Air Vehicle Design and Technology Considerations for an Electric VTOL Metro-Regional Public Transportation System

Jeffrey D. Sinsay[1]
U.S. Army, Aeroflightdynamics Directorate(AMRDEC), Moffett Field, CA 94035

Juan J. Alonso[2]
Stanford University, Stanford, CA,94305

Dean A. Kontinos[3], John E. Melton[4] and Shon Grabbe[5]
NASA Ames Research Center, Moffett Field, CA, 94035

This paper examines the potential of VTOL aircraft to supplement commuter rail services in a metropolitan or regional transportation system. An interdisciplinary study was conducted to examine the feasibility of integrating an aerial transport system into the existing airspace using a fleet of electrically powered rotorcraft. A notional network of stations and overall operating schedule were constructed based on the existing regional rail networks serving the San Francisco Bay Area. To define the VTOL vehicles, the rotorcraft sizing code NDARC has been modified to accommodate electric propulsion sizing. Initial sizing results indicate that battery technologies available by 2030, coupled with the "short-hop" ranges of the proposed aerial network, result in feasible aircraft designs. These vehicle designs, while significantly larger in gross weight than their Jet A powered turboshaft equivalents, may become economically viable in a business environment dominated by fuel costs. Finally, these initial study results are informing follow-on study efforts.

Nomenclature

AC	=	Alternating Current
DC	=	Direct Currents
E_{batt}	=	Battery stored energy, kWh
HOGE	=	Hover-Out-of-Ground Effect
P_{acc}	=	Accessory power requires, shp
P_{motor}	=	Electric motor power available, kW
P_{rotor}	=	Main & tail rotor power required, shp
P_{batt}	=	Battery power delivered, kW
TRL	=	Technology Readiness Level
W_{motor}	=	Electric motor weight, lb
VTOL	=	Vertical Take-off and Landing
η_{motor}	=	Electrical power to mechanical power conversion efficiency of the motor, ND
η_{pe}	=	Electrical efficiency of power electronics including wiring losses, ND
η_{batt}	=	Battery stored energy conversion efficiency, ND
χ_{batt}	=	Energy density of battery, kWh/kg

[1] Stanford PhD Candidate and Aerospace Engineer, Advanced Design Office, MS 219-3, Member AIAA.
[2] Associate Professor, Department of Aeronautics and Astronautics, 496 Lomita Mall, Senior Member AIAA.
[3] Chief, Entry Systems and Technology Division, MS 241-20, Associate Fellow AIAA.
[4] Aerospace Engineer, Systems Analysis Branch, MS 258-1, Senior Member AIAA
[5] Research Scientist, Systems Modeling & Optimization Branch, MS 210-10, Associate Fellow AIAA

I. Introduction

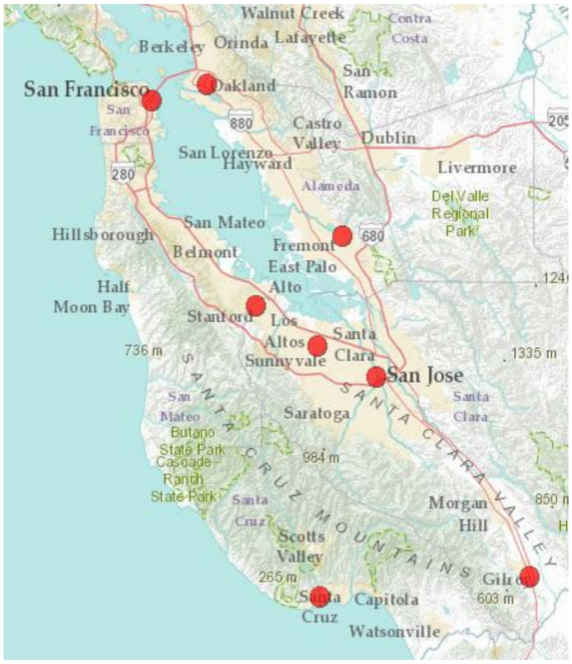
RECENTLY, NASA Ames Research Center and Stanford University engaged in a study to examine the technical feasibility of an aerial mass transit network in the San Francisco Bay Area. The use of Vertical Take-off and Landing (VTOL) aircraft to provide regional transportation has been studied and reported on previously.[1-3] An example of a previously studied concept is pictured in Figure 1. In addition, active research and development continues on “flying cars” and other forms of personal air transportation.[4] From the early 1950’s through the end of the 1970’s several helicopter airlines operated regular interurban service in the New York, Chicago, San Francisco and Los Angeles metropolitan areas. Presently the only remaining helicopter airline in North America operates regular service from Vancouver to Victoria, Canada.[5] The current study envisions a VTOL air vehicle enabled metropolitan air transportation system for public mass transit, in contrast to the predominate interest in previous studies directed towards private air taxi or airline service.

An additional unique aspect of the NASA/Stanford study is the interdisciplinary approach to the problem of aerial mass transit. While this paper focuses on the vehicle conceptual design aspect of the study, work was also performed simulating the impact of the proposed transit system on existing air traffic operations, developing notional operating schedules and simulating regional passenger movements. This paper describes the design of several rotorcraft vehicles, aka Hoppers, for a notional mass transit system and highlights how interactions with the other aspects of the study influenced the designs. The Hopper design information was also used to support this additional study work by providing quantitative performance information for use in the various simulations conducted By including a more complete analysis of the system design problem, trade-offs in the air vehicle design could be considered in a context which resulted in an improved overall aerial transit system concept.

The San Francisco Bay Area is served by several commuter rail systems. Bay Area Rapid Transit (BART) connects San Francisco with the East Bay suburbs and carries 383,700 riders per day.[6] CalTrain connects San Jose with San Francisco along the San Francisco Peninsula and carries 42,400 riders per day.[6] An examination of 5k, 15k and 45k daily ridership numbers on the notional aerial transit system was therefore felt to be reasonable.

