Comparing Electric Sky Taxi Visions

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Introduction

In April 2017, UBER hosted a conference in Dallas Texas titled “Elevate Summit”. Over 500 representatives from industry - both large and small, government and others - heard about UBER’s vision for sky taxis. UBER included many other companies on the program who might contribute to making this vision a reality. UBER’s vision is built around piloted, electric, Vertical Take-Off and Landing (VTOL) service between “Vertiports” placed in urban locations that interface with UBER’s ground transportation system. These sky taxis or Personal Air Vehicles (PAVs) will be designed to best serve the transportation needs of those traveling more than 20 miles. This vision is described in detail in a report released by UBER on October 27 2016 titled; “Fast-Forwarding to a Future of On-Demand Urban Air Transportation”[1] and on their web site with presentations from the Summit.

The exact configuration of UBER’s sky taxi has not been chosen. In fact, there are many different configurations being studied and developed by a myriad of private, public and government organizations. UBER does not plan on developing any aircraft themselves, but are providing an infrastructure for their use. UBER has also presented an economic model, with initial assumptions and conclusions for these 4-place VTOLs.

UBER’s vision is not the only one for sky taxis. Ehang, Volocopter, Tier1, and others are developing electric helicopters or multi-copters as sky taxis. These vehicles rely solely on rotors for lift in all phases of flight. In this paper we will refer to this type of vehicle as “rotor-craft”.

As the development of sky taxis is in its infancy, any viable aircraft configuration option should be duly considered. While the VTOL and rotor-craft approaches are consistent with a vision of the “Jetsons”, Sci-fi books, and movies, it may not be the best route forward, at least for the near future.

Another option for consideration is Ultra Short Take-Off and Landing (USTOL) aircraft, also referred to as eSTOL for “extremely” or near-VTOL. These winged aircraft can take off and land in distances far shorter than their conventional take-off & landing (CTOL) cousins.

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The use of STOL type aircraft as air taxis has been the topic of a series of papers by Dr. Brien Seeley, formerly the head of the CAFÉ Foundation, now of the Sustainable Aviation Foundation. In his four papers, conveniently titled "Regional Sky Transit X" where X is I[2], II[3], III[4] and IV[5], he paints a very detailed picture of a sky taxi system. His main concerns are for the airports, flow of aircraft and people, and noise, with little detail on the aircraft themselves. He envisions certain technologies needed for USTOL craft, but has not well evaluated the options.

The purpose of this paper is to compare and contrast three classes of sky taxis; VTOL, rotor-craft, and USTOL. This comparison is class specific, not configuration specific. In other words, these results cannot be used to compare two VTOL configurations but can be used to support near-term decisions about which class of aircraft to target research efforts and investment dollars to bring viable solutions to market. That said, the underlying model could be used to make intra-class decisions, but that is not done here.

This paper is written to provide whatever depth is needed by the reader. It begins with the results. This is followed by sections describing, in words, how the results were developed; the assumptions made; methods used to verify their accuracy; and their sensitivity to the assumptions. The last two items are very important. It is easy to build system models, but they are only useful if they accurately represent reality. While all these classes of aircraft are under development and evolving, there are limited examples that can serve as reality checks.

Further, models are only as good as the assumptions used and the results may be strongly influenced by them. Thus, the sensitivity to the assumptions, the uncertainty reflected in the model, is also presented.

For those readers who want to understand the equations used and their derivation, there is a separate document available with those details[6].

The results developed in this paper show the best possible performance by aircraft in each of the sky taxi classes explored across: 1) current and future batteries (their energy densities) and 2) the number passengers (total people including pilot, if one is needed). The class, battery potential and number of people are used to estimate the gross weight, potential range, thrust/power required, and cost per unit needed for each example vehicle.

It must be emphasized that for any combination of batteries and number of passengers, there are many different design configurations in each class. Presented here is the upper limit feasible for each configuration.

While this paper is dense in results, and shows good correlation with other models and the sparse real-world data, one plot best summarizes the findings. In Figure 1, the power required by the 3 classes of sky-taxis is plotted versus the range for different gross weight aircraft carrying 2 passengers (including the pilot as one, if needed) with near future batteries (300 wh/kg).

