AIAA 2017-3442
AIAA AVIATION Forum
5-9 June 2017, Denver, Colorado
17th AIAA Aviation Technology, Integration, and Operations Conference

A Study in Reducing the Cost of Vertical Flight with Electric Propulsion

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This initial evaluation of the cost of electric vertical takeoff and landing (VTOL) aircraft and their operations supports the feasibility of an electric air taxi vehicle with 4 passengers at a 100 mile range. Stopped rotor and tilt rotor configurations combining airplane and multi-rotor helicopter features were studied for improved cruise efficiency. Electric and fuel powered single main rotor helicopters were also studied for comparison. Compared to the equivalent conventional piston engine helicopter, the electric VTOL configurations reduced total operating cost per seat mile by about 26%.

NOMENCLATURE

C_L = Lift coefficient
DC = Direct current
DEP = Distributed electric propulsion
eVTOL = Electric vertical takeoff and landing
L/D = Lift to drag ratio
MDAO = Multidisciplinary design analysis & optimization
VLDes = Vertical Lift Design (a conceptual design sizing tool)
VTOL = Vertical takeoff and landing
XML = Extensible Markup Language

INTRODUCTION

Electric propulsion introduces the potential to substantially alter the design of vertical lift vehicles for reduced cost. A substantive operating cost improvement is hypothesized as a result of decreases in the cost of energy for flight propulsion, reduced maintenance hours, and reduced unique part count for electric vertical takeoff and landing (VTOL) aircraft (Figure 1). Energy sourced from the electrical grid costs as little as 30% of equivalent energy delivered from aviation fuel [1]. Considering that fuel typically comprises 20% of rotorcraft operating costs, this 3 times reduction in energy costs offers the potential for a direct 6% reduction in operating costs for energy alone using pure battery electric configurations [2].

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Maintenance and labor hours account for another 20-30% of today's rotorcraft operating cost [3, 4]. Electric propulsion simplifies power transmission relative to mechanical drive trains and encourages transition from traditional rotor systems with collective and cyclic controls to multi-rotor systems with differential thrust control via variable speed rotors. Maintenance cost reductions are hypothesized to follow in parallel with simplification of the rotor system mechanical components; however, this hypothesis must be examined from the standpoint of reliability of components of the distributed electric propulsion (DEP) system and the appropriate aggregation to system-level reliability.

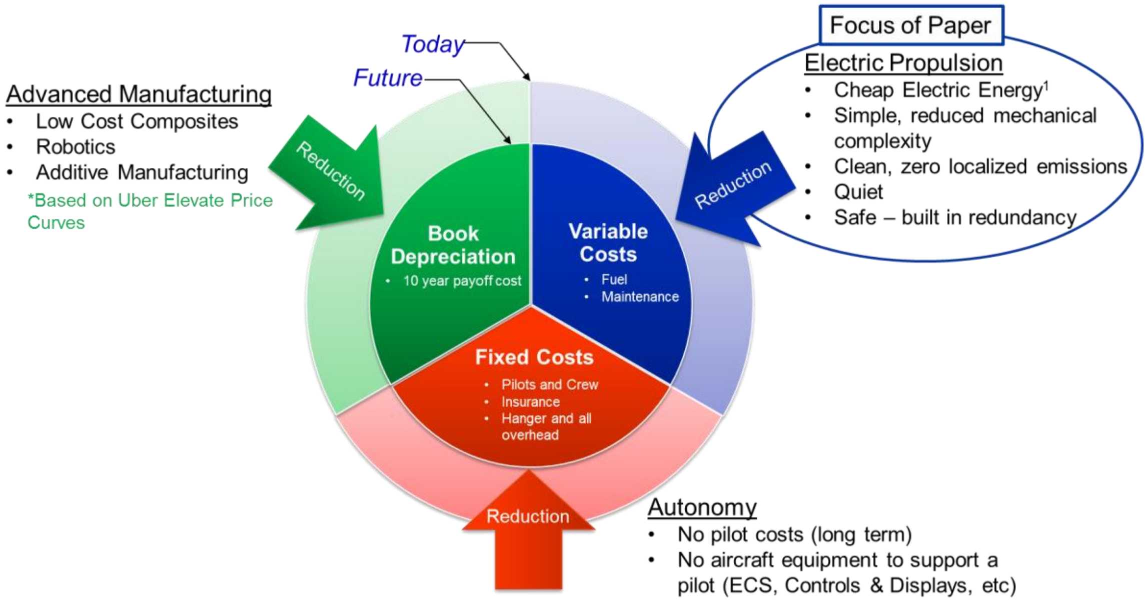

Figure 1: Operating cost components for current vertical lift aircraft and technologies that enable total operating cost reduction

To explore the benefits of electric VTOL, different configurations were sized with a multidisciplinary design analysis & optimization (MDAO) sizing tool that was developed to explore vertical lift vehicle configurations enabled by electric propulsion. Estimates for the operating cost of the sized configurations were made to assess the potential cost reduction from electric propulsion.

CONFIGURATION REQUIREMENTS

With the recent release of the Uber Elevate white paper [5] defining clearer requirements to build a business case for an urban air taxi, some key configuration requirements were adopted for an initial study of the operating cost of such a vehicle.

- Small footprint for landing <50 ft
- >6 effectors for hover to accommodate a loss of one motor or propeller
- Predictable and safe transition from hover to cruise
- Control authority at low speed for safe weather operations
- Winged flight for >25 miles range to reduce energy consumption
- Rotors away from passengers
- Reduce the number of unique parts

CONFIGURATION SELECTION

Electric propulsion allows new design freedom for locating lift and thrust around the vehicle with little constraint from the mechanical complexity of drive systems and shafting (Figure 2). Table 1 shows a list of options considered for fulfilling key functional lift and control functions, highlighting typical selections for a single main rotor helicopter configuration compared to the potential design selections for an eVTOL (electric VTOL) aircraft. Transition from hover to forward flight is a critical design decision, since this drives many of the aircraft major subsystems. This initial candidate configuration was chosen in order to meet the high level requirements defined in the Uber paper. In order to provide a predictable transition from hover to cruise, two configurations were chosen for this initial costing exercise: a high wing multi-rotor with stopped hover rotors and a pusher propeller, and a high tandem wing multi-rotor with tilting rotors/propellers. Future studies will include a detailed sizing and costing effort to determine the best configuration for this mission. The purpose of this study was to get an initial understanding of the sensitivity of operating cost for various electric components.

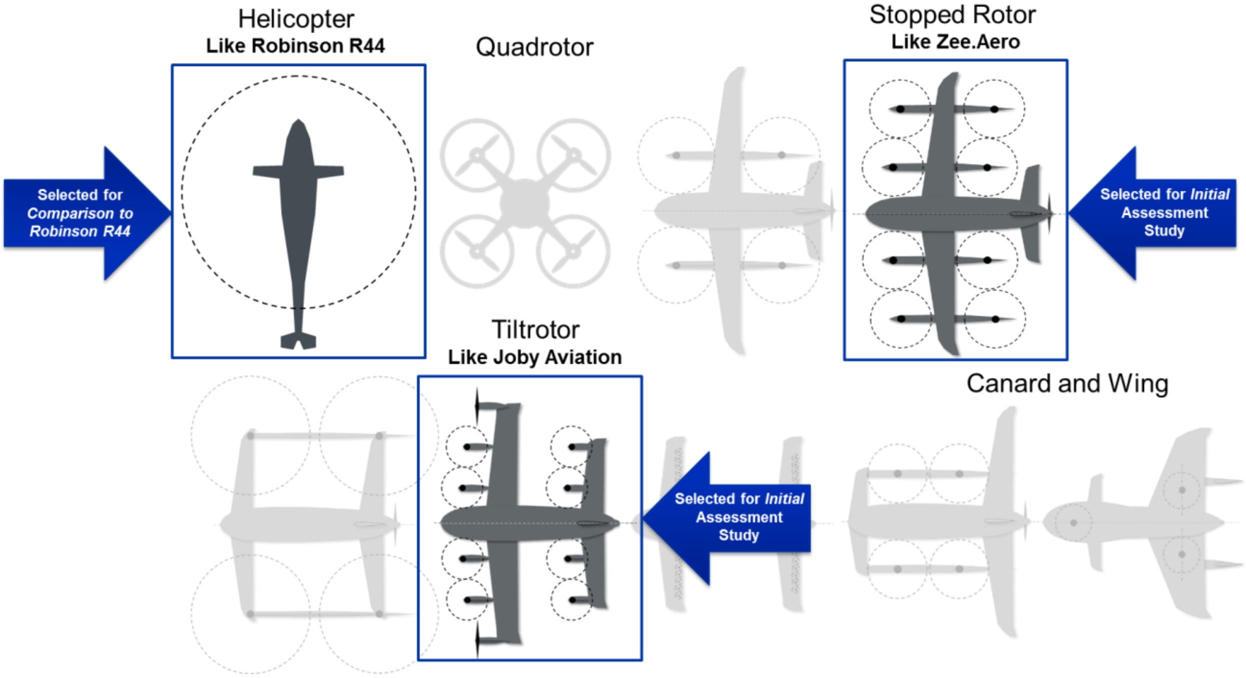

Figure 2: Candidate configuration species

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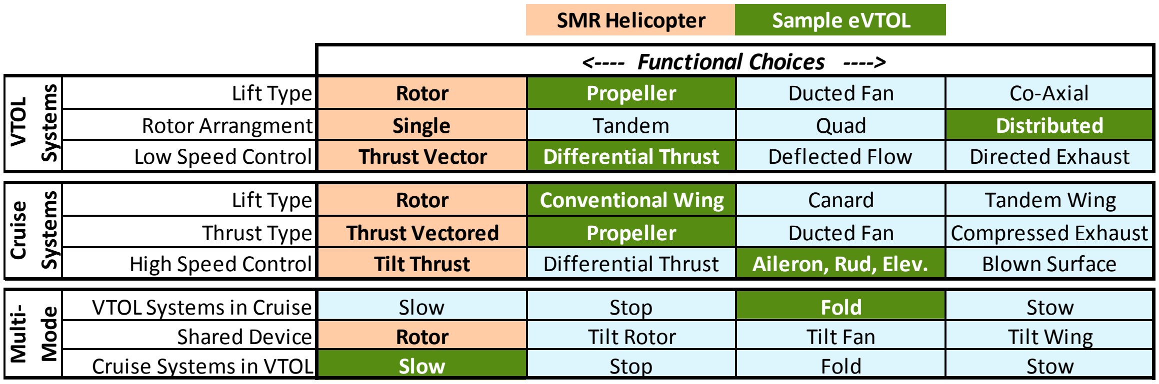
Table 1: Configuration options for eVTOL aircraft