Eight station locations were identified for the notional aerial network, seven of which correspond to existing BART and CalTrain station locations. To highlight the flexibility of an aerial network, a station was also located in the Bay Area exburb and popular weekend destination of Santa Cruz. Formed by uplift due to the San Andreas Fault, the Santa Cruz Mountains, separate Santa Cruz from the greater Bay Area. Extension of the Bay Area rail network south to Santa Cruz would potentially be prohibitively expensive. Presently, construction is planned on an extension to BART to build two stations and bring trains 10 miles further down the East Bay to East San Jose at an estimated cost of $2.1B[7]. For an aerial mass transit network, the addition of a new node to the network is primarily

Figure 1 Hughes Helibus concept circa 1967.



	Fremont	Gilroy	Oakland	Palo Alto	San Francisco	San Jose	Santa Cruz	Sunnyvale
Fremont								
Gilroy	38.6							
Oakland	20.4	58.6						
Palo Alto	11.3	39.0	22.1					
San Francisco	23.8	60.9	6.0	22.7				
San Jose	14.1	25.3	33.4	14.3	35.6			
Santa Cruz	35.2	22.1	51.3	29.1	51.4	22.3		
Sunnyvale	11.0	31.6	27.9	7.5	29.5	6.8	24.4	

Station-to-Station Great Circle Distance, nm

Figure 2 Hopper aerial mass transit network and associated station-to-station distances.

a process of siting and building a new station. The incremental cost to modify the network will, therefore, be significantly lower than extension of a traditional commuter rail system. The location of the selected stations for the aerial transit system and point-to-point distances are shown in Figure 2. Maximum point-to-point distance between any of the stations is 61 nm and the median segment distance is 25 nm. For a hub-and-spoke operation out of, the centrally located, Sunnyvale station the maximum segment distance is 32 nm.

This study performed a daily movement simulation for the three daily ridership levels of 5k, 15k, and 45k passengers to examine the impact of ridership variation. Distribution of passenger origin and destination pairs for each of these scenarios was based on consideration of the general population distribution and job centers location in the Bay Area. A custom-developed discrete-event simulator, BaySim, was developed for the purpose of performing these simulations. Based on the results of the movements simulation, three different Hopper air vehicle sizes were selected, and a daily flight schedule constructed for use in the air traffic simulation portion of this study.

This paper provides information on the design of the three Hoppers at 6, 15 and 30 passenger respectively. The paper also highlights some of the multidisciplinary interactions of the vehicle design activity with the overall aerial transit system design. Particular focus is given to the conceptual design of an electric 30 passenger Hopper concept. This concept best embodies the desired study attributes of being suitable for mass transit, environmentally friendly, and a potential target for focusing technology investment to increase the role of aviation. While success with all-electric rotorcraft to date has been limited[8], continued improvements in energy storage densities and the relatively short range requirements for a mass transit rotorcraft make the possibility of an all-electric rotorcraft intriguing for this application.

II. Hopper Propulsion Technology Survey

Examining ways to reduce the environmental impact of the aerial mass transit system was an additional consideration in the Hopper conceptual design. The aerial mass transit concept under study is intended to operate as a high-volume/high-frequency service, so its potential impact on carbon emissions and air quality in the metropolitan area is a key environmental consideration. While BART is an electrified heavy rail system, CalTrain presently utilizes Diesel-Electric locomotives to provide service. Given the extremely short range requirements necessary to operate the network and the desirability to be no more polluting than a conventional transit rail systems, the conceptual design activity focused on looking at alternative propulsion concepts. A 2030 time horizon was used in considering available technologies. Additional technology improvements over current state-of-the-art rotorcraft were assumed consistent with those of the earlier NASA heavy-lift rotorcraft investigation.[9]

A key challenge in moving away from current Kerosene-based propulsion systems is the very high specific energy of Jet A, 12,000 Wh/kg, as compared to alternative forms of energy storage. This advantage in energy storage is partially offset by the relatively low overall thermal efficiency of turboshaft driven rotor systems (~28%) as compared to electric drive schemes. While currently mass produced Li-ion battery systems are at about 180 Wh/kg specific energy, next generation Li-S battery chemistries achieving 350 Wh/kg have been demonstrated on QinetiQ Zephyr HALE UAV.[10] Further advances in Li Polymer technologies show potential for achieving 650 Wh/kg[11] and beyond (see Figure 3). Battery technology is trending toward not only significantly higher specific energy's, but also higher specific densities. These higher specific densities reduce the needed volumetric space for batteries in the airframe.

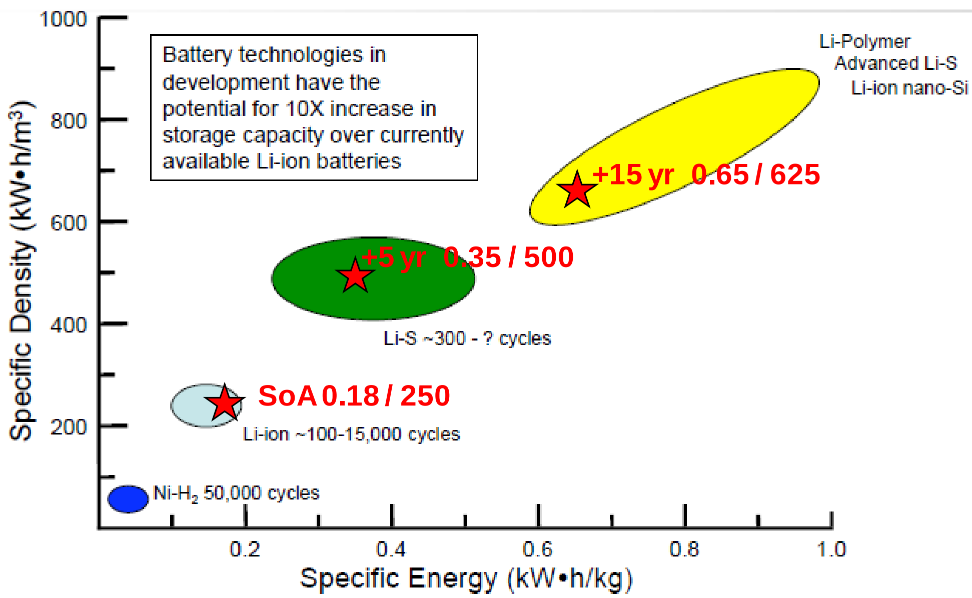


Figure 3 Battery specific energy and density trends.[11]