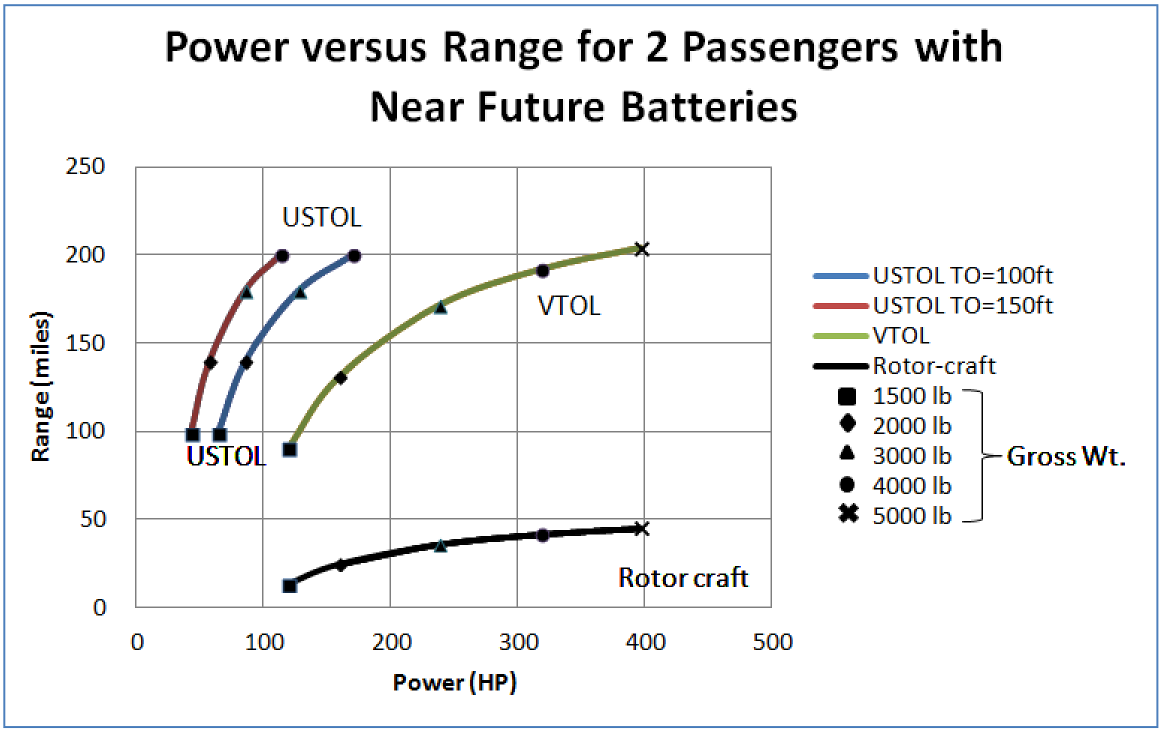

Figure 1: Summary of findings

What is clear here is:

1) Rotor-craft require extensive power and have very limited range.
2) VTOL sky taxis will be heavy, require high power, but can have a significant range.
3) USTOL can have very short ground runs (TO distance noted in the legend) with lighter craft and less power than the other options.
4) Battery weight fractions (the percent of the gross weight made up of batteries) for the heavier aircraft is in the 30% - 36% implying over 2000 lb (900kg) of batteries. For one aircraft this seems unrealistically high and for a fleet of aircraft seems impossible.

Rotor-craft and VTOL performance will further suffer when considerations for additional capability (range and speed), as well as capability (added payload) become critical metrics to economic viability (added utilization).

One aspect not covered in this paper is noise. In general, noise is a function of power. As shown in Figure 1 rotor-craft and VTOL require high power and thus will, most likely, be noisy. While noise is important, beyond its correlation to the power required, it is not included in the range model developed here.

While this paper is exclusively focused on battery powered craft, the resulting high gross and battery weights imply that a similar study should be done with hybrid systems. This is planned for the future.

The results detailed below virtually scream for the development of both USTOL aircraft and hybrid electric systems. The current focus on all battery powered VTOL and rotor-craft does not seem to be the route to a usable system.

Why and Why now?

The reasons "why" are well presented both UBER's report "Fast-Forwarding to a Future of On-Demand Urban Air Transportation" [1] and papers by Brien Seeley [2,3,4,5]. These reasons revolve around a desire to relieve congestion in metropolitan areas and improve transit times. Since the urban mobility goals espoused in these papers are not new, a more important question is; Why now?