🟧 **SMR Helicopter** 🟩 **Sample eVTOL**

		<---- Functional Choices ---->			
VTOL Systems	Lift Type	🟧 **Rotor**	🟩 **Propeller**	Ducted Fan	Co-Axial
	Rotor Arrangment	🟧 **Single**	Tandem	Quad	🟩 **Distributed**
	Low Speed Control	🟧 **Thrust Vector**	🟩 **Differential Thrust**	Deflected Flow	Directed Exhaust
Cruise Systems	Lift Type	🟧 **Rotor**	🟩 **Conventional Wing**	Canard	Tandem Wing
	Thrust Type	🟧 **Thrust Vectored**	🟩 **Propeller**	Ducted Fan	Compressed Exhaust
	High Speed Control	🟧 **Tilt Thrust**	Differential Thrust	🟩 **Aileron, Rud, Elev.**	Blown Surface
Multi-Mode	VTOL Systems in Cruise	Slow	Stop	🟩 **Fold**	Stow
	Shared Device	🟧 **Rotor**	Tilt Rotor	Tilt Fan	Tilt Wing
	Cruise Systems in VTOL	🟩 **Slow**	Stop	Fold	Stow

MISSION ASSUMPTIONS FOR ELECTRIC VTOL

The mission assumptions for the vehicle studied in this paper are indicated and compared against mission assumptions for Uber Elevate [5] in Table 2. The mission profile used to size the vehicles is sketched in Figure 3. Hover is modeled for two minutes at the beginning and ending of the mission to account for takeoff and landing. Acceleration from hover to climb speed is modeled to provide checks on transition between rotary wing and fixed wing flight. Propeller systems become active at the end of the acceleration. Climb, cruise, and descent are flown in fixed wing mode with rotors stopped or stowed. Distance traveled in climb and descent is counted toward the 100 mile range. Deceleration from descent speed to hover is modeled to provide checks on transition. A 20 minute loiter at 500 ft is modeled to account for reserves.

Table 2: Mission assumption comparison

	Uber Elevate	**Commercial Urban Air Taxi (Vision)**
Range	100 mi	100 mi
Cruise Speed	170 mph	150 mph
Payload	4 passengers (800 lb)	4 passengers (800 lb)
Cruise Altitude	1000 ft	1000 ft
Footprint	< 50 ft	< 50 ft
Battery Specific Energy	400 Wh/kg	400 Wh/kg
Reserve Cruise	20 min	20 min
Battery Discharge Reserve Limit	20%	20%
Blade Tip Speed	445 ft/s	<500 ft/s
Take-Off Conditions	Sea Level Standard	Sea Level Standard

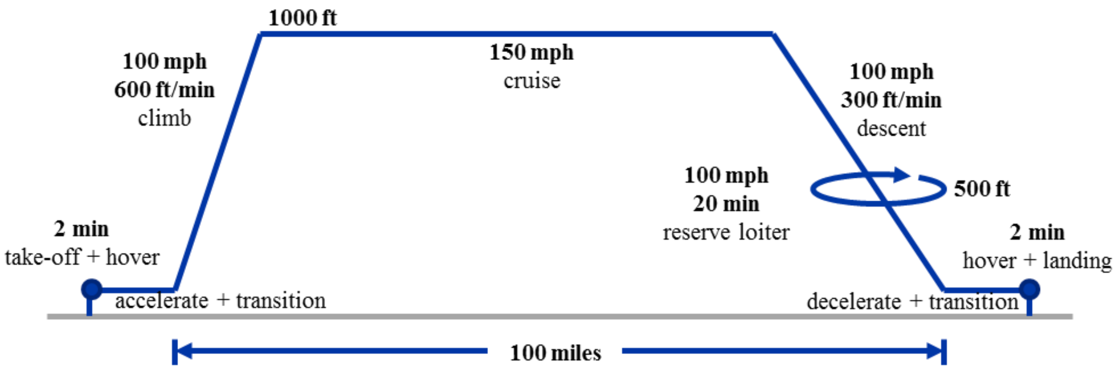


Figure 3: Mission diagram

VERTICAL LIFT DESIGN TOOL

The Vertical Lift Design (VLDes) MDAO sizing tool provides for modeling and optimizing the design of vertical lift vehicles. It provides analysis components for rotors, engines, motors, generators, and batteries. Connections between these power train components can be specified to model arbitrary configurations. A vehicle built from the connected components can be evaluated at many conditions, and the resulting performance can be summed for mission level values. These core vehicle and mission analyses are integrated with configuration specific analyses for structures and aerodynamics. The sizing tool is integrated with a nonlinear optimization package that allows vehicle and mission parameters to be designed with constraints on condition or mission performance to ensure proper sizing of the power components. This sizing tool has supported various concept studies looking at feasibility and benefits of electric propulsion on vertical lift vehicles.

The analysis classes for the sizing tool are indicated in Figure 4. The analysis classes for component definition are scripted in Jython, while the other classes are coded in Java. The augmented analysis class contains methods for estimating weight, lift, and drag characteristics of various components, including fuselage, wing, tail, propulsion pods, and landing gear skids. These component analyses tend to be configuration specific and are scripted in Jython to simplify modification for different configurations. Structural weight is based on composite stiffened skins sized to minimum gauge or bending loads. Factors are applied for internal structure and non-optimal material. Fixed weight components track allowances for furnishings and systems weights that are not otherwise estimated by analysis. Aerodynamic drag is estimated based on skin friction with form factors for streamlined shapes or frontal area times typical drag coefficient for bluff bodies. Component weights and aerodynamic characteristics are transferred to vehicle and aerodynamic component classes for use in the core Java based analysis.

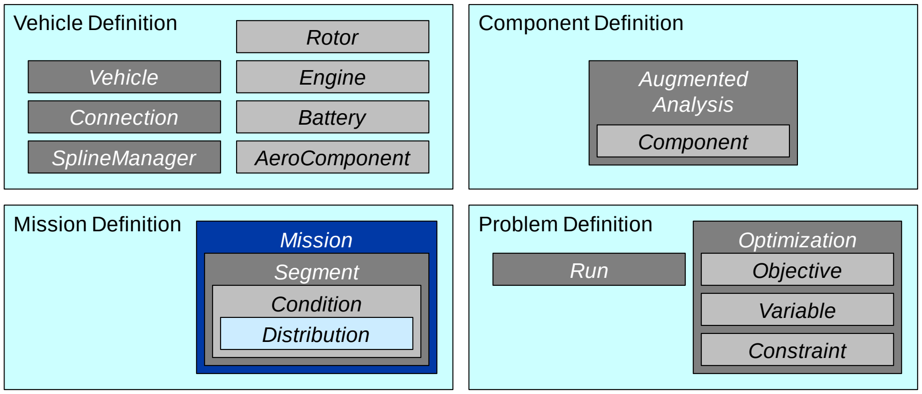


Figure 4: Modular analysis toolset for electrified vertical lift design

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A set of classes handles the definition of the vehicle. The vehicle class captures miscellaneous vehicle information and sums up component weights. The aerodynamic component class captures component drag and lift characteristics. The rotor class contains characteristics used to evaluate rotor power and performs the evaluation of rotor weight. Rotor and propeller weight is based on helicopter rotor sizing trends. Typical helicopter trends are used for single main rotor configurations. Rotor weights for multi-rotor configurations with fixed pitch blades are calibrated to data on propellers used on the Boeing LIFT! project [6, 7]. The resulting fixed pitch rotor weights are lighter than for rotors with collective and cyclic controls. The engine class is used for engines, motors, and generators. Motor or engine weights are derived from specific power applied to a reference power that is set during vehicle sizing. Motor weights cover related motor controllers. Power consumption for motors and generators is handled with a simple efficiency. Engine fuel flow is varied with power based on a trend from the NDARC (NASA Design and Analysis of Rotorcraft) referred parameter turboshaft engine model [8]. The battery class evaluates battery weight via specific energy or specific power. The connection class is used to describe connections between rotor, engine, and battery components. The ability to define connections provides flexibility to model different architectures, including parallel hybrid, series hybrid, single main rotor, and multi rotor configurations. A class for working with spline data allows data from higher fidelity or computationally costly sources to be incorporated. Evaluation of rotor induced power involves solution of induced velocity via an iterative process. To save the computational cost associated with the iteration, rotor induced power is captured with a spline based on pre-computed tabular data.

A set of classes evaluates performance over a mission. The classes are arranged in a nested structure. A mission can be divided into a number of segments. The segment class models a period of time typically dedicated to a task such as hover, acceleration, climb, or cruise. Inputs for a segment include parameters such as altitude, speed, acceleration, climb rate, and duration. A segment also includes inputs to control pitch attitude, rotor thrust, and rotor speed. A segment sets up evaluation of typically two conditions, one at the start and one at the end of the segment. The condition class evaluates power and fuel flow for a single condition in a segment. Rotor induced power is evaluated via momentum theory, using the spline described earlier. Rotor profile power is based on blade element drag given the rotor speed. The rotor speed needed to get the required thrust is solved during optimization. Lift and lift dependent drag are calculated from flight condition and aerodynamic component characteristics (including angle of attack, dynamic pressure, lift curve slope, and span efficiency). Longitudinal and vertical direction forces are balanced during optimization through variation of pitch attitude and rotor thrust. Starting from the rotors, power is tracked through the connections, with component efficiencies increasing the required power until it can be converted into electric power drawn from a battery or fuel supplied to an engine. The condition evaluation results in estimates for battery power and fuel flow. The segment evaluation integrates these estimates into energy and fuel consumed over the duration of the segment. The mission evaluation sums over segments to get energy and fuel consumed during the mission.

An optimization problem is described with classes containing information on the optimization objective, design variables, and constraints. These classes identify the analysis variables to use in optimization, and they specify bounds and scales applied to those values in the optimization. The optimization class collects the objects describing an optimization. More than one optimization may be defined. The run class is used to define the series of optimizations to run.

The sizing analysis is integrated with a numerical optimization package in Jython. A Java based data management library handles communication of data between analyses and optimization. The data management library also provides for loading and storing data in XML (Extensible Markup Language) files. A user typically works with the XML file to define the vehicle and optimization.

The optimization setups used to size the vehicles in this study are indicated in Table 3. The vehicles were usually sized with a series of optimizations, with groups of design variables and constraints introduced in successive optimizations to make it easier to troubleshoot problems when the optimizer declared solutions infeasible with no path to satisfying violated constraints. The table indicates the large problem solved at the end of each series as well as typical groupings of design variables and constraints.