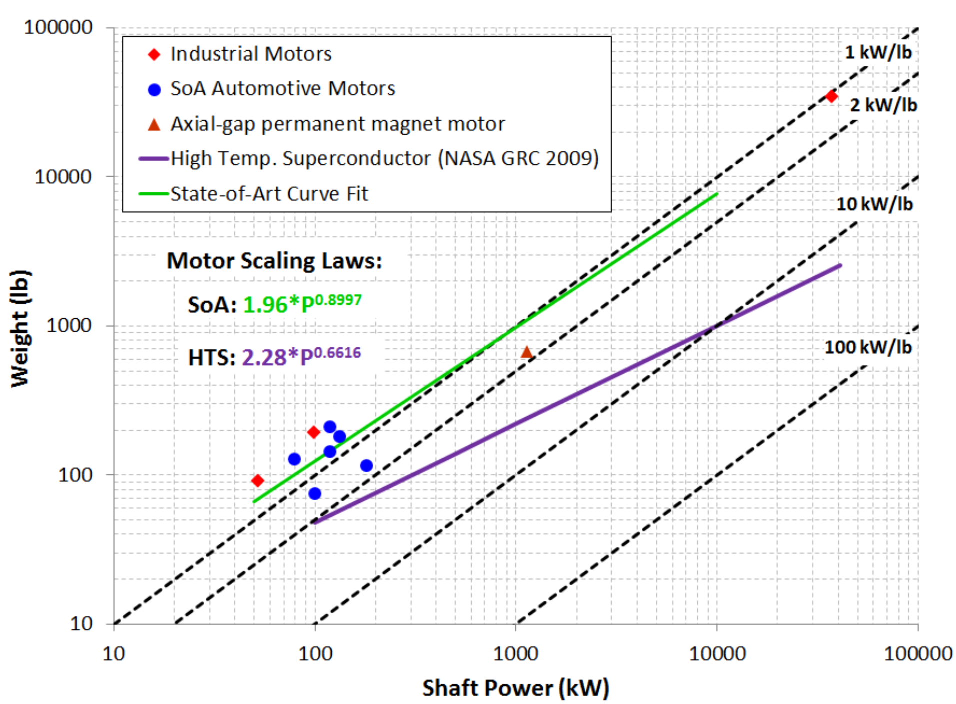


Figure 4 Electric motor scaling trends for both state-of-the-art automotive and industrial motors, and high temperature superconductor motors.[13]

Conventional powered rotorcraft enjoy not only an advantage in their energy storage density, but also in the power density of the turboshaft engine used to power the rotor. A modern turboshaft engine, like the GE CT7-8 has a power density of 7.7 kW/kg[11]. This compares favorably to a best in class 3.5 kW/kg for the Tesla Model R Roadster electric motor. The power required to hover a Hopper vehicle is significantly higher than that need to propel an automobile, and it is anticipated that an electric Hopper concept will require a significantly more powerful motor than those currently being developed for automotive use. Using large industrial electric motors as a guide, a scaling law for state-of-the-art electric motors was developed (Figure 4):

$$W_{\text{motor}}(\text{lb}) = 1.96 \times P_{\text{motor}}^{0.8997}(\text{kW})\,. \tag{1}$$

The favorable power density scaling, indicated by this trend, suggest that propulsion architecture trades will favor a system with fewer large motors as opposed to a large number of distributed small motors for driving the main rotor. The state-of-the-art automotive motor data also shows significant scatter compared to trend, suggesting that factors other than power may be important. Improved scaling considering these factors is an item for future consideration. Considering the Tesla motor as representative of good design, a 40% improvement relative the state-of-the-art trend appears to be a reasonable assumption for the electric Hopper designs. Looking beyond continued improvements in AC induction and brushless DC motors, a NASA Glenn study[13] of high temperature superconducting motors suggests that even greater improvements in motor power-to-weight are possible. NASA proposes the following scaling law for these motors:

$$W_{\text{motor}}(\text{lb}) = 2.28 \times P_{\text{motor}}^{0.6616}(\text{kW})\,. \tag{2}$$

While the proposed scaling of these motor is very favorable, a Hopper 1000 kW class motor would be expected to have a power density of 10.0 kW/kg, the relatively low technology readiness (TRL) of high temperature superconducting materials makes achieving this high risk in the 2030 timeframe. As such this level of technology was not considered in the conceptual design activities.

III. Propulsion Alternatives

In exploring low-emission alternatives to conventional Jet A powered turboshaft rotorcraft, a number of potential energy storage and power transfer alternatives exist. A subset of the possible combinations was considered qualitatively using the Pugh matrix shown in Figure 5. These included two all-electric concepts, an alternative fuel, and hybrid concept.