Admittedly, urban congestion is growing worse and has been for years, but there are four, interrelated technological advances that explain why the focus on sky taxis is happening now:

- The most pervasive of these advances is the promise of Distributed Electric Propulsion (DEP). Until recently aviation has been limited to aircraft with a single or a few large internal combustion or turbine propulsors. The use of electric motors offers new ways to power aircraft with many, small propulsors designed to enhance aerodynamics in ways not possible before. The potential is embodied somewhat in new VTOL concepts and is seminal in the USTOL class of vehicles described in detail below.
- More efficient electric motors being developed for drones and other uses will enable the design of radically new DEP aircraft for use as sky taxis.
- The technologies that are enabling autonomous automobiles will have extensive sky taxi applications. In the long term, these may lead to autonomous sky taxis, arguably an easier to solve problem than autonomous automobiles.
- Powering these sky taxis will require low cost batteries with high energy densities. The demand for light weight consumer products and high range electric cars is fueling the development of denser, lower cost batteries. While the sky taxi market is riding on these shirt tails, flight will require even more development on power/weight energy density and cost per kwh.

The Classes of Distributed Electric Propulsion (DEP) Sky Taxis

In order to study what type of vehicle is best suited for sky taxi use, the possibilities have been grouped into three broad classes:

1. Rotor-craft including multi-copters and helicopters
2. VTOL , aircraft that take-off vertically and then transition to winged flight before transitioning again to a vertical mode for landing
3. USTOL or Ultra Short Take-Off and Landing, winged aircraft take advantage of Propulsion Airframe Interaction (PAI) to leverage DEP to take off and land in a very short distance while providing very efficient cruise potential.

These classes might seem to be too broad to compare and contrast, but using the logic developed in this paper, the potential best-in-class for each can be compared sufficiently to make important decisions. Each class is briefly introduced in the following sections.

Rotor-craft

The thought of scaling up multi-copter drones so they can carry passengers is very appealing. To date (July 2017), at least two DEP drone-like vehicles have flown with people on board, the Ehang 184 and the Volocopter 2x. Further, an electric helicopter with a single rotor has flown and is included here based on its success.

Figure 2: The eHang 184

The eHang 184[7] (1 passenger, 8 rotors, on 4 stalks) is a quad-copter for people as shown in Figure 2. In early 2017 there was much publicity about the Ehang 184 as Dubai contracted for delivery of these air taxis. Specs for this aircraft are:

- Gross weight: 240 kg (empty) + 100 (payload) = 340 kg (748 lb)
- Total power: 152 Kw from 8 motors (206 hp)
- Battery capacity: 17 kWh
- Speed: 60 km/hr = 55 ft/sec

This is expected to fly at low altitudes and is totally autonomous. The model developed in this paper will later be used to further explore this craft.

Figure 3: The Volocopter X2

A second DEP rotor-craft is the Volocopter 2x[8] (Figure 3). Specs on it are:

- Power: 45kw (60 hp)
- Weight: 450kg with two passengers (990 lb)
- Speed: 100 kph (62 mph)
- Motors: 18 motors at 2kw each (2.7 hp). Total 36 kw (49 hp).

As of this writing, both the eHang and the Volocopter have flown. It is not clear for how long, but the model developed here will give some insight into their potential.

While the electric helicopter, EPSAROD (Electric Powered Semi-Autonomous Rotorcraft for Organ Delivery), is not a DEP vehicle, its 30 minute electrically powered flight in early 2017 is useful as a benchmark. This project funded by Martine Rothblatt, Chairman of United Therapeutics, and built by Tier1 Engineering[9] is a Robinson R44 helicopter modified for a single electric motor. The mission specification for this craft is to carry two people and three manufactured artificial organs for transplant (a total payload weight of 600 pounds) for not less than 150 minutes, including a 30 minute reserve. Through the model developed here, the reality of this spec can be assessed.

