market, data security is an important issue that has received large amounts of attention. Systems can be expected to be available that provide sufficient security for the dispatch database.

Finally, to ensure tight security, auditing methods and procedures will be defined to allow regular review of the security measures as a whole. The auditing procedures would occur on a regular basis, requiring an independent organization to report on the system. Regular updates to security would ensure that the system passes the periodic audit.

7.5   System IT Conclusion

System-level IT requirements dramatically impact vehicle design, and the complexity of the communications, processing, package handling, and flight control systems, cause IT costs to make up the majority of the total vehicle cost. Many of the IT requirements discussed are unrelated to the method of control. These systems include a TCAS and OASys type collision avoidance system, sensors to provide information for flight control, package handling capability, some type of transponder with GPS or DGPS locating capability, and some form of communication.   The ultimate communication requirements depend on the control system chosen. In the event that Stand-alone control is selected, an intermittent satellite communication link will be needed that provides one single frequency to all vehicles with coded information that can relay specific information to any one vehicle or to all vehicles. Additional IT requirements (specifically for more secure communications or improved decision-making capability) would exist for an autonomous military cargo vehicle, and many depend on having the ability to carry personnel. The purpose of this section was to determine equipment needed and supply cost parameters for the economic analysis section, specific brands or model numbers have not been identified.

8 ECONOMIC ANALYSIS

The final task in Phase I was to complete an economic analysis of the architecture as a whole. During the cost analysis, some basic vehicle economics were derived, though a more in-depth analysis is needed to show the overall architecture cost. These costs include system costs for IT and necessary personnel, vehicle costs, security costs, development costs, and continuing operational costs.

8.1 IT costs

As discussed in Section 7, system IT requirements are dependent on the type of control structure used. The economic analysis that follows is based on using the recommended Stand-alone control method. The items shown below depict purchasing costs without considering financing of the equipment. In order to provide an accurate financing model, the amount financed, the duration of financing, and the expected interest rates ten to twenty years from now are all required. Since this type of prediction is difficult, direct purchasing costs are used for comparison instead. The dollar figures used are listed in both year-2000 values and an approximated year-2020 value. An inflation calculator was used to determine the value of the dollar in 2020.[57] Table 8-1 shows the resulting costs.

Table 8-1: Economics of system IT costs.

<table>
<tr><th colspan="5">Economics of a System IT Requirements</th></tr>
<tr><th></th><th colspan="2">2000</th><th colspan="2">2020</th></tr>
<tr><th></th><th>One time Cost</th><th>Ongoing Cost</th><th>One time Cost</th><th>Ongoing Cost</th></tr>
<tr><td>Dispatch Computer</td><td>$65,000.00</td><td>$0.00</td><td>$161,384.00</td><td>$0.00</td></tr>
<tr><td>Dispatch Software</td><td>$10,000,000.00</td><td>$2,600.00</td><td>$24,828,264.00</td><td>$6,455.00</td></tr>
<tr><td>Dispatch Server Software</td><td>$1,500.00</td><td>$0.00</td><td>$3,724.00</td><td>$0.00</td></tr>
<tr><td>T-1 Line (annual)</td><td>$0.00</td><td>$10,200.00</td><td>$0.00</td><td>$25,325.00</td></tr>
<tr><td>Satellite Connection (annual)</td><td>$0.00</td><td>$162,000.00</td><td>$0.00</td><td>$402,218.00</td></tr>
<tr><td>Traffic Server</td><td>$100,000.00</td><td>$0.00</td><td>$248,282.00</td><td>$0.00</td></tr>
<tr><td>Weather Server</td><td>$100,000.00</td><td>$0.00</td><td>$248,282.00</td><td>$0.00</td></tr>
</table>