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Table 3: Optimization setups used for study aircraft

Setup	Variables	Constraints	Single Main Rotor Fuel	Single Main Rotor Electric	Stopped Rotor	Tilt Rotor
Mass	design weight	design weight difference	✓	✓	✓	✓
	segment fuel weight	segment weight difference	✓			
Range	cruise duration		✓	✓	✓	✓
		mission range	✓			
		reserve energy		✓	✓	✓
		final energy		✓	✓	✓
Battery	energy	mission range		✓	✓	✓
		battery power fraction		✓	✓	✓
Engine	engine max power	engine power fraction	✓			
Motor	rotor motor max power	rotor motor power fraction		✓	✓	✓
	tail rotor motor max power	tail rotor motor power fraction		✓		
	propeller motor max power				✓	
		propeller motor power fraction			✓	✓
Rotor	rotor blade aspect ratio	blade lift coefficient	✓	✓	✓	✓
	rotor diameter		✓	✓		
	rotor blade incidence				✓	✓
Propeller	propeller blade aspect ratio	blade lift coefficient			✓	✓
	propeller design thrust	thrust fraction			✓	
	propeller blade incidence				✓	✓
Trim	tail rotor thrust	yaw moment	✓	✓		
	rotor thrust	vertical acceleration difference			✓	✓
	propeller thrust	longitudinal acceleration difference			✓	✓
	pitch attitude	wing lift coefficient			✓	✓
Rotor Speed	rotor speed	rotor thrust match			✓	✓
Propeller Speed	propeller speed	propeller thrust match			✓	✓

The mass setup matches the design weight used to size the structure to the built up vehicle weight. This match is often handled via iteration in traditional sizing tools, but it is more efficiently solved in optimization with a design weight variable and a constraint that drives the difference between design and actual weight to zero.

For a fuel powered vehicle, the mass setup also matches the assumed fuel consumed in each segment with the actual fuel burned. The assumed fuel weight is used to determine power, which affects actual fuel consumption. As with design weight, the optimization directs the iterative solution.

For an electric vehicle, the range setup allows optimizing the duration of the cruise segment while ensuring there is enough battery energy for reserves. The reserve energy constraint checks that the battery has at least 20% capacity remaining after the regular mission. Leaving 20% capacity under ordinary operations is intended to preserve battery life. The final energy constraint checks that the battery is not drained at the end of reserves. For a fuel powered vehicle, the range setup determines the cruise duration to get the required mission range.

On electric vehicles, the mission range constraint is used to set battery sizing. The battery is also sized to provide enough power throughout the evaluated conditions.

For engines and motors, maximum power is sized to provide adequate power through the flight conditions. Actual power in a condition is divided by the maximum available power to get a power fraction, which is typically constrained to be less than one. The exception is for hover, where single main rotor configurations are sized to accommodate 10% additional thrust for takeoff and multi-rotor configurations are sized to accommodate 5% additional thrust for maneuver with one motor failed and another powered down to balance moments. These considerations limit normal hover power fraction to 87% for single main rotor configurations and 60% for stopped and tilt rotor configurations. The tilt rotor configuration assumes a common motor for rotors and propellers, so it does not have a propeller motor design variable.

The rotor setup designs the rotor blade aspect ratio so that blades are at or below a specified lift coefficient in hover. For the single main rotor configuration, the specified lift coefficient leaves margin against stall to handle a 2-g maneuver. For the stopped and tilt rotor configurations, fixed pitch rotor blades cause the blade lift coefficient to remain essentially constant in hover, regardless of thrust level. The specified hover lift coefficient provides margin against stall, but is higher than that used for the single main rotor configuration. Blade incidence was optimized for the vehicles using fixed pitch rotors. Rotor diameter was optimized on the single main rotor configurations. Rotor diameter was set to the maximum allowed by span limits and omitted as a design variable on the winged vehicles. For rotor weight calculations, the design thrust of the rotors is set outside the optimization by dividing the design weight of the vehicle among the rotors.

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The propeller setup designs the propeller blade aspect ratio such that blade lift coefficients remain below specified limits throughout the conditions where the propeller is used. The setup also matches the propeller design thrust with the maximum thrust in the mission, which is experienced at the top of the climb segment.

For single main rotor configurations, the trim setup determines tail rotor thrust needed to balance yaw moments. For the other configurations, the trim setup determines rotor thrust, propeller thrust, and pitch attitude to balance vertical and longitudinal forces as measured by differences in actual and target accelerations. The target accelerations are typically zero, but acceleration segments between hover and forward flight are included to provide checks on the ability to transition from rotary wing to fixed wing flight. Most conditions are modeled with either the propellers or the rotors stopped. There is an extra degree of freedom for balancing forces when both the propeller and the rotors are used, which occurs in the conditions used to evaluate transition. The optimization is free to use the extra degree of freedom to improve the objective, typically by reducing power consumption for those conditions. Wing lift coefficient constraints are included in the trim setup, but the optimization has no way to satisfy the constraints if they are violated. Such violations signal the need for a manual intervention such as increasing wing area.

The rotor and propeller speed setups solve for the rotor and propeller speeds required to generate the required thrust through the flight conditions. The difference between the thrust estimated from blade element theory and the required thrust is constrained to be zero.

Different objectives are applied as appropriate in the series of optimizations used to size each vehicle. A design weight objective is typically used because it encourages reduced sizing of components. It also encourages lowering energy consumption to reduce fuel or battery weight. A minimum energy consumption objective is used in some early stage optimizations where the sizing of the vehicle fixed. For initial trim solutions, this objective favors solutions that use less power when there is a choice between using rotor and propeller thrust. For electric vehicles, a maximum range objective is used to improve the performance of the vehicle until it can meet the design range. The objective is switched to minimum design weight when the addition of the battery setup allows designing for a fixed range.

SIZING RESULTS

As a check on the sizing tool, a model resembling a Robinson R44 was sized and compared against available data for that vehicle. Since details of the R44 sizing mission were unavailable, the assumed mission for the urban air taxi was used except that range was increased to 345 miles with no reserves and cruise speed was set at 125 mph. The modeled vehicle geometry was matched to the R44 (Figure 5), otherwise this check used the same analysis assumptions as the trade study. Estimates from the sizing tool are compared to R44 data in Table 4. Composite structure assumptions contributed to the lower estimate for empty weight. The lower fuel weight follows the

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reduction in empty weight. The higher estimate for engine power suggests that assumptions in the analysis for hover efficiency may be slightly conservative. Short hover durations prevent this conservatism from significantly affecting energy use estimates. The comparison to the R44 suggests the sizing tool generates reasonable conceptual design level estimates for a vehicle that would be appropriate for the urban air taxi mission.

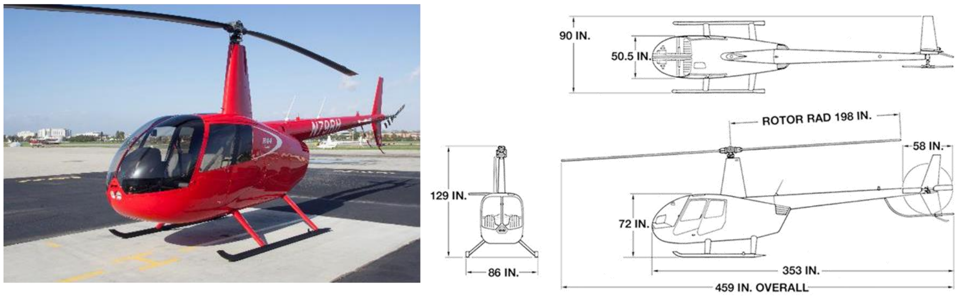

Figure 5: Robison R44 vehicle geometry used for sizing tool correlation

Table 4: Comparison of sizing tool estimate against Robinson R-44 data

	Robinson R44	Sizing Tool Estimate	Difference
Range (No Reserves) (mi)	345	345	-
Speed (mph)	125	125	-
Payload (lb)	716	716	-
Rotor Diameter (ft)	33	33	-
Gross Weight (lb)	2,500	2,458	-1.7%
Operating Empty Weight (lb)	1,505	1,470	-2.3%
Fuel Weight (lb)	279	273	-2.2%
Engine Power (hp)	245	270	+10.2%

Three different all electric configurations and a fuel powered single main rotor configuration were sized for the commercial urban air taxi mission (Figure 6). Characteristics of the sized vehicles are presented in Table 5. The fuel powered single main rotor vehicle is similar to the R44 used to check the sizing tool. It has a fuselage that is largely common with the other trade study configurations. This fuselage is larger than the R44, resulting in a higher empty weight. The payload weight requirement is also higher than on the R44 check case. Rotor diameter was optimized, and ended up smaller than the R44. Differences in the assumed tip speed and allowed blade aspect ratio likely resulted in hover power being reduced relative to the R44 model despite the smaller rotor diameter. Fuel weight is reduced relative to the R44 because of the shorter range. The reduction in fuel weight is less than proportional to the reduction in range because of increased drag from the larger fuselage and higher cruise speeds (150 mph instead of 125 mph) plus the addition of a 20 minute reserve.

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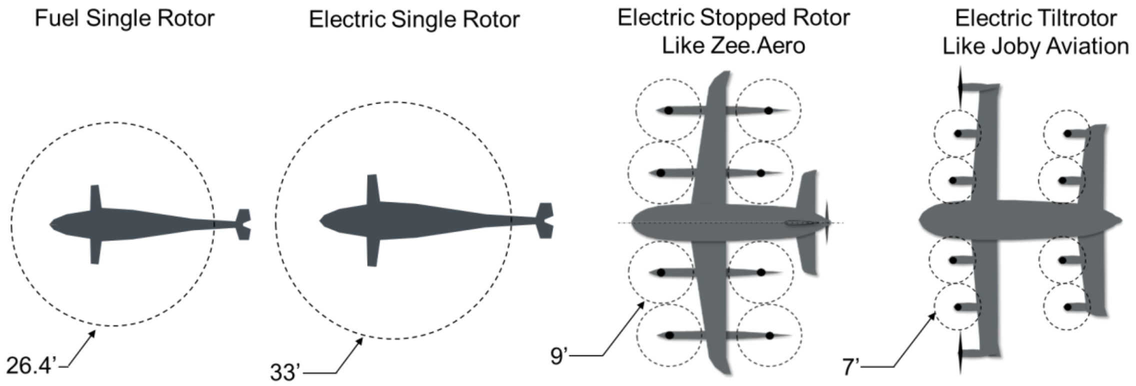

Figure 6: Four configurations sized for the Urban Air Taxi Mission (800 lb payload, 100 nm)

Table 5: Comparison of configurations for air taxi mission

	Single Main Rotor Fuel	**Single Main Rotor Electric**	**Stopped Rotor**	**Tilt Rotor**
Energy Type	Fuel	Electric	Electric	Electric
Number of Rotors	1 + tail	1 + tail	8 + prop	8 tilting + 2 props
Propulsor Out Hover	no	no	yes	yes
Rotor Diameter (ft)	26.4	33.0	9.0	7.0
Hover Disk Area (ft^2)	547	855	509	308
Hover Rotor Tip Speed (ft/s)	682	683	518	481
Disk Loading (lb/ft^2)	4.6	4.1	7.3	12.8
Power Loading (lb/hp)	10.1	10.0	9.5	7.3
Wing Span (ft)	-	-	36.5	39.2
Cruise Wing Area (ft^2)	-	-	169	181
Cruise Lift to Drag Ratio	-	-	9.1	11.0
Cruise Propeller Tip Speed (ft/s)	682	683	508	472
Wing Loading (lb/ft^2)	-	-	22.0	21.7
Drag Area (ft^2)	3.1	3.2	6.2	5.3
Cruise Power Required (hp)	189	250	199	187
Hover Power Required (hp)	249	347	389	542
Total Motor or Engine Power (hp)	285	401	648 (rotors) 199 (prop)	903 (rotors) 226 (props)
Operating Empty Weight Inc. Batt. (lb)	1,597	2,670	2,910	3,130
Payload (lb)	800	800	800	800
Battery or Fuel Weight (lb)	108	1,170	948	965
Gross Weight (lb)	**2,505**	**3,470**	**3,710**	**3,930**

The stopped rotor and tilt rotor configurations add a wing and forward thrusting propellers to harness the cruise efficiency of a fixed wing vehicle. The stopped rotor configuration has a single propeller at the back of the fuselage; the tilt rotor configuration has two wing tip propellers. With lift to drag ratios greater than one, these configurations require less thrust and less power in cruise than an equivalent rotary wing vehicle. Both of these winged vehicles use less cruise power than the electric single main rotor vehicle. The fuel powered single main rotor vehicle does better than the stopped rotor vehicle because of the large difference in weight between fuel and batteries. With

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significantly lower cost for electric energy, the near equivalence of cruise power suggests the electric winged vehicles should have an energy cost advantage over a conventional helicopter.