In February 2017, the EPSAROD prototype (Figure 4) stayed aloft for 30 minutes. Specs on it are:

- Gross weight 2500 lbs
- 183 kw electric motor
- Battery weight 1100 lbs (500 kg). The battery weight fraction is 44%.
- 100 amp-hrs at 700 volts, so 70 kwh
- Energy density 140 wh/kg
- 1 passenger

Figure 4: The EPSAROD prototype

VTOL

UBER is currently exclusively focused on VTOL for sky taxis. They feel that vertical take-offs and landings are essential for sky taxi success. Not all share this conviction as is discussed in the next section. In their presentation at the UBER Summit, Rob McDonald and Brian German[10] discussed the potential for various types of VTOLs. They began with the American Helicopter Society (AHS) “VTOL Wheel of Fortune” [11] (Figure 5) and selected the most promising VTOL concepts for analysis. The wheel shows forty different VTOL configurations that have been explored over the years. McDonald and German developed a typical sky taxi mission and calculated the potential range for the most promising types. Their analysis is leveraged in this paper and their results used as benchmarks.

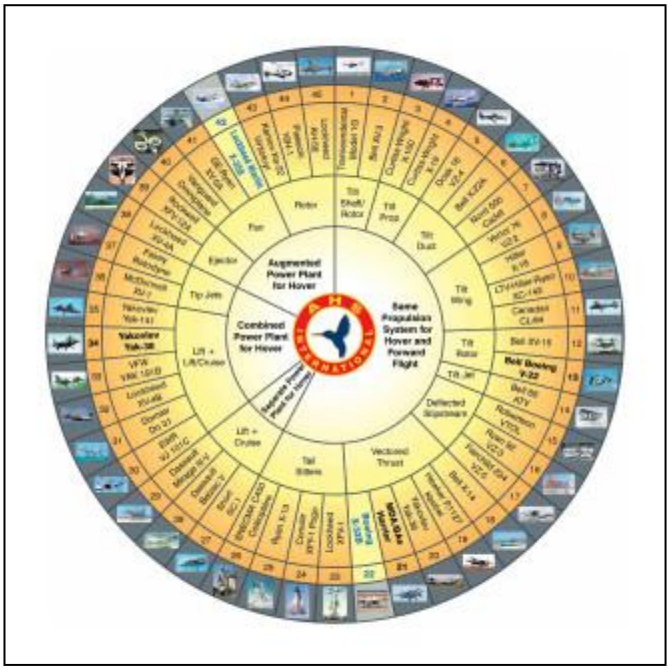

Figure 5: The AHS wheel of fortune

Where many call the AHS diagram, the “Wheel of Misfortune” due to the many failures over the years, DEP and advanced energy storage give the field new life. Recent developments by Aurora[12] (DARPA funded) their XV-24A Lightning Strike and the Lilium Jet are prime examples of this new direction.

Figure 6: The Lightning Strike

The XV-24A shown in Figure 6 is an Electric Ducted Fan (EDF) tilt wing VTOL demonstrator. It is designed to fly at 300 kts and obtain a hover flight efficiency of 75%. This aircraft is a hybrid, not battery powered as are the other examples. A single turbine engine mounted in the fuselage drives three Honeywell one-megawatt electric generators that power 24 EDFs distributed across the wings and canards. A 20% scale model of this craft has successfully flown.

Figure 7: The Lilium Jet

The Lilium Jet (Figure 7) also uses ducted fans distributed on the wing and canard, but rather than titling the wing, it is a “tilt rotor” vehicle, rotating only the EDFs along the trailing edge of the wing and the entire chord of the canard. The specs on it are:

- The 36 EDFs
- Battery capacity: 320 kwh
- 4 passengers
- Gross weight 4400 lb (2000 kg)
- Range 300 km at 300 kph (See section on Confirmation of Model Fidelity)

USTOL

In many ways the maturity of DEP aircraft development is analogous to the design of airplanes in 1906, a few people have gotten off the ground, many dream about how to do it, but nobody knows what a viable DEP configuration is or how to best “distribute” the propulsion.

One DEP concept is Ultra-STOL, or USTOL. The term “USTOL” has been adopted here to differentiate it from earlier efforts and to focus on potential of using the distributed propulsion offered by electric ducted fans in new and unique ways achieving near VTOL and high cruise efficiency in one vehicle. USTOL is defined as aircraft that have very short take-off and landing distances.

Currently, conventionally powered STOL aircraft such as CubCrafters’ Carbon Cub can be flown in and out of a 100 foot (30m) circle, depending on weight and wind conditions. STOL aircraft such as those produced by CubCrafters could serve as sky taxis, but they are not a viable mass mobility solution. While they can fly in and out of a 100 ft circle, they take an experienced pilot, very high power to weight ratio, very light weight (only the pilot, a very austere interior, and minimal fuel), comparatively large wings, and operation right above the edge of stalling.