These concepts were evaluated relative to the baseline in terms of performance, environmental factors, technology readiness (TRL), cost and operational considerations. All four alternatives are less attractive than the

++: significant improvement, +: improvement, 0: neutral, -: degraded, --: seriously degraded

Energy Storage / Propulsion Alternatives

Criteria		Jet A Turboshaft	Fuel Cell AC Motor	NH_3 Turboshaft	Adv. Li-po Battery AC Motor	Jet A / Li-ion Generator AC Motor
Energy Density	kJ/kg	BASELINE	--	-	-	-
Power Density	kW/kg		--	-	-	--
Emissions	kg/kW		++	+	++	+
TRL	-		--	0	--	0
Procurement Cost	$/shp		--	0	-	-
Energy Cost	$/kW		--	-	+	0
Complexity	-		-	0	+	-
Reliability	MTBF		+	0	+	0
Re-energize Rate	kW/min		-	0	--	0
Total		**0**	**-9**	**-2**	**-2**	**-4**

Figure 5 Pugh trade matrix of propulsion concepts considered for an electric Hopper design.

baseline Jet A/Turboshaft propulsion concept when considering the trade criteria on an unweighted basis. However, when one considers the potential importance of reducing greenhouse emissions and an associated rise in hydrocarbon based energy prices, the advanced Li-polymer battery with AC motor configuration appears to be a potentially attractive alternative configuration that deserves further study.

The alternative fuel concept is based on using ammonia (NH_3) as a fuel source. This has the advantages of an existing infrastructure for production, the ability to be combusted in existing turboshaft engines with minor modifications, and no CO_2 combustion by-products. It's primary disadvantages are the energy intensive process presently used to create ammonia from natural gas, lower energy density than Jet A and overall toxicity.

A hybrid drive system using a combination Li-ion battery storage system and Jet A fueled generator to drive an AC motor was also considered. Such a system would be able to take advantage of recharging opportunities at each station to store electric energy from clean generation sources in the Li-ion battery, reducing the use of Jet A. Battery capacity and weight would be less than for a full electric system, but at the added cost of needing a generator and fuel system in parallel to the motor and battery electric system. This complexity would likely negatively affect the system performance. It was also assumed that a hybrid system would tend to utilize lower tech (lower energy density) Li-ion batteries to reduce technical risk and cost.

Fuel cell technology continues to mature, but generally lags battery technology in achieving higher specific energy densities.[14] The reduction in moving parts and elimination of the high temperature environment associated with gas turbines should result in favorable system reliability as the fuel cells mature. The future cost of hydrogen fuel remains an important unknown. Lower relative performance of the complete hydrogen storage and power system, coupled with increased complexity, development risk and cost negatively impact this alternative.

An advanced Li-polymer battery coupled with high performance AC motors offers potential for improved reliability and reduced greenhouse gas emissions, assuming clean sources of electric power. The relative simplicity of the battery, power control electronics and electric motor should result in good reliability. One major challenge of battery powered approaches is the relatively slow recharge rate, which will negatively affect turn-around time at each station. This can be overcome potentially by a battery quick swap system with sufficient batteries appropriately pre-positioned at each aerial station.

Current Li-ion technology does not have a high enough energy density to enable the desired electric Hoppers. Demand for high specific energy batteries in a variety of industries, however, has helped to ensure continued advancement in the technology, and significant improvements can be expected to continue in the next few decades. These advances make Li-polymer batteries a potentially acceptable alternative to Jet A. The battery system also becomes particularly attractive if economic incentives are introduced which help favor concepts that result in reduced emissions.

IV. NDARC Modification

Using the NASA Design and Analysis of Rotorcraft (NDARC) tool[15], Hopper sizing was performed. A key advantage of NDARC is the ability to easily synthesize topologically-diverse rotorcraft configurations using a library of pre-existing components. As is typical of most conceptual design rotorcraft codes, NDARC combines parametric estimation of component weights, lower order aerodynamic models, referred parameter engine modeling and flight performance calculation routines to size a configuration. Sizing is the process whereby configuration design variables are adjusted until a specified set of mission and performance criteria are satisfied. Design optimization can be performed either by wrapping an optimizer algorithm around this sizing procedure or in an ad-hoc manner where design parameters are systematically swept to establish sensitivities to guide designer selection of the final design. This approach to sweeping parameters was utilized in this study.

For the electric Hopper configurations it was necessary to extend the NDARC v1.6 components to include a model of a battery and motor. For this early conceptual design study a simple model of each was used which only considers the peak power requirements, energy conversion efficiencies, and total energy required to complete the mission profile. NDARC's basic approach of apportioning rotor and mechanical accessory power required to one or more turboshaft engines is followed for the apportionment of power to the electric motors.

Details of the mechanical transfer of power from the motors to the rotor system and mechanically driven accessories were simplified to consider just user input power transfer efficiencies. Hopper is designed using the existing model in NDARC for transmission efficiency as a function of RPM and power. Efficiency for the motor in converting electric power to mechanic power is a user input, set to a constant 95% for this study. The motor is idealized to have a constant efficiency regardless of power output; for a real motor, a significant reduction in efficiency can be expected when operating well off the design-point torque and shaft speed. The losses associated with the necessary power conversion and conditioning hardware is assumed to be 3%. This hardware is needed to convert the DC power supplied by the batteries to the appropriate AC signal for driving the motor at the desired speed. Finally, the batteries themselves have losses associated with the conversion from chemical to electric potential energy. This loss is taken as a constant 2% regardless of power draw. The ratio of the power required at the rotor to the power required from the batteries (or other electric storage source) is then the equal to the cumulative effect of the various component efficiencies:

$$\frac{0.746 \times \left(P_{\text{rotor}} + P_{\text{acc}}\right)}{P_{\text{batt}}} = \eta_{\text{batt}} \eta_{\text{motor}} \eta_{\text{pe}} . \tag{3}$$

From this equation the necessary battery power can be determined at each flight condition or mission segment. Integration of the power required with time yields the necessary energy required for the design mission.