8.2 Personnel Requirements

Although unmanned vehicles eliminate the need for pilots or drivers, there are still many personnel requirements for maintenance, fueling, IT maintenance, billing, engineering, and general maintenance. Therefore, the number of necessary personnel is decreased by the number of drivers in the current delivery system. In 1999, according to their annual report, the FedEx delivery system employed 156,386 people full-time. Eliminating all driving related personnel, this number would be reduce to roughly 105,000 employees (a 33% reduction). By reducing the number of employees, salary costs are similarly reduced by 33%. This reduction does not account for the number of personnel required in customer service that provide dispatch and delivery order information. By using an Internet or server based service, a large portion of the personnel needed can be further reduced to a few customer service agents that provide troubleshooting to customers. In addition, personnel required to maintain and guard the ground-vehicle fleet during off times can be reduced. This is the result of needing less storage space, and smaller vehicle shops to maintain and keep the air vehicles.

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[57] Inflation was mimicked from 1979 to 1999, using information from the *Statistical Abstracts of the United States.*

Military personnel costs are less sensitive to the number of pilots in the system, but the savings in terms of human life in combat can be significant; minimizing unnecessary pilot risk is a major factor in considering the implementation of a military UAV cargo system. However, this benefit is difficult to quantify monetarily, and hence the personnel cost savings for military and commercial heavy-transport are both tabulated based on the costs of hiring additional pilots. Table 8-2 shows the salary ranges for military and commercial flight crew.

Table 8-2: Standard salary ranges for military and commercial helicopter pilots.

Position	Military	Commercial
Pilot*	$34,500 - $52,700	$30,000 - $50,000/pilot
Co-pilot*	$34,500 - $52,700	$30,000 - $50,000/navigator

* Data determined from Military Paygrade Scale (July 1, 2000) and Wagewatch at JobMonthly.com

8.3   Vehicle Costs

The AVSLA will not be developed for some time and is largely unique, but the large number of vehicles the system would use means that recurring costs should drive system cost. Two different cost models were used to predict a likely vehicle cost. The first model is a simplified Airframe Cost Model provided by NASA. The results of this model are shown in Table 8-3, including a final per aircraft cost. The second economic model is a more detailed cost analysis created using Price Models[58] sizing and cost analysis software. Development costs for Sikorsky's Cypher UAV program were used to calibrate the system. Table 8-4 displays the results of this analysis including per aircraft cost.

Table 8-3: Simplified vehicle cost model.

Vehicle Input Data	
Empty Weight	140 lb
Maximum Speed	100 knots
# of Flight Test Aircraft	3
Production Quantity	185,000

Cost Output Results		
Non-recurring Costs	*Manhours*	*Cost*
Engineering	27,000	$3,000,000
Tooling	15,000	$1,000,000
Development Support		$1,000,000
Flight Test		$2,000,000
Recurring Costs		
Engineering	158,000	$17,000,000
Tooling	421,000	$39,000,000
Manufacturing	2,895,000	$250,000,000
Material		$45,000,000
Quality Assurance	8,454,000	$725,000,000
Total:	11,970,000	$1,083,000,000
Per Vehicle Cost:		$5,854

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[58] Economic pricing model software previously owned by RCA, GE Aero, and Lockheed Martin.

Table 8-4: Price Model's pricing results.

Program Cost	Development	Production	Total Cost
Price Hardware Model			
Engineering			
Draft	$155,100	$2,900	$158,000
Design	$642,900	$7,500	$650,400
System	$224,000	$0	$224,000
Proj. Mgmt	$602,200	$76,051,700	$76,653,900
Data	$1,842,800	$97,460,200	$99,303,000
Manufacturing			
Production	$0	$650,632,900	$650,632,900
Prototype	$874,000	$0	$874,000
Tool Test Eq.	$89,100	$8,136,300	$8,225,400
G & A / CoM	$720,100	$61,235,600	$61,955,800
Fee / Profit	$525,600	$122,341,400	$122,867,000
Total Cost	$4,051,700	$939,806,400	$943,858,100