The use of Propulsion Airframe Integration[13] (PAI) to achieve very high lift at very low speeds was introduced many years ago (it appears on the AHS Wheel of Fortune), but as with VTOL, it too is being re-explored with distributed propulsion. The authors of this paper are developing such a technology that they have dubbed as Integrated Distributed Electric-Augmented Lift or IDEAL.

Simply explained, IDEAL uses the thrusting power to improve the aerodynamics. Part of the power used by a propeller provides thrust and part increases the velocity of the air going through it. The energy put into increasing the air velocity is wasted in traditional aircraft design. By using many small propulsors blowing over a major portion of the upper surface of the wing this "wasted energy" can be put to work. The faster moving air over the wing's upper surface increases the lift and greatly reduces induced drag. This Upper-Surface-Blowing (USB) significantly lowers the distance needed for takeoff and increases the cruise velocity.

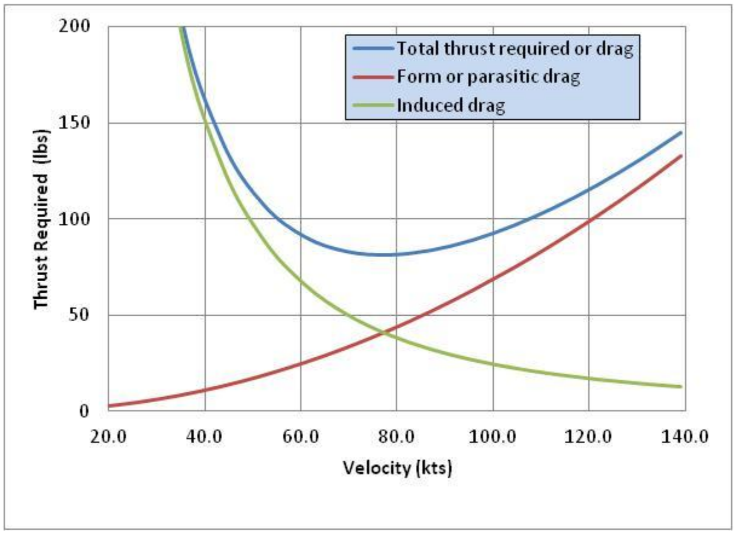

Figure 8: A common Thrust - Velocity relationship

To understand this, first consider Figure 8 showing the thrust needed for a typical 1320 lb (600kg) LSA (Light Sport Aircraft) versus its velocity. The blue curve, representing the drag or the total thrust needed, is made up of two parts. At the low end, the thrust needed is to overcome induced drag, the drag due to lift (green curve). The high end is dominated by the thrust needed to overcome parasite or form drag, the drag of the airplane pushing air out of its way (red curve). The sum of the two drag curves give the total drag, or the thrust required curve. The lowest point on this curve is the point of best performance where half the drag is due to each of the two drag components.

Traditionally, the only way to reduce the total drag was to make the wings longer and thinner reducing the induced drag; or make the airplane more streamlined, improving the form drag. However, with IDEAL, the distributed propulsion offers other ways to modify this curve.

Distributed electric propulsion can be configured to blow air over the top surface of the wing so the air velocity seen by the top surface can be substantially higher than the actual velocity of the airplane[2]. Consider that for any airfoil; about 80% of the lift is generated by the increased airstream velocity over the top surface of the wing with the remaining contributed by the bottom surface pushing the air down. The faster this airstream over the top, the more lift is generated per unit area. In fact, the lift goes up as a function of the velocity increase squared. Thus, the wasted increase in airstream velocity from the propulsors can be well utilized to increase the lift on the wing.

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[2] In the words of Willard Custer, the inventor of the Custer Channel Wing: "It is the speed of the air, not the airspeed."

Distributed propulsion can positively impact the overall system performance by reducing the overall wing weight. Spanwise distribution is an effective way to provide wing load alleviation via wake filling, and effectively higher wing t/c, thus reduced wing root bending moments, and lighter weight. Less weight, same power, lower wing loading, additional STOL capability.

IDEAL distributed propulsion can be used to change the lift distribution of a wing such that the normal drag penalties associated with podded interruptions (such as motors) are negated,

Even more important, the induced drag is greatly reduced. In fact, the induced drag is reduced in proportion to the ratio of the top surface airstream velocity to the free stream velocity to the fourth power. This dramatic effect has been demonstrated both analytically and experimentally.