A simple power law scaling model for motor mass, based on the rated power of the motor is used based on the trend developed in Eqn. 1. For this study, details of the scaling of motor physical dimensions, as well as other intrinsic properties were not considered (e.g. no slip speed, maximum torque and no load current values). A higher-fidelity propulsion analysis would require scaling laws for these properties as well. Battery weight is determined based on the installed battery capacity and an input battery energy density:

$$W_{\text{batt}} = E_{\text{batt}} / \chi_{\text{batt}} \tag{4}$$

Overall battery volume is also estimated based on an input volumetric density. The necessary inputs and relations were added to NDARC by modification of the existing engine component and addition of a battery component, making it possible to model the motor-battery propulsion arrangement considered for this study.

Beyond adding the inputs and performance models for the additional sub-system components described above, it was necessary to modify the mission performance and sizing solution procedures in NDARC for the electric Hopper. The typical NDARC mission performance solution procedure iterates until the fuel burned on the mission is equal to the fuel available at take-off. Fuel burned is calculated by initially guessing a take-off gross weight and then sequentially evaluating each mission segment and decrementing the gross weight from the previous segment by the fuel burned on that segment. Mission total fuel burn is then used to update fuel available at take-off and the corresponding take-off gross weight. This forms a method of successive solutions which can be iterated on to convergence in most cases.

For the case of the electric Hopper aircraft, where no fuel is burned, a different iteration scheme is required to calculate mission performance. Recognizing that in the case of a turboshaft powered rotorcraft fuel weight is actually a convenient surrogate for the energy required to complete the mission, an alternate formulation based on comparing energy required to complete the mission to the energy available at take-off can be used. This formulation has the advantage of being generalizable to many propulsion arrangements including hybrid approaches where energy may come in multiple sources, to include both battery and liquid fuel. NDARC was therefore modified to calculate the energy required for each mission segment and to iterate until the energy available at take-off equaled the energy required.

The sizing process in NDARC acts as an outer loop on the mission and flight performance routines. Similar to the mission performance solution procedure, a method of successive substitutions with relaxation is employed to converge critical design variables such as take-off gross weight, rotor diameter, installed power and fuel tank size. For the electric Hopper it was necessary add battery capacity to this procedure. Convergence of the design is achieved when changes to gross weight, empty weight and battery capacity are all within the specified tolerance for successive iterations.

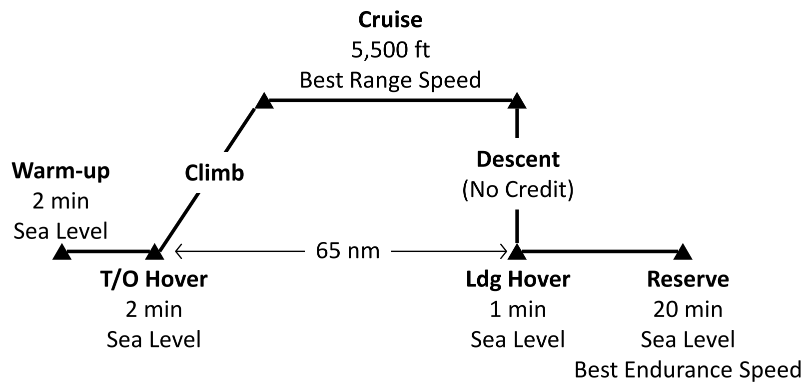


Figure 6 Hopper sizing mission profile.

V. Aircraft Sizing Results

Selection of three air vehicle sizes was completed based on initial passenger movement data from the 5k, 15k and 45k daily ridership simulations. The 6 and 15 passenger Hoppers were designed as single main rotor helicopters, while the 30 passenger Hopper is a tandem configuration. All three aircraft were designed with relatively low disk loading. This low disk loading helps to reduce hover power loading. This was seen as beneficial to the electric powered Hopper, where specific power density is significantly lower than for turboshaft aircraft, and hence will tend to favor lower power-to-weight ratios.

A simple mission profile (Figure 6) was developed for use in the sizing process. A design mission range of 65 nm was initially selected so that all stations on the network could be served point-to-point. It includes hover out-of-ground effect (HOGE) at the take-off and landing, a small amount of start-up/warm-up time and cruise at 5,500 ft. This baseline cruise altitude was selected in recognition of a desire to reduce community noise impacts.[5] Initial results from the air traffic conflict simulation indicate that 5,500 ft cruise altitude may not be the best system solution because of the increase in loss of separation events relative a 3,000 ft cruise altitude.

Additionally, rotor tip speed was kept low to reduce noise. Noise is one of several important considerations that are part of community acceptance of an aerial mass transit system. No further examination of noise was conducted in the present activity, but is an important consideration for future work. An additional 20 minutes of flight time at best endurance speed is assumed at the end of the mission profile. This reserve flight time is consistent with typical FAA minimums for day VFR flight. On these types of short-haul missions, the reserve fuel/energy requirement can be a significant portion of the take-off fuel/energy. Twenty minutes was felt to be sufficient to allow for the Hopper air vehicle to either hold for landing or divert to an alternate landing site and is consistent with previous studies[2]. Real-time situational awareness and automation are intended to provide continuous adjustment to the Hopper flight speed and path, so as to minimize, or eliminate conflicts, between Hopper aircraft operating to-from the dedicated landing pads at each of the stations.

For a high-tech aerial mass transit system, of which there are presently no operating examples, it was prudent to make a number of basic assumptions regarding acceptable design requirements that will ultimately be impacted by FAA regulation. Continued advances in cockpit automation should enable at least safe single-pilot operation. For a future mass transit system, consideration should also be made for a fully automated system. Current commercial rotorcraft operations require Category A hover performance at take-off. This ensures that the aircraft can either safely return to the landing pad or has sufficient altitude to accelerate to a safe one engine inoperative forward flight speed. This requirement typically results in an increase in installed power beyond that required to HOGE. For this study, installed power sizing was done at a 3,000 ft / ISA+20°HOGE, under the assumption that a combination of descent energy management via advanced flight control, smart actuating landing gear, electric motor emergency torque capability and overall reliability of the electric motor systems would bring the design to the same level of catastrophic hover risk level as is achieved by simply installing additional power to meet current Category A requirements.