Monthly Production Rate	$4,240	Unit Production Cost	$1,655

Factors used in creating the Price Model economic analysis take into account the financial impact of creating a new model without existing manufacturing or production technology. In addition, the complexity of manufacturing vehicles using nanotechnology is assumed to be high, representing an added cost. The outcome of the analysis shows a vehicle production cost of just over $4,000; however, many of the design factors were set to a complex system with complex building materials. It is conceivable that learning curves and advanced manufacturing techniques could reduce recurring costs even further; however, the initial cost analysis showed that a unit cost of approximately $4,000 is competitive to current markets. Lowering the unit cost only widens the gap and increases the competitive margin.

8.4 System Development

Further development costs are incurred while setting up the vehicle and customer support systems. The system costs are a combination of personnel, IT, security, and real estate costs. Personnel and IT related costs have already been discussed; additional software and hardware will need to be developed to provide vehicle, data, and package security. Currently, 464-bit encryption software is available for less than $2,800,000 (paying a $15 individual license-fee per vehicle)[59]. Hardware that incorporates a processor, emergency coding, lock-down features, and a tracking device would be added to each vehicle for added protection in the event of a forced or unplanned landing. Devices are currently available that provide vehicle tracking; however, prices are around $4,000 per piece. Therefore development of appropriate hardware is needed to produce a security system that costs approximately $200 per vehicle.

Real estate costs should be fairly low for this system. Necessary facilities include a dispatch location located in the Manhattan area, refueling sites, and a maintenance/vehicle storage location. To determine approximate rental/lease rates for office space in Manhattan, a compilation of 25 office sizes and rates was used to determine that office space sells for a monthly average of $4.32 per square foot for spaces under 2500 square feet. A small 200 square foot office should be sufficient for the dispatch center, costing just under $10,500 annually.

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[59] License information provided by Encryption Software, Inc.

Refueling and maintenance/storage sites can be strategically located in low cost lots, most likely in the center of the northeast region (near New York City). Land outside of New York City in Columbia and Dutchess counties sells for an average $5,860 per acre for properties 8 acres and larger. Therefore, a large 8 acre site could be purchased for $46,880. It is clear then that facility costs are very minor, and make up a very small percentage of total system costs.

8.5   Operational Costs

The largest recurring cost for the AVSLA is vehicle operational costs. Of these costs, fuel consumption is the largest. Assuming zero idle time and 10 hours of operation per day, 5 days per week, total fuel cost would be $1.8 billion. However, one can predict that this usage will not occur, and that each vehicle will incur some amount of idle time. In addition, many vehicles may not be needed on a daily basis. Therefore, 50-60% idle/down time is assumed, which incurs a fuel cost of near $900 million, annually. Maintenance for the Light Lift concept is the second largest operating cost, nearly $60 million annually. Again, a 50% idle/down multiplier is used. Annual fuel consumption cannot be accurately estimated for the Heavy Lift category, since annual usage is highly variable and depends on military and commercial transport use. However, the per hour fuel cost is approximately $255, with an hourly maintenance cost of $1,303.

Other operational costs include personnel, which was already analyzed, and administrative costs, such as insurance, landing fees, taxes, etc. These costs are minimal when personnel costs are subtracted out. Approximate insurance for the Heavy Lift platform is fairly costly at $295 per hour, accounting for approximately 16% of the total operational costs.

9 AVSLA CONCLUSION AND PHASE II RECOMMENDATIONS

9.1 Conclusion

Despite the high cost of contemporary air transportation in the area of maintenance, vehicle price, and fuel costs, an autonomous airborne cargo system is both a viable and beneficial alternative. By using the recommended Autonomous VTOL Scalable Logistics Architecture (AVSLA), the time currently taken to deliver a package is dramatically reduced from a minimum of one day to a minimum of a couple hours. In addition to improved delivery times, delivery costs are also lower than the current delivery system.