High induced drag is also largely due to high angle of attack at low speeds to generate lift. Distributed blown surfaces however provide relative high speed flow, thus do not require high angle of attack, and as such can reduce induced drag. This flow can be provided in several configurations.

Induced drag is also seen as high pressure flow formed at tips. This causes vortices that can be reduced in their effect by using tip thrusters, part of the distributed system to improve overall lift distribution.

To see how these effects can drastically change the thrust required for flight, reconsider Figure 8. In Figure 9, as before, the blue line is the stock aircraft showing high drag (i.e. high needed thrust) at take-off and cruise velocities. By adding a minimal upper surface blowing (the red line), the needed thrust at low speed is dramatically reduced due to the reduction in induced drag.

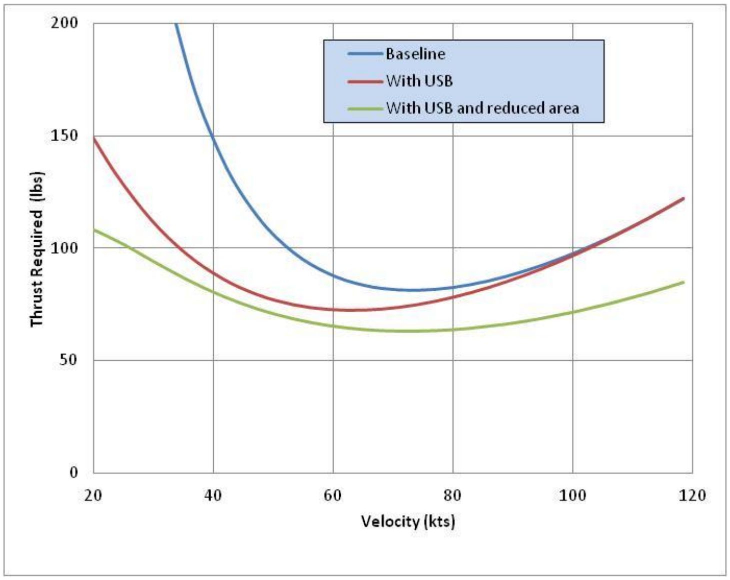

Figure 9: The IDEAL thrust - velocity relationship

While useful at takeoff and landing the distributed IDEAL system can cause elevated drag during the often much longer cruise segment. To gain reduction at higher velocities the area of the wing can be reduced combined with upper surface blowing and the green line can be achieved. This clearly shows less power needed at all velocities and flight at very low, near VTOL velocities.

Recent wind tunnel tests and analysis have shown lift coefficients > 10, even without the use of flaps. With the addition of flaps, much high lift coefficients are possible.

Propulsion airframe integration (PAI) used in IDEAL is not a new concept, but one that is made practical by the use of DEP. In the past it has been tried with two propellers (e.g. the Custer Channel wing in the 1950s, Figure 10), two jet engines (the Boeing YC-14 in the 1960s, Figure 11) and with four jet engines (NASA's QSRA in the 1970s). In fact, the QSRA could achieve a lift coefficient of 10[14]. These earlier efforts only provided improved aerodynamics over a small portion of the wing upper surface as they did not have distributed capability. Further, the Boeing and NASA efforts used jet turbine engine exhaust air to enhance the aerodynamics. The very high velocity, very hot and extremely concentrated air made managing the aerodynamics difficult.

Figure 10: The Custer Channel WIng

Figure 11: The Boeing YC-14

With distributed electric propulsion, the success of these programs can be greatly leveraged with well distributed, near ambient temperature flows. One of the goals of this paper is to explore that promise in comparison to that of rotor-craft and VTOL vehicles.

The State of and Promise for Electrical Energy Storage

This paper addresses only battery powered aircraft. As described above, the XV-24A "Lightning Strike" is a hybrid relying on a gas turbine to provide electricity for DEP. Hybrid aircraft have a small engine that can produce enough power for cruise and use energy storage for supplemental power during take-off, altitude change and emergency situations. However, the vision being pursued by UBER and others - a vision to not use fossil fuels - relies solely on battery power, so that is the focus here.