Table 1 Summary of sizing results for turboshaft powered Hopper designs.

No. Pax		6	15	30
Design Gross Wt.	lb	5,421	9,770	20,313
Weight Empty	lb	3,547	5,763	12,364
Wt. Empty Fraction		65%	59%	61%
Prop. Grp.+Fuel Wt.	lb	988	1,674	3,723
XMSN Power	kW	486	843	1,896
Prop Spec. Pwr	W/kg	1,083	1,108	1,120
Rotor Diameter	ft	39.2	52.6	53.6
Disk Loading	psf	4.5	4.5	4.5
Solidity (Geo.)	-	0.0524	0.0524	0.0524
No. Blades	-	4	4	3
Blade AR	-	24.3	24.3	18.2
Tip Speed	fps	650	650	650

All three aircraft classes were initially sized to the nominal 65 nm mission using a traditional turboshaft engine propulsion architecture. These aircraft provide a baseline for comparison when considering electric propulsion. Table 1 provides a summary of the three turboshaft powered aircraft designs. The power density of the propulsion system including storage and power generation is 5x that power density of current Li-ion batteries, and highlights the challenge of designing an all-electric Hopper.

Figure 7 shows an estimate of the necessary take-off weight fraction that must be available for energy storage as a function of mission range. Estimates were generated using the Bregeut range equation and assumptions of an air vehicle L/De = 4.0. The strong increase with range of necessary energy storage take-off weight fraction drives the growth of the electric Hopper designs. Figure 7 also highlights need to be extremely aggressive in reducing the empty weight fraction in all other areas of the vehicle design to provide margin for growth in the battery weight

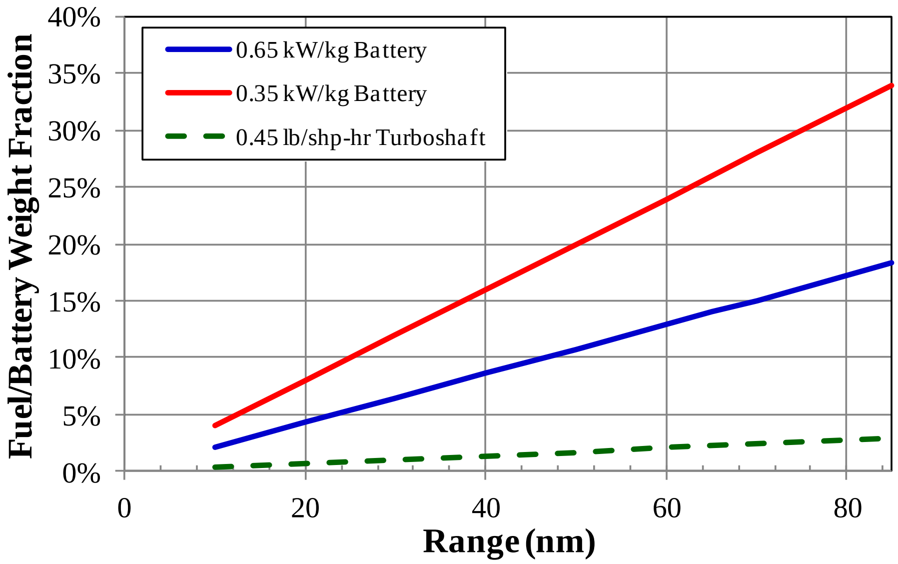


Figure 7 Impact of range on necessary stored energy required at take-off for Jet A and Li-polymer.

fraction. Given that the smaller 6 passenger Hopper design will tend to have a higher empty weight fraction because of non-favorable down-scaling of items such as furnishings, cockpit and vehicle management system, it will be harder to close on a feasible design for the same level of battery technology and design mission range as compared to the larger 30 passenger Hopper.

Initial focus was on the 30 passenger tandem electric Hopper since this size was found to be most relevant to the 45k daily ridership system, and is consistent with the vision of a high-capacity aerial mass transit system. Figure 8 shows that even with the advanced Li-S battery technology (0.65 kW/kg) and relatively light weight electric motors, the electric Hopper aircraft is significantly heavier than the conventional design. A reduction in design range to an unusually short distance is required to achieve parity. The initial range of 65 nm was selected to ensure point-to-point service between any of the stations in the network. This initial sizing study indicates that moving to a centralized network, which would reduce the required aircraft range to 32 nm, would lead to an appreciable reduction in air vehicle size. An additional consideration in the design range not yet fully explored is the potential need for non-direct routing between stations to integrate with the existing air traffic flows in the Bay Area. This is an excellent example of how a multidisciplinary approach to the overall mass transit system optimization can open up needed design space to achieve a better result.

The strong impact that improving battery specific density has on electric Hopper size and viable mission range is seen in Figure 9. At the current state-of-the-art 0.180 kW/kg level the aircraft is intolerably large at even extremely short mission ranges. A sweep of diskloading (Figure 10) for two levels of battery specific energy and three motor weight trend levels shows that the optimum diskload remains relatively constant at 4 lb/sq-ft regardless of the technology level of the electric components. Also apparent is the stronger effect of battery technology improvements as compared with motor weight reductions.

Table 2 summarizes several 30 passenger electric Hopper designs as compared the baseline turboshaft design. The initial results indicate a desirability to reduce the design range and the importance of higher specific energy battery technology. Because of the cascading effect that increased battery mass has on overall vehicles size, the results also indicate that paying more in $/kW-h terms for a higher specific energy battery system is likely preferred. It is also clear from the intial results that the long-term economics electricity and hydrocarbon based fuels play are important. Even with the highest specific energy battery considered and the shortened design range, the electric tandem would still be 20% heavier in terms of empty weight, a significant potential penalty in flyaway costs.