The greatest benefits are seen from the point-to-point delivery architecture. During initial deployment stages, customers will see delivery cost and time reductions. However, once the entire network of vehicles is operational, shipping facilities can take advantage of the "just in time" delivery system. "Just in time" means that a customer can order a product prior to their need for it. Since delivery time is so short, the delivery can be scheduled to arrive "just in time" to be used. In addition, the shipper of the product can time their operation to finish packaging the product for shipment "just in time" to have a delivery vehicle pick-up the shipment and perform the delivery. As the timing of this type of system is perfected, use of warehouses, material stores, and miscellaneous holding methods is minimized or eliminated for many types of operations.

The logistics portion of this study has shown that a two-tiered vehicle development approach that develops a Light Lift vehicle that can travel up to 500 miles with a payload of 100 lb. and a Heavy Lift vehicles that carry 10,000 lb. payloads up to 250 miles will effectively capture a majority of regional shipping in the region studied. The Light Lift vehicle was compared to the average FedEx/UPS delivery van and was shown to be a viable option, as the cost and time for the Light Lift vehicle was lower than current FedEx rates and times. However, during the cost analysis modeling, it was shown that a VTOL with a 10,000 lb. payload capacity is not economically comparable to today's long and short haul trucks. Alternate uses of the Heavy Lift design were sought and found that provide economical usage of the payload and range requirements.

Once the vehicle design requirements were determined, system IT requirements and system scheduling, routing and architecture analyses were performed to further define the system and narrow the focus of future studies. A posture-based service with predictive-adaptive scheduling abilities was selected. The need for long-term planning and cooperation with the FAA was identified as a means of ensuring that routing will not be overly burdened by FAA regulations. So, a final recommendation of using an unconstrained "free flight" system was made, but further Phase II work will need to be made to determine the direction the FAA is headed with UAV regulations. Finally, the physical architecture conclusion is that a distributed (point-to-point) architecture takes the most advantage of the small VTOL aircraft's capabilities.

The vehicle design study viewed various VTOL aircraft platforms for the Light Lift vehicle and selected the two most viable options. Each of these vehicle types was sized using Sikorsky's VTM+ sizing software, and then compared to determine the best design for the Light Lift class. The Heavy Lift vehicle was assumed to be a conventional helicopter, but a control system conversion was recommended as the low cost alternative for autonomous Heavy Lift carrying capability. Further study during Phase II is recommended to determine if customers expect the Heavy Lift platform to be capable of both manned and unmanned operation.

Finally, an economic analysis was completed to show the overall resulting cost of both the system and the vehicle design. Recurring and non-recurring costs were examined to separate the development costs from ongoing operational costs. The resulting per vehicle cost for the Light Lift system is as expected (just over $4,000 per vehicle), and further development costs are fairly low for the entire system. Overall, the design proves to be a viable option for future effort.

During the study, areas of further recommended research were found. Much of the vehicle benefits are attributed to upcoming nanotechnology, which is promised to be available around 2020. The effect of nanotechnology in the aircraft industry will be astounding, and the benefits of light-weight/high-strength nano-materials, will be most pronounced for small vehicles requiring high payload fractions. Therefore, the Light Lift cargo transport vehicle is an ideal candidate for use of these materials. In addition, benefits from nanotechnology based computer chips will have a large impact on both Light and Heavy Lift vehicle processing performance. Ultimately, it is recommended that further funding be placed into nanotechnology research, which will benefit not only the AVSLA, but the aircraft industry as a whole.

9.2   Phase II Recommendations

Recommended Phase II tasks have been identified throughout the AVSLA Phase I study. They include areas of analysis in vehicle design, choice of routing, further defining of the distributed architecture derivative, and a cost study of mainframes for vehicle control. These items of study are in addition to the proposed plan to look at scaling the AVSLA from a regional deployment to a national one.