Here batteries are characterized by their energy density (ρ_b) in watt hours per kilogram (wh/kg), and battery energy capacity (Ec) in kw-hrs. Three different levels of energy density are considered:

- Current Reality - 150 wh/kg
- Near term - 300 wh/kg
- Far future possibility - 600 wh/kg

These three levels span what is commonly considered as realistic.

The battery energy capacity (Ec) is treated as variable in the model developed below. Note that the two battery variables combine to give the weight of the batteries, Wb = Ec/ ρ_b.

There are other forms of energy storage that are not based on chemical batteries. Some of these have the potential for specific energy of 750 wh/kg or better with remarkably low system penalties for safe public use and acceptance. A battery is part of a system including controllers and other infrastructure. Further, not all the energy in a battery can be used. Naïve optimism or casual ignorance of these battery installation issues (50% efficiency losses, mass subsystem growth) can doom commercially viable integrations. Alternatives are evolving.

Model Used

The goal of this study is to develop a relatively simple model to compare and contrast the various classes of sky taxi vehicles: rotor-craft, VTOL and USTOL. As with any comparison, many assumptions need to be made, but efforts were made to keep assumptions to a minimum and clearly state them. Further, a later section of this paper is a what-if analysis that relaxes the assumptions to explore how the conclusions might change if the assumptions are wrong.

The model is designed to identify:

- Range
- Weight
- Needed thrust and power
- Cost per a vehicle

The model is driven by four input values:

- Aircraft class
- Battery energy density
- The battery size in kilowatt hours
- The number of passengers

With these four independent variables, fairly accurate predictions can be made about the potential for each aircraft class without detailing the exact configuration of any aircraft.

Assumptions

The following assumptions have been made. Whenever possible they are consistent with McDonald and German's model so that comparison between the results of the two studies can be easily made.

- Cruise velocity (mph/fps/kts) =150/220/130
  These values are those used by McDonald and German. Seeley assumes 121.5 mph (105 kts) cruise in his papers. UBER suggests that 150-200 mph is desirable for VTOL aircraft.
- Cruise altitude (ft/m) AGL = 1000/305
  FAR 91.119 requires 1000ft AGL over any congested area. This is the altitude used by McDonald and German, however, the UBER paper keys on 500 ft which seems too low for noise reasons.
- Time to climb, based on 500 ft/min climb rate = 2 minutes
  This is a common climb rate that is fast enough to get to altitude yet not so fast that it might be objectionable to passengers. However, this value is probably too low. See the section titled "Ground and Air Space" for more realistic values. Assuming a low time to climb does not affect the comparative results.
- Electrical and propulsor efficiency = 0.76
  McDonald and German suggest a propulsor efficiency of 0.85 for cruise and climb and an electrical system efficiency of 0.9. These two values seem reasonable, thus 0.85 x 0.9 = 0.76 is used. Installation features can reduce this efficiency factor considerably.
- Airframe weight fraction including motors and controllers = 55%
  This is the percentage of the total weight required for the airframe, Wa/Wo. For this study it does not include the weight of the batteries, but does include any motors, wiring and controllers. Composite GA aircraft without engines have a weight fraction = 0.44. McDonald and German used 0.55. They assume 5000 lb vehicles. This is optimistic and is definitely a function of the systems as a whole. Typically, this will be more like 60% to 65% to accommodate commercial safety, noise, as well as battery margins. Sensitivity to this assumption is addressed below.
- Passenger and luggage weight (kg/lb) = 100/220
  Note that, the pilot, if any, is considered a passenger.
- Factor Of Merit = 0.7
  This is a measure of rotor efficiency – the actual power/ideal power. FOM = 0.7 is a typical value for rotor-craft and VTOLs, and is used by McDonald and German.
- Hover time (sec) = 60
  Both rotor-craft and VTOL need to hover during take-off and landing. McDonald and German assumed 30 - 120 sec. Sixty seconds seems a good compromise. The sensitivity to this assumption is studied later.
- Reserve time (min) = 10
  FAR Part 91 Section 151 requires 30 minutes reserve for VFR day flights and 45 minutes at night. Since sky taxis will be operating in an urban setting, this is extensively long. McDonald and German assume 120 seconds for climb, 2 nm for diversion and 120 seconds to land. Here we assume 10 minutes as optimistically reasonable.