Table 2 Comparision of 30 passenger electric Hopper designs with baseline turboshaft concept.

		TS	Electric		
No. Pax	-	30	30	30	30
Design Range	nm	65	65	40	40
Design Gross Wt.	lb	20,313	24,148	30,096	21,768
Weight Empty	lb	12,364	12,382	14,986	14,918
Wt. Empty Fraction		61%	51%	50%	69%
Energy Storage Fraction		5%	20%	27%	14%
Prop. Grp.+Energy Storage Wt.	lb	3,723	6,906	10,660	5,386
Max Rotor Pwr	kW	1,896	1,834	2,227	1,677
Prop. Grp. Spec. Pwr	W/kg	231	121	95	142
Stored Spec. Energy	kW-h/kg	12.0	0.650	0.350	0.650
Conv. Efficiency	-	28.1%	90.3%	90.3%	90.3%
Storage Volume	gal	858	554	645	390
Rotor Diameter	ft	53.6	62.0	69.2	58.9
Blade AR	-	18.2	20.5	20.5	20.5
Tip Speed	fps	650	650	650	650

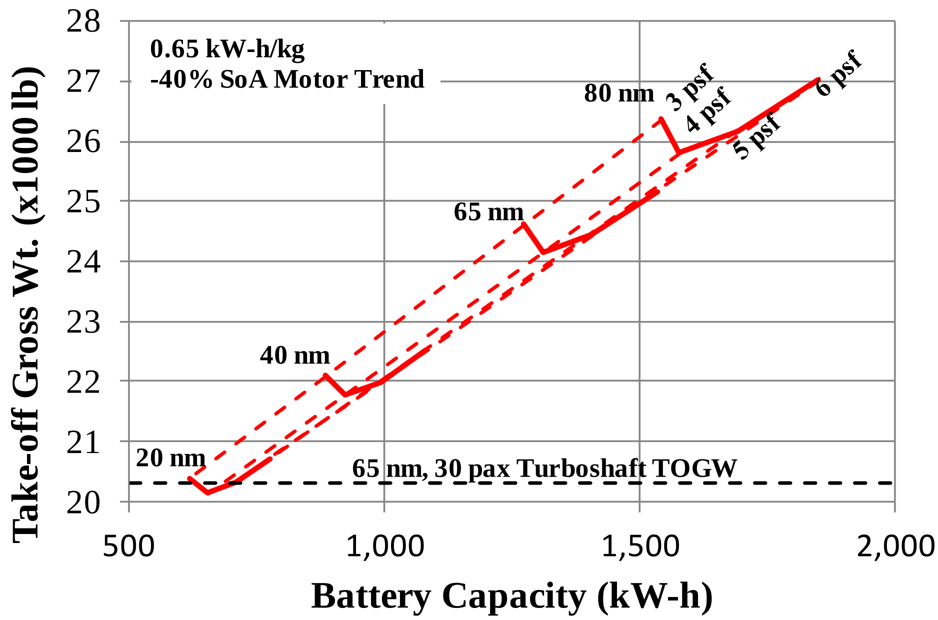


Figure 8 Variation in 30 passenger Hopper size with mission range and diskloading.

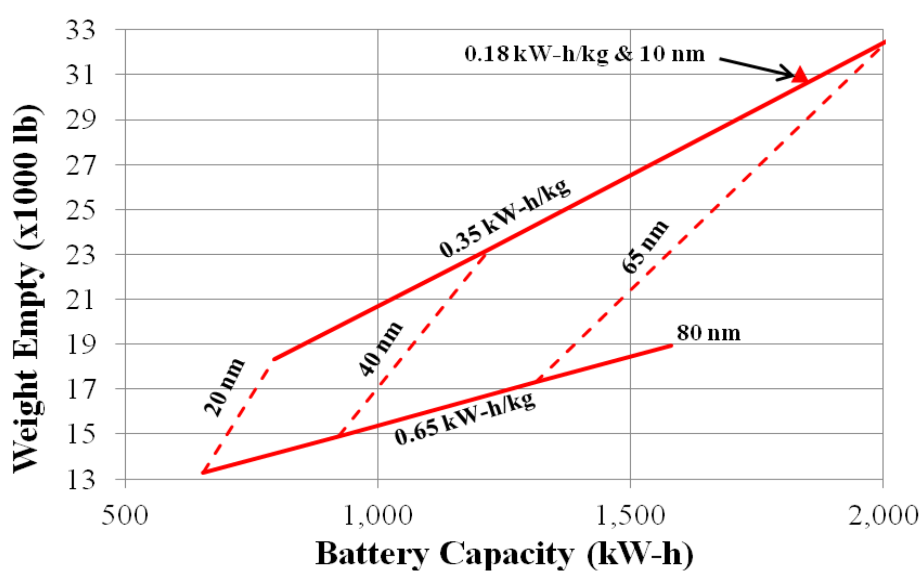


Figure 9 Impact of battery specific energy density and mission range on 30 passenger Hopper size.