For vehicle design, it was found that more information is needed on customer expectations. In the Heavy Lift category, both the military and commercial users need to be queried for their intended use of an autonomous flight capable, Heavy Lift platform. Would the vehicle be strictly used as a UAV transport vehicle? Or would it be beneficial to have a vehicle that could have alternating use as a UAV or a manned aircraft? An answer to this question is needed to determine which of two vehicle options is the most cost effective for the intended customers.

Routing questions arose during Phase I due to the connection between available routes over populated areas and FAA restrictions imposed on UAVs. A contact with the FAA is needed to determine where current guidelines are headed, and how routing can be designed to include any regulations that are imposed. It is best to start this process as early as possible so that the systems being deployed today can be built with provisions for a future AVSLA.

During Phase I, a distributed architecture was chosen as the best method of delivering packages within the Northeast Region. However, as the AVSLA is scaled up to a national level, the restrictions on architecture change, and a derivation of the distributed architecture may prove more effective and efficient. Therefore, during the scaling portion of Phase II, a further look at the architecture will be necessary.

Finally, as this system was defined, it became apparent that some of the IT requirements were based on processing power that is not yet available or designed. Therefore, a partnership or contract should be made with a computer manufacturer to further define the cost associated with developing large mainframes, capable of manipulating large numbers of complex vehicles (50,000 to 185,000). These defined costs will provide a more in-depth analysis for the type of vehicle control needed for the AVSLA.

Phase II is an important step in bringing this system to reality. Although the majority of the architecture has been conceptualized, further analysis will finish the analysis and allow work to begin on providing the nation with an advanced form of cargo transport that will revolutionize

the way manufacturers produce goods. "Just in time" delivery is an advanced concept that promotes lower cost goods, due to the removal of holding costs, and ensures direct transport of goods into the intended customers hands without involvement of a middleman. VTOL aircraft are essential to this type of system, due to their ability to drop-off and pick-up packages in virtually any available space. The high-speed ability of a tilt-shroud type design also ensures safe and quick transport of packages to the intended location. Sikorsky Aircraft sees the AVSLA as the cargo shipment network of the future.