To avoid the complexity of collective and cyclic blade pitch controls associated with a single main rotor configuration, the stopped rotor and tilt rotor configurations assume differential thrust control with eight variable speed fixed pitch rotors. The arrangement of the rotors ahead of the wing and between the wing and tail provides pitch and roll control. Eight rotors provide a redundant rotor in each quadrant of the vehicle to accommodate a failure on a single rotor. Unfortunately, this arrangement limits rotor diameter if the vehicle is to fit within a 50 ft box for compatibility with anticipated vertiports. Total disk area for lifting rotors is reduced relative to the single main rotor configuration. Adding wing tip propellers on the tilt rotor configuration further reduces its allowed rotor diameter and total lift rotor disk area. The reduction in disk area causes the stopped rotor to require more hover power than the single main rotor vehicle. Further reduction in disk area causes the tilt rotor to require more hover power than the stopped rotor.

The rotors and motors on the stopped and tilt rotor vehicles are sized to allow hover with one propulsor failed and another propulsor powered down to balance moments. The single main rotor configurations are not sized to hover with a failed engine or motor. Designing to allow for a propulsor failure is intended to make the multi-rotor vehicles safer than conventional single main rotor vehicles, but it is also necessary for achieving equivalent safety because the use of fixed pitch rotors prevents these multi-rotor vehicles from using autorotation. The difference in motor sizing requirements combined with reduced disk area causes the stopped rotor and tilt rotor vehicles to require considerably more motor power than the single main rotor vehicle.

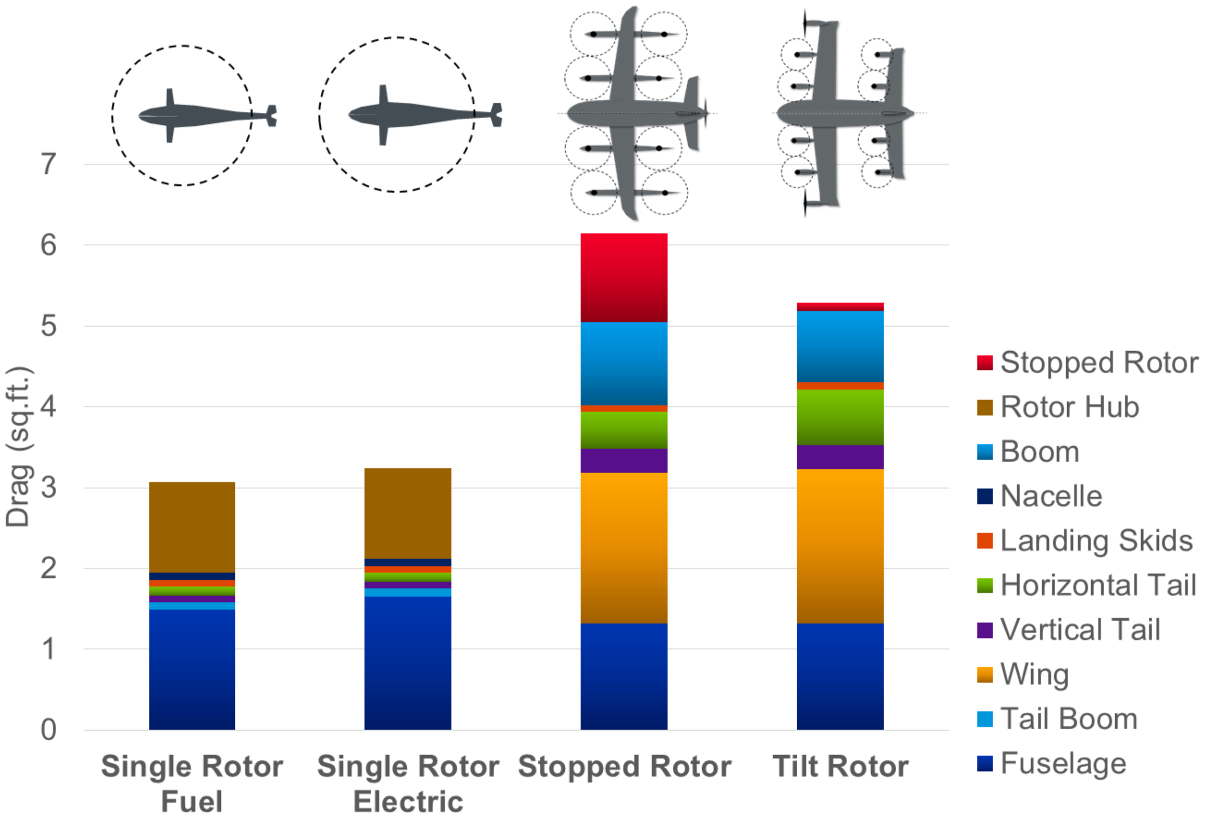

Figure 7: Drag breakdown comparison

Although the stopped rotor and tilt rotor vehicles eliminate the weight associated with the drive system on the single main rotor vehicle, increases in total motor weight plus the addition of wing weight cause the stopped rotor and tilt rotor vehicles to weigh more than the equivalent single main rotor vehicle. The winged vehicles also have more drag than the single main rotor vehicles because of the addition of wings and pylons for carrying the rotors.

To reduce cost, the tilt rotor configuration assumes some commonality across all rotors, whether used primarily for lift or for thrust. Rotor diameter and aspect ratio are the same, and a common motor is assumed. A common motor is somewhat oversized for the propellers, which require maximum power in cruise.

It is not practical to use a common blade pitch for the lifting and thrusting rotors on the tilt rotor vehicle. The blade pitch needed to make the propellers efficient in cruise would cause the blades to be stalled in hover. A lower blade pitch is used on the lifting rotors than the thrusting propellers. The lifting rotors are expected to carry the vehicle from hover to a transition speed where the propellers can take over the production of thrust.

A breakdown of cruise drag area is presented in Figure 7. The winged configurations have a larger minimum drag than the single main rotor configurations because of wings, larger empennage, and rotor carrying booms. Although fuselages are similar between the configurations, the single main rotor vehicles carry a term for interference between rotor and fuselage, resulting in higher fuselage drag relative to the winged vehicles. Compared to the stopped rotor, the tilt rotor configuration provides a cleaner way to stow rotor blades when they are not being used. The tilt rotor blades fold flat against the nacelle body while the stopped rotor blades remain exposed. The benefit is reflected in significantly lower drag area assessed for stopped rotors. The lower drag area gives the tilt rotor a higher lift to drag ratio and lower cruise power compared to the stopped rotor, as indicated in Table 5. Although the winged vehicles have larger minimum drag, their lift to drag ratios improve cruise efficiency as indicated by the cruise power for the stopped rotor, tilt rotor, and electric single main rotor vehicles (199 hp, 187 hp, and 250 hp, respectively).

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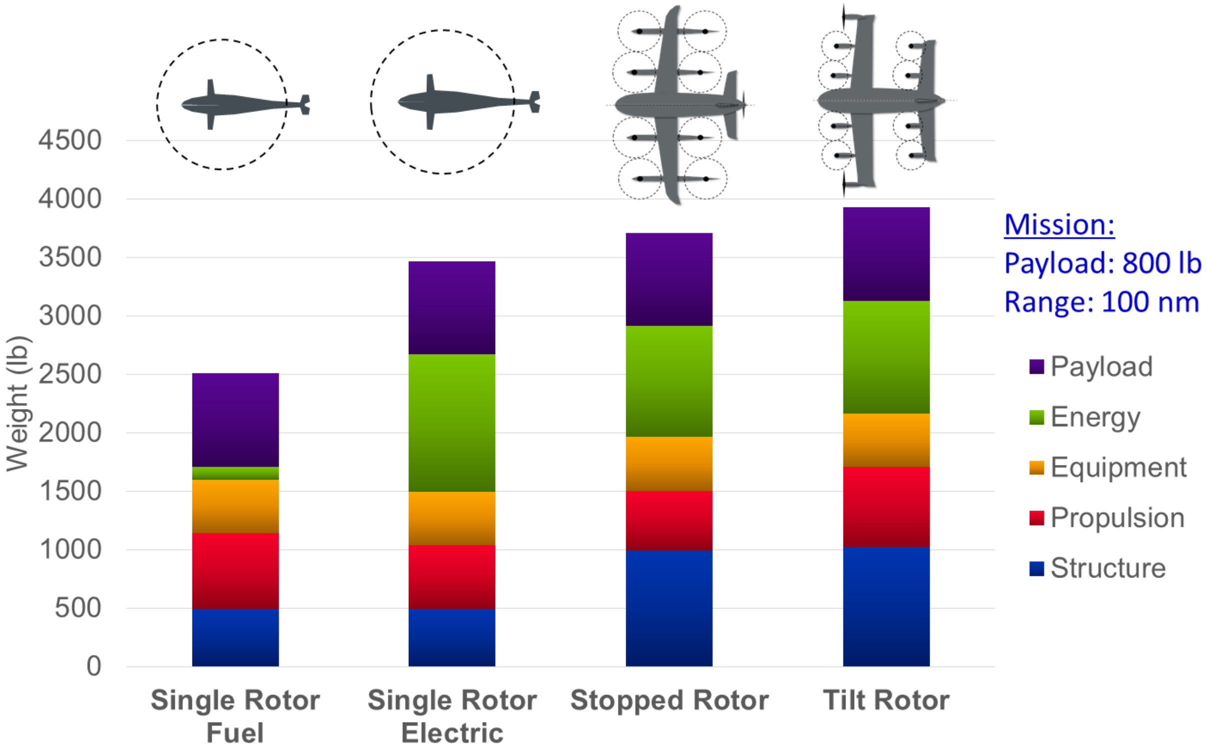

Figure 8: Vehicle Weight Breakdown Comparison

Figure 8 shows a weight breakdown for the four configurations sized for urban air taxi mission. The largest difference in weight is between the piston powered and electric single main rotor configurations. The difference is primarily driven by batteries being much heavier than fuel for the same energy. The increase in energy weight drives the increase in sizing between piston and electric powered single main rotor vehicles. Propulsion system weight was reduced on the electric configuration because of higher specific power assumed for electric motors compared to a gas engine (1.8 hp/lb versus 0.7 hp/lb). The structural weight of the winged vehicles is greater than the single main rotor vehicles because of the addition of wings and rotor carrying booms plus the increase in tail size. The single main rotor vehicles carry a drive system weight associated with main rotor gear reduction.