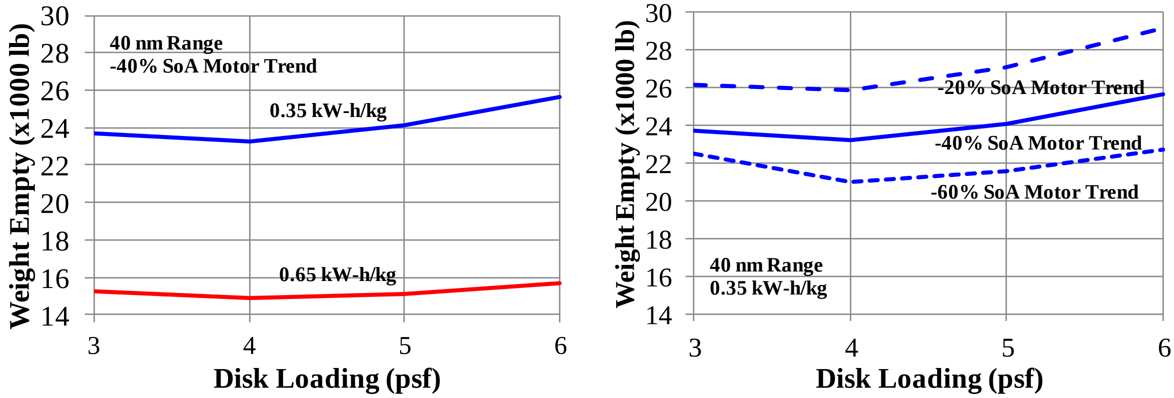


Figure 10 Impact of diskloading on 30 passenger electric Hopper size, for various battery and motor technology levels.

VI. Summary and Future Work

The conceptual design of an electric VTOL mass transit vehicle has been explored in this study and shown be be feasible when enabled by advanced battery technology. The value of a multidisciplinary system level approach to design is seen in the various potential trade-offs that are presented in the results. Network topology, scheduling and air traffic integration are not typically considered at the conceptual design level, but have been shown to provide constraints and important measures of performance that impact the design mission profile and aircraft sizing. Selection of design parameters such air vehicle range, cruise altitude and passenger capacity need to be considered in context of the classic vehicle performance and cost metrics as well as system-wide metrics such as number of loss of separation events and passenger demand behavior.

Having demonstrated the feasibility of the concept, NASA and Stanford intend to explore this system in greater depth. A follow-on study activity has been recently initiated as part of the NASA Aeronautics Research Institute. The activity to date has surfaced additional questions about the proposed concept and it's optimization that will be considered in the follow-on activity. Specifically, assumptions in the electric system design are to be explored with more in-depth preliminary design activities. The current study postulated that a solution enabling rapid exchange of battery packs existed. This is an interdisciplinary problem coupling design of the ground station with the air vehicle. A critical failing of previous attempts at VTOL regional transportation have been associated with the economics of the systems developed. The very high capital costs of expanding rail lines suggest that a total life-cycle view of the economics may find VTOL systems to be less disadvantaged than previously thought. It is hoped that this study will spur a broader invigoration of aerospace community to reexamine the potential for future air vehicle systems to have impacts on society beyond those roles and missions currently being performed today.

Acknowledgments

The authors are grateful to the NASA ARMD Seedling Fund and the NASA Aeronautics Research Institute (NARI) for their continued support of this study. Brendan Tracey's efforts in developing a flight schedule for the scenarios were invaluable. Appreciation is given to Larry Young for his thoughtful review of the paper and willingness to carry the project forward into the next phase. J. Sinsay acknowledges the DoD SMART Scholarship program in enabling his pursuit of doctoral studies and related participation in this study.

References

[1]"Systems Analysis of Short Haul Transportation," Massachusetts Institute for Technology Flight Transportation Laboratory, TR 65-1, 1965.

[2]Wood, C. C., "Vertical Take-off Aircraft for Metropolitan and Regional Service," *AIAA 4th Annual Meeting and Technical Display*, AIAA 67-940, Anaheim, CA, 1967.

[3]"Transportation by Helicopter: 1955-1975," Port Authority of New York, 1952.

[4]Moore, M. D., "Aviation Frontiers: On-Demand Aircraft," *10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, AIAA 2010-9343,Fort Worth, TX, 2010.

[5]Glaze, K., "Vertical Flight Passenger Services: Past, Present and Future," *Presented to the San Francisco Bay Area Chapter of the AHS*, Moffett Field, CA, March 7, 2012.

[6]Dickens, M., “APTA Public Transportation Ridership Report: First Quarter 2012,” URL: http://www.apta.com/resources/statistics/Documents/Ridership/2012-q1-ridership-APTA.pdf [cited 23 August 2012].

[7]Richard, G., “BART extension to San Jose getting $250 million in federal funds – more than expected”, *San Jose Mercury News*, San Jose, CA, February 13, 2012.

[8]Chretien, P., “The Quest for the World’s First Electric Manned Helicopter Flight: From Concept to Prototype in 180 Days,” *Vertiflite*, Vol. 58, No. 2, 2012, pp 38-42.

[9]Johnson, W., Yamauchi, G.K., Watts, M.E., “NASA Heavy Lift Rotorcraft Systems Investigation,” NASA/TP-2005-213467, Moffett Field, CA, 2005

[10]Jost, M., “UAV Flight Time Increased By 80% Using New High Energy Battery System,” *Press Release*, SION Power, Tuscon, AZ, June 21, 2011.

[11]Dudley, M., “Promising Electric Aircraft Drive Systems,” *EAA Electric Aircraft World Symposium*, ARC-E-DAA-TN2019, Oshkosh, WI, 2010.

[12]Gunston, B., “General Electric CT7,” *Jane’s Aero-Engines*, 19th ed., Jane’s Information Group Limited, UK, 2006, pp. 574-578.

[13]Synder, C., et al., “Propulsion Investigation for Zero and Near-Zero Emissions Aircraft,” NASA/TM-2009-215487, Cleveland, OH, 2009.

[14]Datta, A. and Johnson, W., “Requirements for a Hydrogen Powered All-Electric Manned Helicopter,” *12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, Indianapolis, September 17-19, 2012.

[15]Johnson, W., “NDARC: NASA Design and Analysis of Rotorcraft,” NASA/TP-2009-215402, Moffett Field, CA, 2009.