APPENDIX A
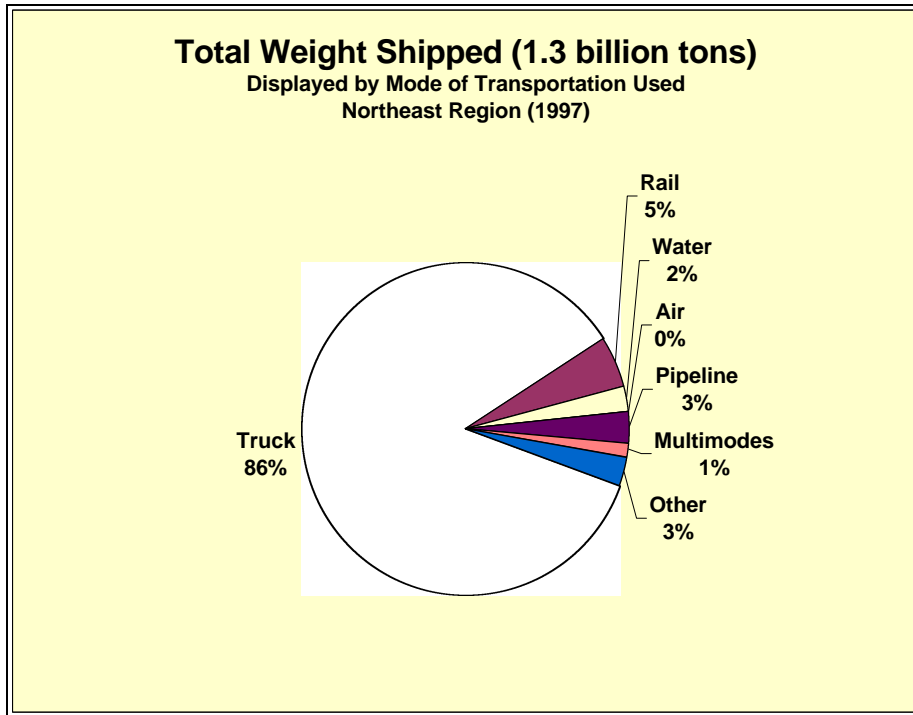
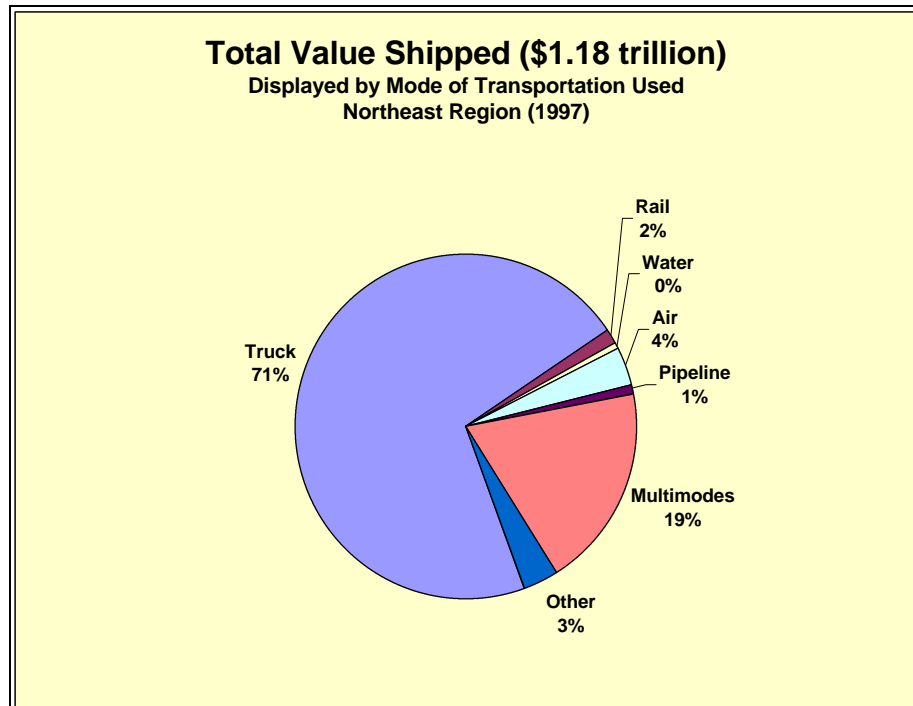**Table A-1: Weight Shipped by Mode of Transportation**

Total Weight Shipped (1.3 billion tons)
Displayed by Mode of Transportation Used
Northeast Region (1997)

- Rail 5%
- Water 2%
- Air 0%
- Pipeline 3%
- Multimodes 1%
- Other 3%
- Truck 86%

Table A-2: Value Shipped by Mode of Transportation

Total Value Shipped ($1.18 trillion)
Displayed by Mode of Transportation Used
Northeast Region (1997)

- Rail 2%
- Water 0%
- Air 4%
- Pipeline 1%
- Multimodes 19%
- Other 3%
- Truck 71%

APPENDIX B

Light Package Transport (FedEx)*:*

Fuel Cost:

1999 FedEx Annual Report states $604,929,000 in fuel costs annually. Also, it is reported that 8,600 vehicles are required to transport 1.5 million packages/day. In 1999, 3.13 million packages were delivered. Therefore;

$$\$604{,}929{,}000/yr*1yr/260days = \$2{,}326{,}650/day \qquad \%\,overnight = \frac{1{,}500{,}000\,pkgs}{3{,}133{,}000\,pkgs} = 48\%$$

**Note: Assumption made that since 48% of packages are overnight, 48% of daily fuel costs are used to deliver overnight packages.

$$\$2{,}326{,}650/day*48\% = \$1{,}116{,}800/day \qquad \frac{\$1{,}116{,}800/day}{1{,}500{,}000\,pkgs/day} = \$0.74/pkg$$

**Note: Assumption made that the average overnight package spends 6 hours in the system.

$$\frac{\$0.74/pkg}{6hrs} = \$0.12/(pkg*hr) \qquad\qquad \mathbf{\$0.12/pkg*hr}$$

Misc. Finance Cost:

1999 Depreciation and amortization, rentals and landing fees and miscellaneous 'Other' expenses from FedEx = $5,421,069,000 or 8.96 x fuel costs.