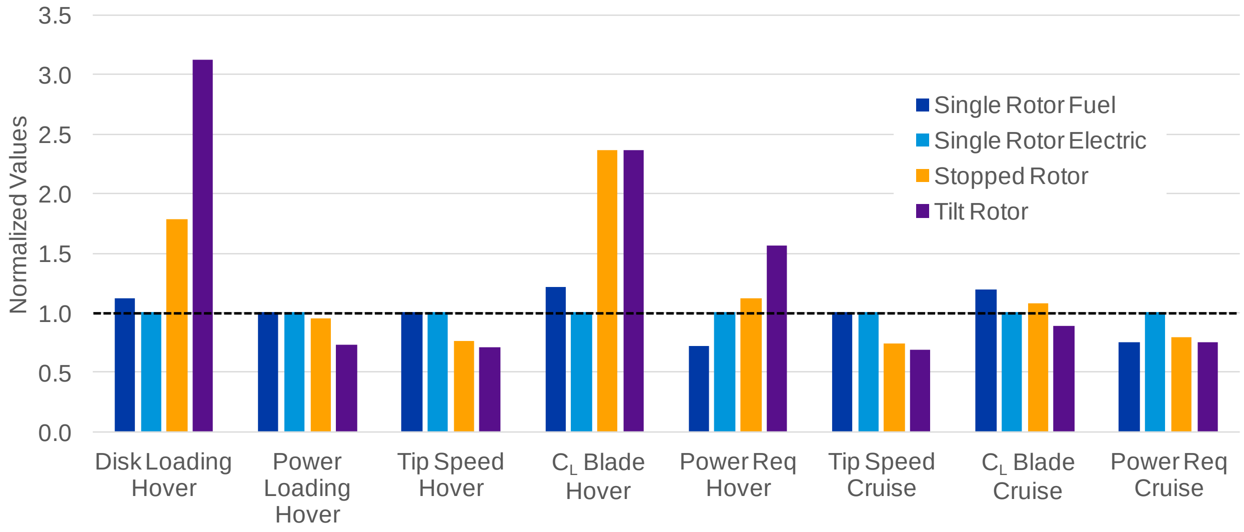

Figure 9: Hover & cruise characteristics (normalized to single rotor electric)

Key characteristics for hover and cruise performance are summarized in Figure 9. The characteristics are normalized against values for the electric single rotor vehicle. The stopped and tilt rotor vehicles end up with higher disk loading because of rotor diameter limits driven by the arrangement of rotors along wings combined with span constraints for vertiport compatibility. Power loading (thrust divided by power) drops as disk loading is increased. Power required for hover increases with disk loading except that the fuel powered vehicle requires less power because it is much lighter. The winged vehicles were allowed to operate at higher blade lift coefficients (C_L) in hover because their fixed pitch blades essentially operate at constant C_L, with thrust variations generated by changing rotational speed. The single main rotor vehicles had fixed speed rotors that would have to increase blade C_L via collective control to achieve elevated maneuver load factors. The winged vehicles use less power in cruise than the electric single rotor vehicle, with the tilt rotor doing better than the stopped rotor because of a higher lift to drag ratio. Since the fuel powered single rotor weighs less than the other vehicles, it ends up with cruise power between the winged vehicles. With cruise performance heavily influencing the sizing of rotors and propellers, there is limited variation in cruise blade C_L across the configurations. The tilt rotor propellers and rotors were given the same diameter and aspect ratio with the hope that blades could be made common for lower cost. That choice likely led to the tilt rotor blades being somewhat oversized, as indicated by lower C_L compared to the stopped rotor. Rotor speed was also reduced relative to the stopped rotor to compensate.

The single main rotor vehicle has collective and cyclic blade pitch control plus a constant speed rotor. Rotor speed is typical for this type of vehicle, not optimized, but the requirement to operate the rotor at higher edgewise speeds favors higher rotor speeds than used on the stopped rotor or tilt rotor vehicles, which discontinue use of lifting rotors well below cruise speed. Cruise propeller tip speeds for the stopped rotor and tilt rotor vehicles also end up lower than the single main rotor tip speed. Lower tip speeds in hover and in cruise suggest the stopped rotor

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and tilt rotor vehicles should be quieter than a conventional helicopter. With lower tip speeds than the stopped rotor vehicle, the tilt rotor vehicle is likely the quietest configuration in the trade study.

A power usage time history for the air taxi mission is shown in Figure 10 for the electric single main rotor vehicle. Power used by the main rotor and tail rotor are shown separately, along with power limits from motor sizing. Hover requires the greatest amount of power. The gap between available and required power allows the rotor to pull 10% additional thrust for vertical takeoff.

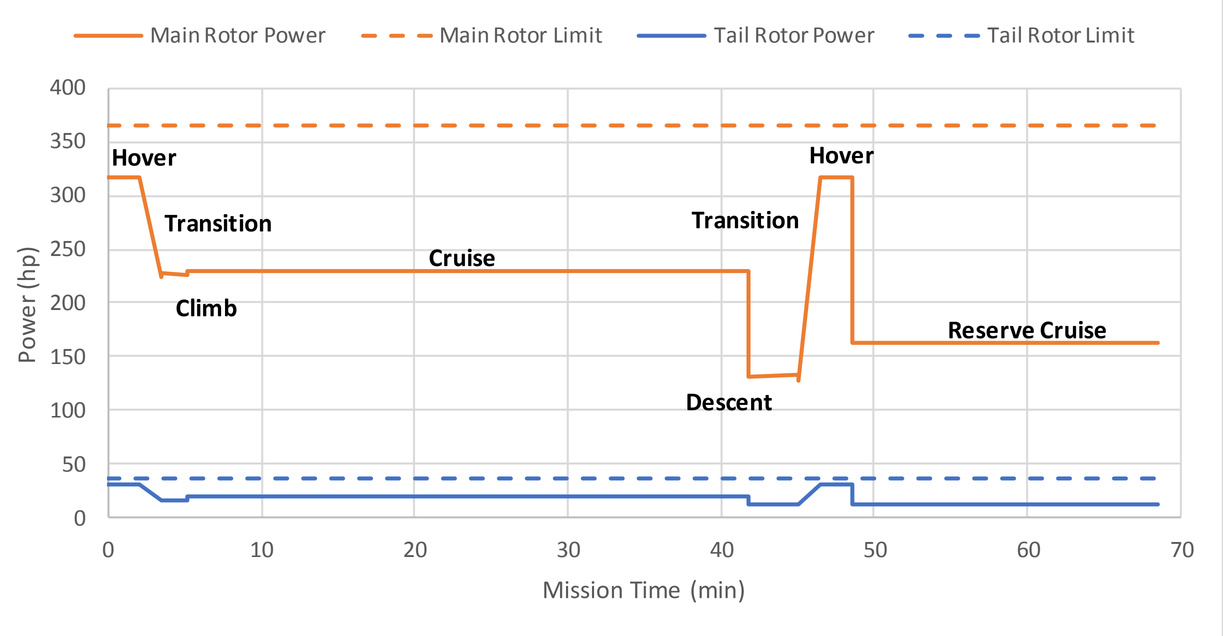

Figure 10: Electric single main rotor vehicle power time history

A power usage time history for the air taxi mission is shown in Figure 11 for the stopped rotor vehicle. Combined power used by the hover rotors and power for the pusher propeller are shown separately, along with power limits from motor sizing. The rotors and propeller are active together only during transition. The available hover power is oversized to allow for one failed motor and one powered down motor. The propeller motor is sized to fit the maximum required propeller power, which is encountered during cruise.

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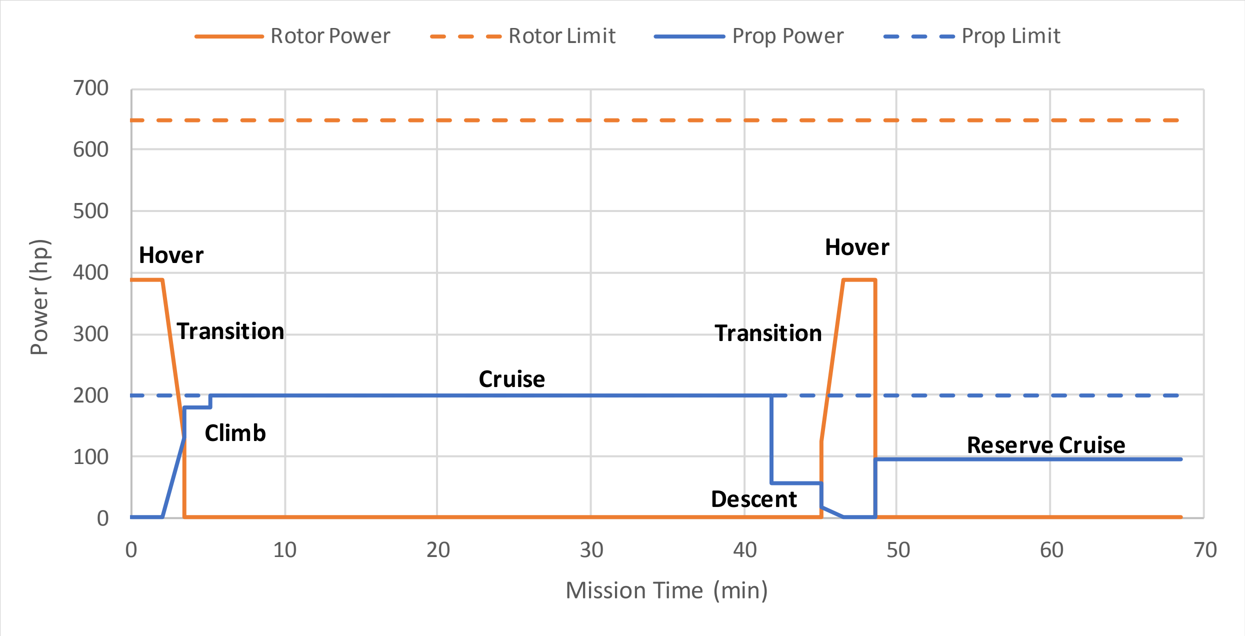

Figure 11: Stopped rotor vehicle power time history

A power usage time history for the tilt rotor vehicle is shown in Figure 12. Power usage between rotors and propeller follows the same pattern as on the stopped rotor. Motor sizing also allows hover with a propulsor out, following the same rules as the stopped rotor. For commonality, the same motor is used for the propellers and rotors. For this reason, the motor is slightly oversized for cruise, resulting in the gap between required and available cruise power.