$1.08/pkg*hr

Maintenance Cost:

1999 Maintenance and repairs from FedEx = $958,873,000 or 1.59 x fuel costs.

$0.19/pkg*hr

Personnel Cost:

1999 Salaries and employee benefits from FedEx = $7,087,728,000 or 11.7 x fuel costs.

$1.40/pkg*hr

Speed of Transport:

An assumption of 15 mph was made, taking into account the multiple stops, and traffic encountered along the typical FedEx Van route.

15 mph

Vehicle Cost Factor:

See Table 2-1.

Light Package Point-to-Point: **$0.11/pkg*hr**

Fuel Cost:

Cypher I data shows fuel consumption of 27 lb/hr of JP-5 fuel. Density of JP-5 is 6.8 lb/gallon, and cost is $1.30/gallon (listed at http://logs-web.gsfc.nasa.gov/CTLG/Cat9130.txt).

$$\frac{27\,lb/hr}{6.8\,lb/gallon} = 3.97\,gallon/hr \qquad 3.97\,gallon/hr * \$1.30/gallon = \$5.16/hr$$

Misc. Finance Cost:
Depreciation and amortization, rentals and landing fees and miscellaneous 'Other' expenses assumed similar to FedEx amount.

$1.08/pkg*hr

Maintenance Cost:
Maintenance and repairs approximated as higher than FedEx Van maintenance; therefore, amount is set to 1.5 times the FedEx per/vehicle maintenance value.

$0.25/pkg*hr

Personnel Cost:
Due to the automated nature of the VTOL, personnel can be cut by nearly 2/3.

$.43/pkg*hr

Speed of Transport:
As traffic is no longer a concern, and point-to-point travel eliminates interim stops, full cruising speed of 120knots could be maintained between pick-up and drop-off. Acceleration, deceleration, and pick-up/drop-off time would reduce the average speed to approximately:

90 mph

Vehicle Cost Factor:
See Table 14.

$0.10/pkg*hr

Heavy Package Transport (Trucking):

Fuel Cost:
Average diesel cost = $1.45/gallon, average mileage = 6.3 miles/gallon, and average speed is 50 miles/hour.[60] Therefore:

$$\frac{\$1.45/gallon}{6.3\,miles/gallon} * 50\,miles/hour = \$11.51/hour \qquad \textbf{\$11.51/truck*hr}$$

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[60] Truckinfo.net (statistics compiled from several governmental sources; US-DOT, ICC NHD, BTS, etc.)

Misc. Finance Cost:
   1999 total road costs paid by the trucking industry = $21.4 billion. This is spread out among 15.5 million trucks operating on the road. Therefore;

$$\frac{\$21,400,000,000}{yr} * \frac{1}{15,500,000\, trucks} * \frac{1\, yr}{2600\, hrs} = \$0.53 / truck * hr \qquad \textbf{\$0.53/truck*hr}$$

Maintenance Cost:
   1999 Maintenance and repairs from Dept. of Transportation = $239,616,000.

$$\frac{\$239,616,000}{yr} * \frac{1}{192,000\, trucks} * \frac{1\, yr}{2600\, hrs} = \$0.48 / truck * hr \qquad \textbf{\$0.48/truck*hr}$$

Personnel Cost:
   1999 average trucker's salary = $32,000. Therefore;

$$\frac{\$32,000}{truck * yr} * \frac{1\, yr}{2600\, hrs} = \$12.30 / truck * hr \qquad \textbf{\$12.30/pkg*hr}$$

Speed of Transport:
   An assumption of 40 mph was made, taking into account the traffic encountered along the typical route and slowing within city limits (i.e., industrial areas typical of loading docks).