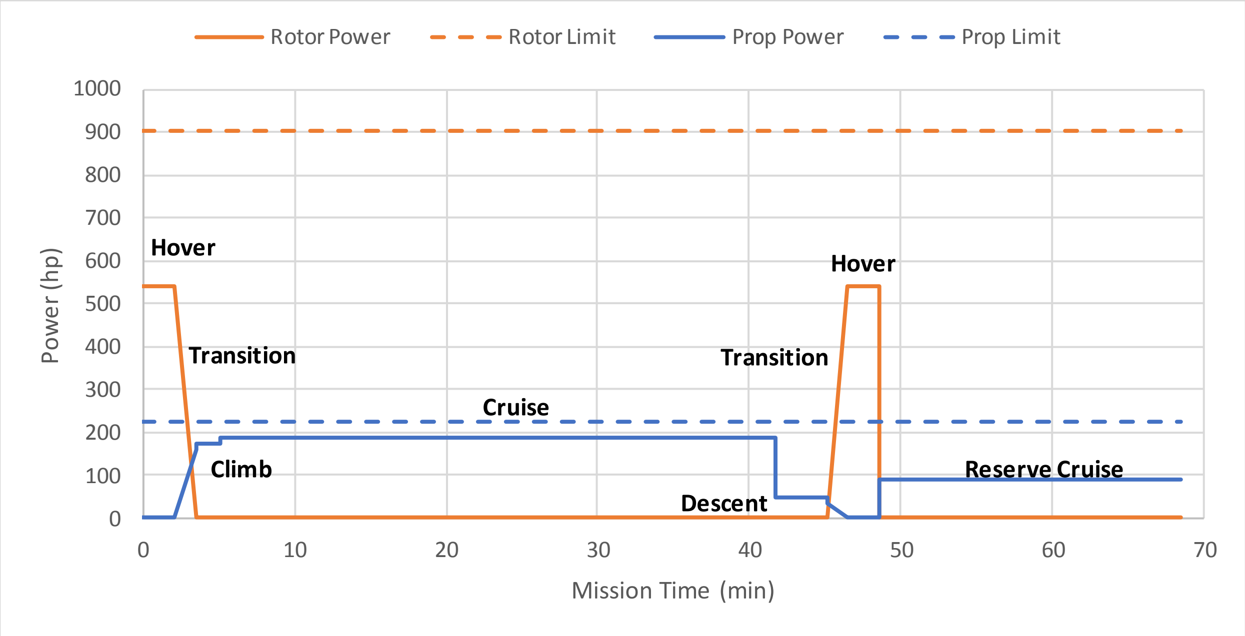

Figure 12: Tilt rotor vehicle power time history

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Since battery specific energy is a critical sizing constraint for all electric aircraft, trends for gross weight with battery specific energy are shown in Figure 13. The trends were estimated with a simpler analysis than the MDAO sizing described in this paper, with resulting gross weight somewhat higher than the MDAO sized vehicles. Vehicle gross weight increases rapidly as specific energy is reduced from the level assumed for the vision vehicle. Near term, it may make sense to produce a vehicle with reduced range capability, and incorporate better battery technology later in production or by retrofitting for better performance.

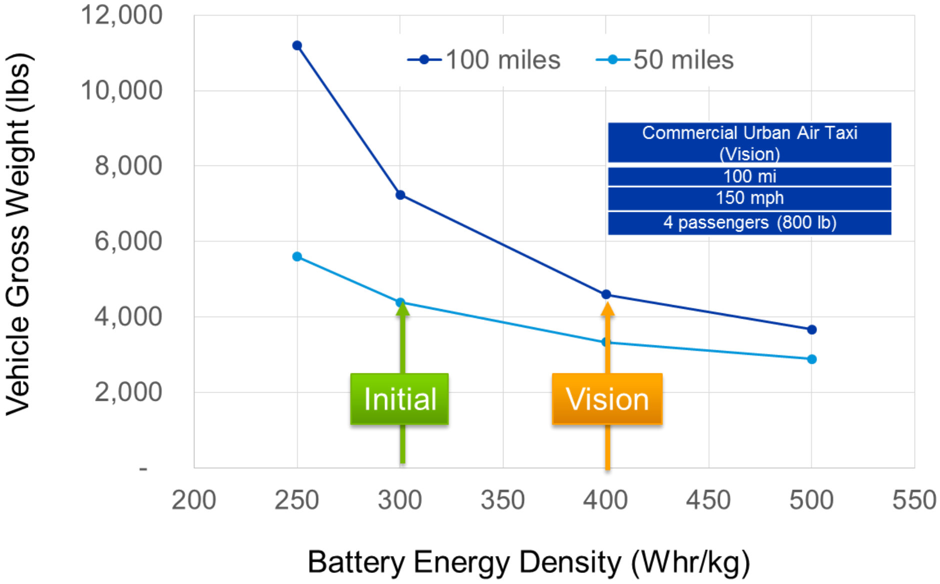

Figure 13: Vehicle gross weight trends with battery specific energy

REDUCING COMPLEXITY

Modern helicopters with traditional fossil fuel engines have hundreds of unique moving parts (Figure 14). The large number of parts translates into higher maintenance, qualification, and purchase cost compared to electric aircraft, which tend to have fewer unique dynamic components. Similar to electric vehicles on the ground, these cost reductions can translate to a substantial cost reduction during the life of the system. For the cost study to follow, a comparable helicopter is used to compare operating cost between traditional fossil fuel propulsion and electric propulsion. The Robinson R44 is a single main rotor helicopter with a piston engine. The R44 is optimized for low operating cost with a simple teetering two bladed rotor connected by a transmission to a two bladed tail rotor. The R44 could meet the Uber Elevate range and payload requirements with accommodation for 4 people (including pilot) plus baggage for a total payload weight of 818 lb.

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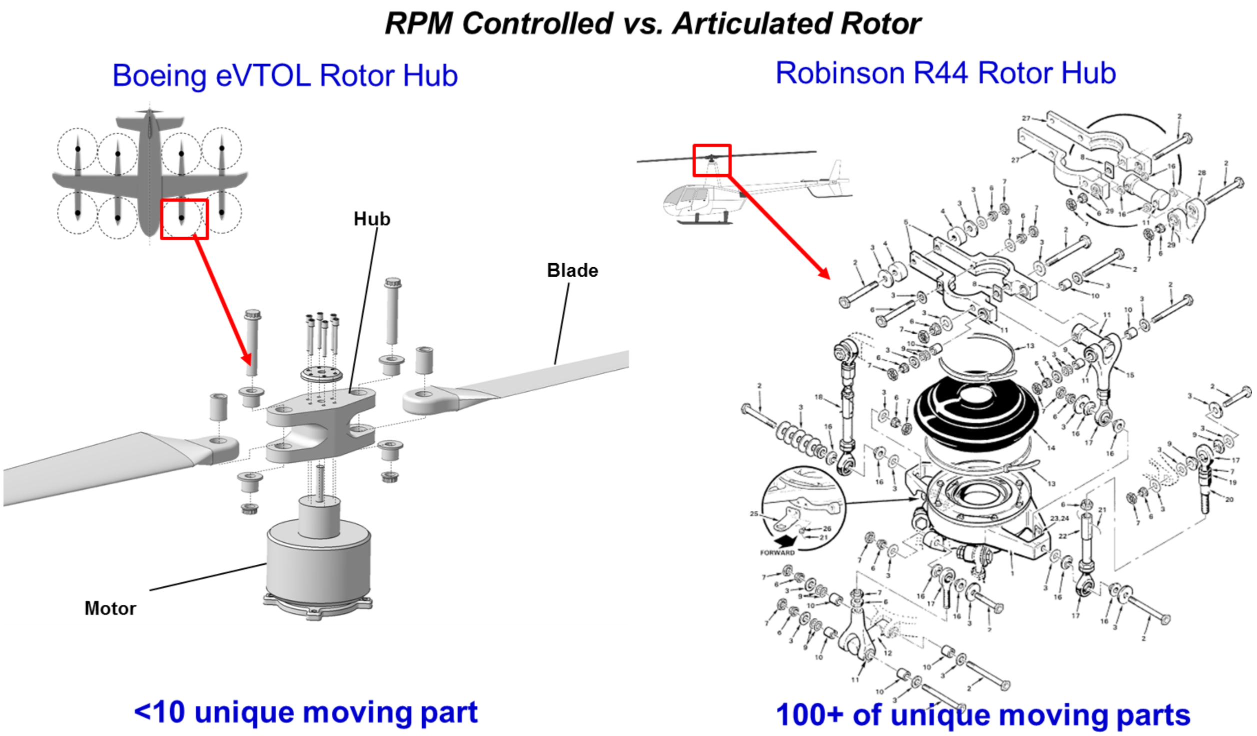

Figure 14: A comparison of rotor hub parts between an eVTOL vehicle and the Robinson R44

OPERATING COST

For this cost study, several eVTOL configurations were compared with the Robinson R44 as shown in Figure 15. The eVTOL aircraft were sized to only meet the Uber Elevate mission requirements of 800 lb and 100 miles, with reserve. The R44 carries 716 lb of payload with a range of 300 nm without reserves. It can carry up to 818 lb payload at shorter ranges, which would include the 100 mile mission. The R44 cruises at up to 125 mph while the eVTOL were sized to cruise at a 150 mph, which is faster than most traditional small helicopters. The Robinson R44 was selected for comparison as the closest match in capability to the eVTOL aircraft sized for the Uber Elevate mission.