40 mph

Vehicle Cost Factor:
   Approximation of tractor/trailer average price is made at $90,000. Average life cycle of the vehicle is approximated at 15 years. Therefore;

$$\frac{1}{15} * \frac{\$90,000}{truck * yr} * \frac{1\, yr}{2600\, hrs} = \$2.30 / truck * hr \qquad \textbf{\$2.30/truck*hr}$$

Heavy Package Point-to-Point:

Fuel Cost:
   From the standard Sikorsky design rules-of-thumb, fuel costs are derived using the following equation (where fuel price is chosen at $1.30/gallon):

$$0.00485 * (GrossWeight)^{1.042} * Fuel\, \Pr ice$$

Misc. Finance Cost:
   This amount is left equal to the trucking industry road costs to provide an extra buffer for the Heavy Lift AVSLA landing fees.

$0.53/flight*hr

Maintenance Cost:

Maintenance and repairs approximated as 0.036*Gross Weight via standard Sikorsky methods.

Personnel Cost:

Flight crew is eliminated due to the autonomous nature of the vehicle. Maintenance and administrative staff are considered negligible.

$0/flight*hr

Speed of Transport:

As traffic is no longer a concern, and point-to-point travel eliminates interim stops, full cruising speed of 130 knots could be maintained between pick-up and drop-off.

130 mph

Vehicle Cost Factor:

A median price equation was used following a single turbine engine equation as follows:

$$100*(GrossWeight)^{1.1} = \$10.3 \text{ million}$$

Insurance Costs:

Liability insurance can be assumed to be more expensive on an automated vehicle than a human piloted craft, so a multiple of 1.5 times the typical insurance cost was assumed. The equation used is as follows:

$$1.5*(\frac{0.07*price}{utilization}) = \$417.71 \text{ per vehicle (where } utilization \text{ is approx. 2600 flight hours/year)}$$

Environmental Savings:

Since such a large negative impact on the environment is made by the trucking industry, it seems reasonable to calculate the reduction in impact from using delivery aircraft. Table 1-5 in section 1.4.3 shows the total environmental impact in the continental US due to the trucking industry.

Therefore, given the values in the table, it's fair to assume that a VTOL vehicle would still create air pollution, noise, waste disposal, and greenhouse gases. Redundant systems and computer control can minimize if not eliminate crash costs. As mentioned the amount saved would still be approximately $710,000,000 annually.

An additional calculation then must be made to account for the number of vehicles replaced by the AVSLA (1.76% of the total truck population in the US). Assumptions were needed for this calculation and are listed as follows:

192,000 tractor-trailers purchased annually $\Rightarrow$ 63,990 tractor-trailers in NE (33%)

1.76% of NE trucks = 1,126 tractor-trailers $\Rightarrow$ 600 VTOL vehicles (10,000 lb. max.)

or   400 VTOL vehicles (20,000 lb. max.)

or   300 VTOL vehicles (30,000 lb. max.)

Therefore, depending on maximum payload, actual environmental savings is based on:

$$\frac{\$710,000,000}{\#vehicles} * \frac{1\,yr}{2600\,hrs}$$

Weight Factor:

The weight factor is determined by making a study of the current rating system for the trucking industry. Differences in pricing between shipment weights can be broken down into a dollar/pound weight factor. An assumption is made that the weight factor for a few companies is a consistent indicator of the overall weight factor for all companies.

Profit Percentage:

From 1999 data, the average profit per dollar for the trucking industry is 4.8 cents. Therefore, a profit of 4.8% was used in the model to represent the VTOL system, also.