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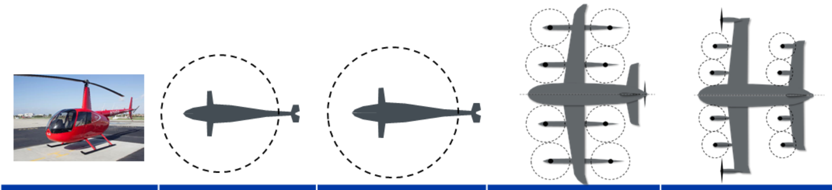
Mission:
Payload: 800 lb
Range: 100 nm



	Robinson R44	Single Rotor Fuel	Single Rotor Electric	Stopped Rotor	Tilt Rotor
Cruise Speed (mph)	125	150	150	150	150
Energy Type	Fuel	Fuel	Electric	Electric	Electric
Number of Rotors	1 + tail	1 + tail	1 + tail	8 + prop	8 tilting + 2 props
Rotor Diameter (ft)	33	26.4	33	9	7
Wing Span (ft)	n/a	n/a	n/a	36.5	39.2
Operating Empty Weight (lb)	1,505	1,597	2,670	2,910	3,130
Payload (lb)	818	800	800	800	800
Battery/Fuel Weight (lb)	177	108	1170	948	965
Gross Weight (lb)	**2,500**	**2,505**	**3,470**	**3,710**	**3,930**

Figure 15: **Vehicle characteristics for operating cost comparison between the Robinson R44 and several eVTOL concept configurations**

Total operating cost is comprised of three major components as indicated in Figure 1. Variable cost is further comprised of fuel, maintenance, and overhaul. For piston engine general aviation aircraft like the R44, fuel cost is driven by the price of AvGas (aviation gasoline). AvGas as of January 2017 was around $5.82/gal including all taxes and service charges based on a national average in the United States [12]. For this study, an average AvGas and Jet-A cost of $5.50/gal was used. Electricity cost varies state by state and by end user (commercial vs. residential) [13]. For this study a cost of $0.12/kWh was used with a 90% efficiency factor for charging.

For helicopter maintenance, the R44 website provides a cost per flight hour break down [9]. For general aviation helicopters, Conklin and de Decker provide an estimate based on the vehicle and mission type [3]. For the eVTOL vehicles, engine maintenance is zero; however, electric motor and power electronics are determined by estimating the cost and life replacement for these components. The cost of the electric components was based on several Joby Aviation studies [14] and the Airbus Vahana study [15], which showed an average $300/kW for motor, speed controller and propeller. For this study the motor life was assumed to be 6,000 hours of flight based on getting 60% of the life expected for a brushless DC (direct current) motor [16]. This 60% factor is applied to account for the harsher environment for aviation aircraft. The speed controller and propeller life was assumed to follow the same life as the brushless DC motor. Battery life was assumed to be 2,000 cycles based on the same cells used in the Tesla battery pack, which are Panasonic NCR18650B [17]. Cost per kWh was based on doubling the cost of the Tesla battery at the pack level to account for aviation qualification [18]. The current Tesla battery pack is $190/kWh [18]; the Uber elevate study assumed $400/kWh initial and $200/kWh near term [5]; Joby Aviation assumed $200/kWh [14]; therefore, $400/kWh was conservatively chosen for this cost study.

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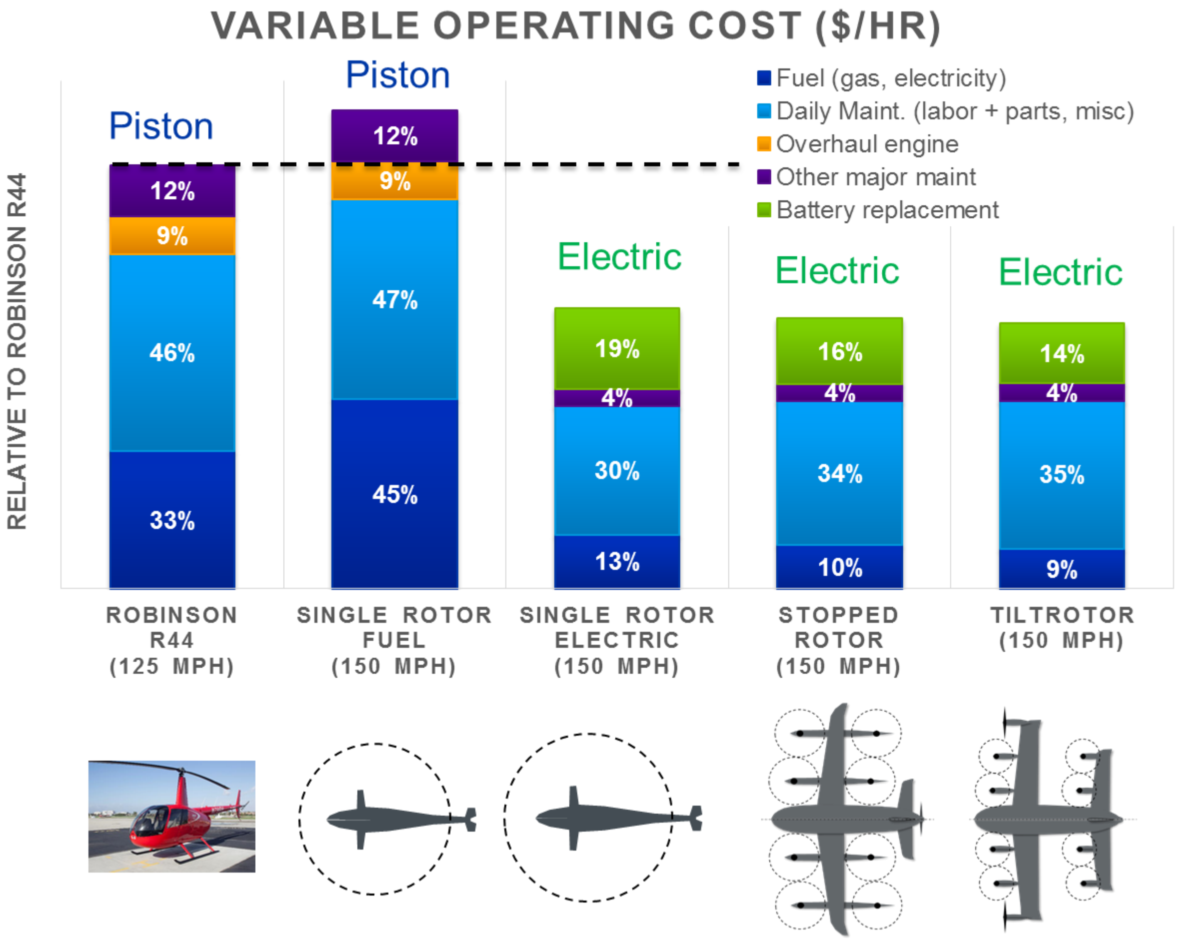

Figure 16: **Variable operating cost ($/hr) normalized by the Robinson R44 helicopter**

Figure 16 shows the variable cost comparison between eVTOL configurations and the Robinson R44. All operating costs were normalized against the Robinson R44. All eVTOL configurations show reduction in operating cost due primarily from the reduction in fuel and maintenance costs. The R44 has a range of 300 nm at a speed of 125 mph while the eVTOL aircraft were sized for a range of 100 miles at a speed of 150 mph. To provide a more equivalent comparison, a fuel powered single main rotor vehicle was sized to the requirements of the eVTOL configurations. This fuel powered comparison vehicle has about 12% higher operating cost per hour than the R44, but since its cruise speed is 20% higher, its cost per mile is actually lower. The electric vehicles show a greater variable cost advantage when compared to the equivalent fuel powered vehicle instead of the R44.

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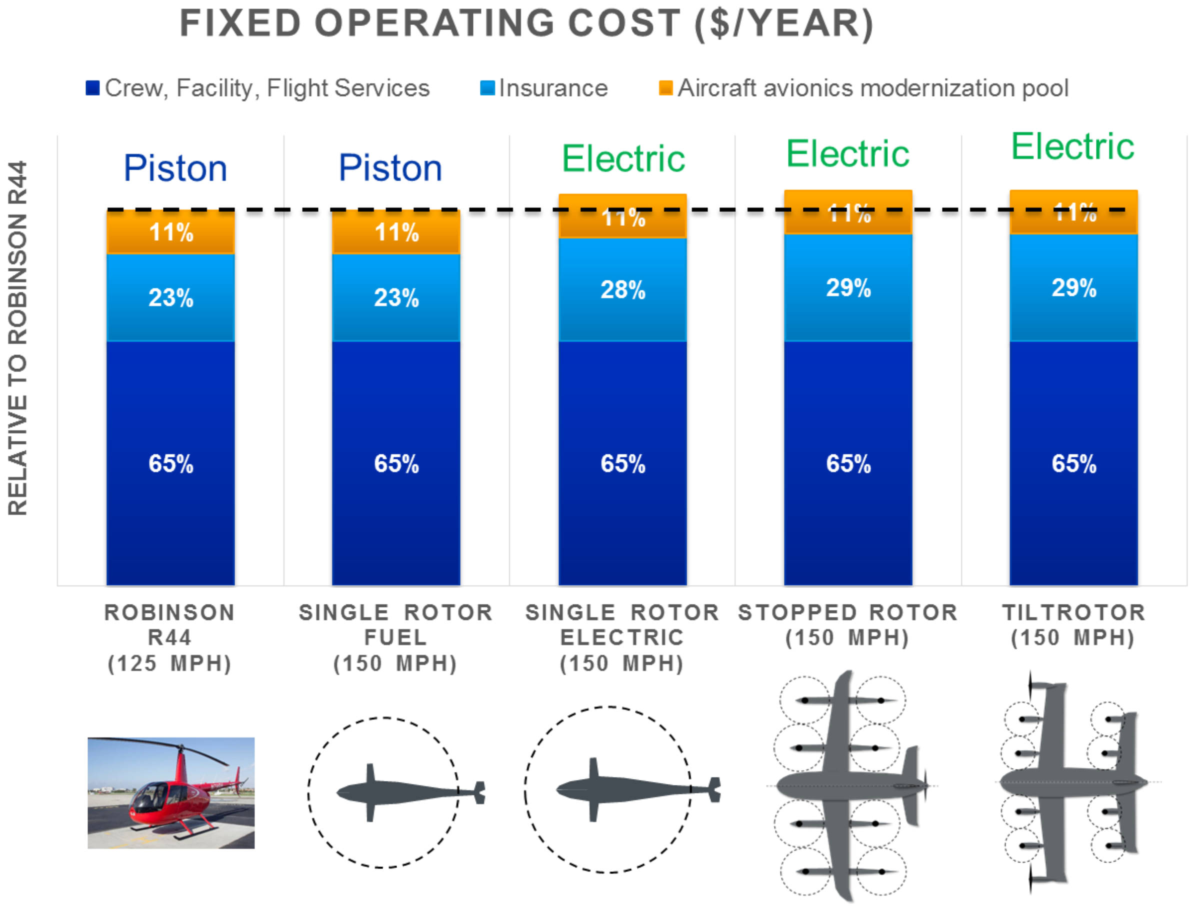

Figure 17: **Fixed operating cost ($/year) normalized by the Robinson R44 helicopter**

Yearly fixed costs include avionics, crew, and insurance. For this study, crew and avionics were assumed to be constant for all aircraft since the mission would be the same. Only insurance varied, since it is based on vehicle price. Figure 17 shows only a slight variation in fixed cost between aircraft.

Book depreciation, compared in Figure 18, is based on a vehicle cost and a 10 year amortization. For this exercise, it was assumed that these vehicles would be scaled based on the cost and weight of the Robinson R44, with a price listed at $473,000 [5] and a gross weight of 2,500 lb. Vehicle cost was then scaled based on gross weight compared to the R44. The resulting costs show up in the book depreciation and follow the same trend as gross weight. The assumption is that added cost for batteries is captured in the gross weight scaling method.

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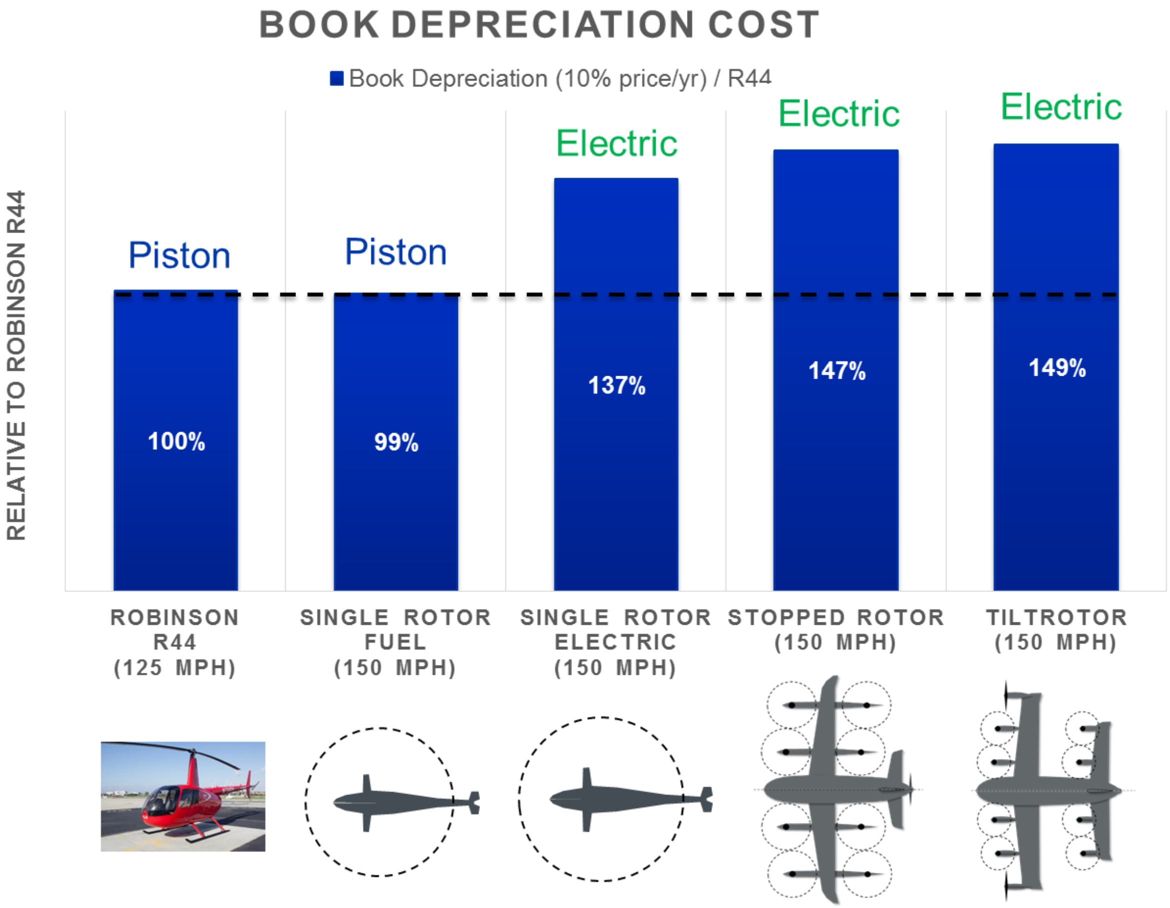

Figure 18: **Book depreciation cost (10% price/yr) normalized by the Robinson R44 helicopter**

Aircraft utilization is critical to total operating cost per mile. Greater utilization increases the number of miles over which the aircraft cost is amortized. The Uber Elevate white paper specified 2,080 hours of operation per year [5]. For an all-electric aircraft, this utilization might translate into 6 hours of operation a day with 10 or more hours available on the ground for charging, 7 days a week.

Finally, when all operating costs (variable, fixed, and book) are rolled together and divided by the number of passengers per trip mile, a comparison can be made for total operating cost. In Figure 19, the total operating cost per passenger seat mile for a high utilization business operation is shown relative to the baseline Robinson R44. Since the R44 has a lower cruise speed, it does not fly as many miles over the same time as the other vehicles. The fuel powered single main rotor vehicle ends up with over 9% reduction in total operating cost per seat mile compared to the R44. The electric vehicles reduce total operating cost per seat mile by about 35% relative to the R44. Compared to the equivalent fuel powered single main rotor vehicle, the electric vehicles reduce total operating cost per seat mile by about 26%.

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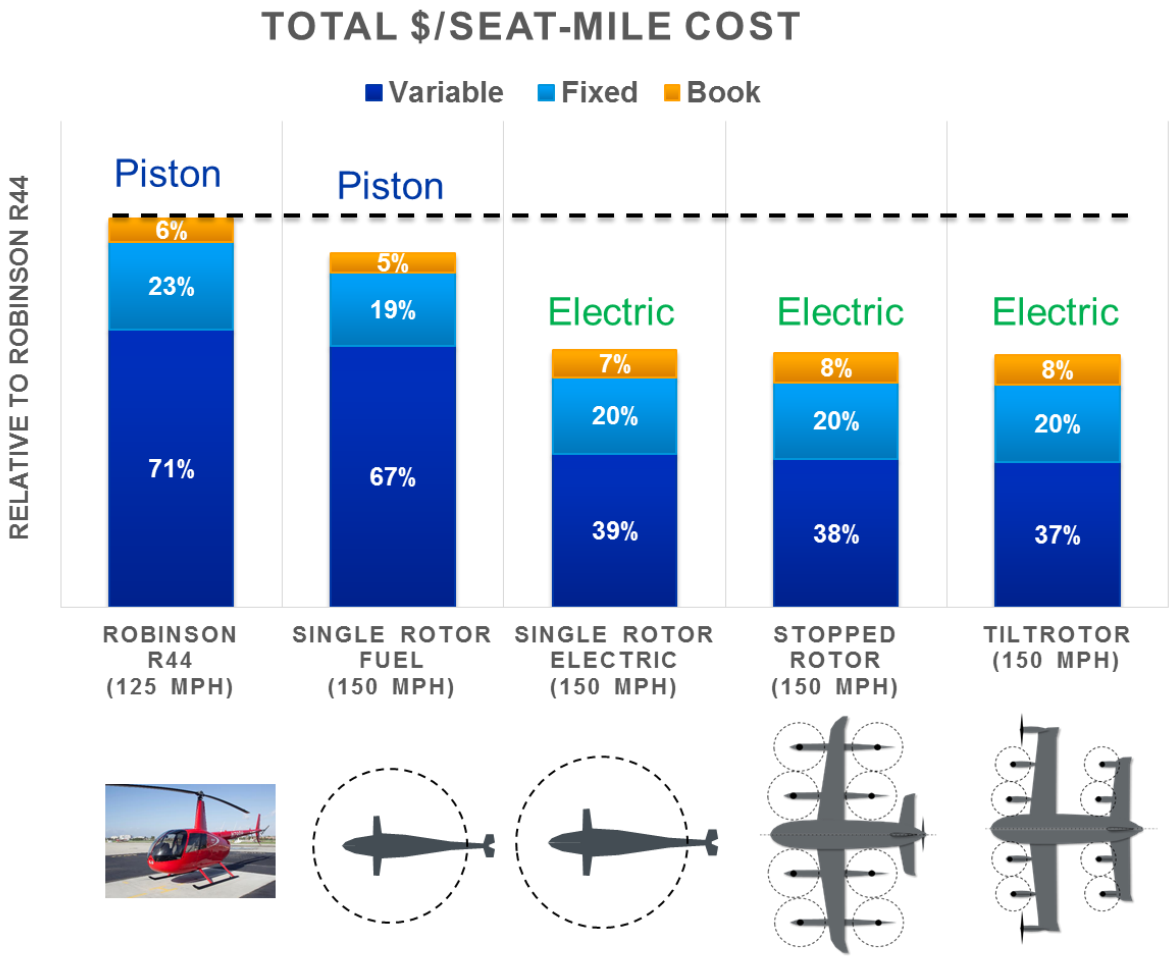

Figure 19: **Cost per seat mile normalized by the Robinson R44 helicopter**

In addition to operating cost, other factors may affect adoption of electric VTOL. Noise is expected to be reduced because electric motors are quieter than piston or turbine engines, and distributed propulsion provides options for reducing rotor tip speeds. Safety can be improved by having a propulsion system with enough redundancy to handle failure of a single component. Environmental considerations should be better as the energy for operating electric vehicles could come from renewable electric power.

CONCLUSION

This initial evaluation of the cost of an electric VTOL aircraft and its operations supports the feasibility of an electric air taxi vehicle with 4 passengers at a 100 mile range. Total operating cost was reduced relative to equivalent piston aircraft. Compared to a conventional fuel powered vehicle, eVTOL configurations reduced total operating cost per seat mile by about 26%. It is interesting to note is how closely the three eVTOL configurations ended in operating cost. Advantages and disadvantages between configurations offset each other such that operating cost was about the same. The single main rotor vehicle had lower structural weight, reducing book depreciation and fixed cost relative to the winged configurations. This advantage was offset by winged configurations having lower variable cost from being more energy efficient in cruise. Although the eVTOL vehicles appear equal in cost in this study, changes in range, speed, or battery capability are likely to favor some vehicles over others.

Other considerations, including noise, safety, and the environment may also determine optimal configuration. If low noise is a requirement, a single main rotor might not be ideal as it would tend to want higher tip speeds for efficiency with higher cruise speeds. If vibration is considered, smaller, distributed propellers will have higher frequencies, which might be more favorable for passenger comfort. Finally, small distributed thrusters could improve safety by providing redundancy to avoid the single point of failure associated with a single main rotor.

Next steps for electric VTOL configuration studies should include broader and higher fidelity evaluation to better understand feasibility. This work should include better definition of the architecture, weights, and reliability of electric drive systems. Further exploration should be done to determine the best vehicles and requirements for an air taxi to compete with other modes of transportation. Such exploration should include refinement of the current eVTOL vehicles and the study of additional alternative concepts. Trades on range, cruise speed, and battery technology would provide information for refining mission requirements and for determining the feasibility of products with nearer term technology.

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