- Percent battery capacity available= 80%
  This is the value used by McDonald and German and seems reasonable for modern batteries. However, there is evidence that this may be too high in practical application and the reality is closer to 60% with 20% off the top for battery life and 20% off the bottom for safety.
- Battery cost ($/kwh) Currently Li-ion batteries cost about $200/kwh. In the near term future this may come down to $100/kwh.

Further, to make the comparison possible, three additional pieces of information are needed for each class:

- Lift-to-drag ratio for climb (L/D_{climb}).
- Lift-to-drag ratio for cruise (L/D_{cruise}).
- Disk Loading (DL) for rotor-craft and VTOL vehicles.
- Thrust to Weight ratio (T/W).

The values assumed are summarized in Table 1, followed by justification for them. Further, sensitivity to these assumed values is studied later.

Class	L/D Climb	L/D Cruise	Disk Loading (lb/ft^2)	Thrust /weight Ratio
Rotor	4.25	4.25	4.5	1.25
VTOL	7.5	10	15	1.25
USTOL	17.5	15		0.34

Table 1: Assumed aerodynamic values

For rotor-craft and VTOL energy is used for hovering and this is a function of the disk loading. McDonald and German used a disk loading value of 4.5 for multirotor-craft. The EPSAROD electric helicopter has a calculated DL of 2.6 and the Ehang has 4.3 - 8.6 depending on how you account for the stacked rotors. Thus, a value of 4.5 was used here and the sensitivity to this addressed later. Finally, both rotor-craft and VTOL airplanes need thrust greater than their weight to vertically climb out of hover. A 25% margin is commonly considered hence the 1.25 thrust to weight ratio. Some think this ratio is too small.

For VTOL, the cruise lift to drag ratios are similar to conventional aircraft (L/d_{cruise} = 15). McDonald and German used 14 for tilt-rotor-craft and slightly less for tilt-wing configurations. There are no good sources of L/D values for climb so the value of 10 seems generous. The disk loading for VTOLs can range from DL= 15 ((tilt wing) to 40 (tilt rotor) according to McDonald and German. In the simulations here, DL =15 is used as it shows the best performance for VTOLs with the effect of higher values shown in the section on sensitivity.

USTOLs are a class under development. They are characterized by high cruise L/D ratios since they can have smaller wing areas (lower cruise drag) while showing very short STOL performance due to IDEAL. The values in the table above are best estimates of the potential based on theory, past test vehicles and recent (unpublished) wind tunnel testing. These values are relaxed in the sensitivity section.

Model Logic

The modeling goals are to find the weight, range, needed thrust/power, and cost for a specific configuration. The model is based on calculating weight fractions, the percentage of the gross weight required by each element of the aircraft. This technique is commonly used in aircraft design and is tailored here around finding the fraction of the battery weight needed for the various necessary mission segments (e.g. climb and reserve) with an effort to find the battery weight fraction available for cruise. This in turn determines the configuration's range based on the batteries and number of passengers.

The equations used are all relegated to a separate document available on-line (Ref 6). Note that this model is driven by assuming battery density and capacity (the size in terms of kilowatt hours) from which the battery weight and cost can be estimated along with range. The variables input and calculated are shown in Figure 12.

For a specific (i.e. input) class of aircraft, battery energy density, battery capacity and number of passengers, the logic is as follows:

Step 1: Based on the input values find the gross weight of the aircraft.
Step 2: Calculate the battery weight fractions for taxi/take-off, hover, climb, descent, landing and reserve (note that the battery weight fraction for cruise is not included here).
Step 3: Find the battery weight fraction for cruise.
Step 4: Calculate the range.
Step 5: Calculate the needed maximum thrust and power.
Step 6: Estimate the aircraft unit cost.

Each step is discussed here and detailed in Reference 6.

In Figure 12 the variables in the model are grouped and color-coded to note their role in the model. As shown in the legend, the light purple are general assumptions while the dark purple are VTOL rotor-craft specific. The light green variables are the input or independent factors used to drive the model. The ivory and orange variables are calculated with those in orange focused on as results.

Step 1: Based on the input values find the gross weight of the aircraft.

Regardless of aircraft class, the gross weight can be estimated as a function of the battery energy density in wh/kg, battery capacity in kwh and number of passengers.

The gross weight is composed of the weight of the airframe, total weight of the batteries and the weight of the passengers. Here, the airframe includes the engines and controllers, everything but the passengers and batteries.

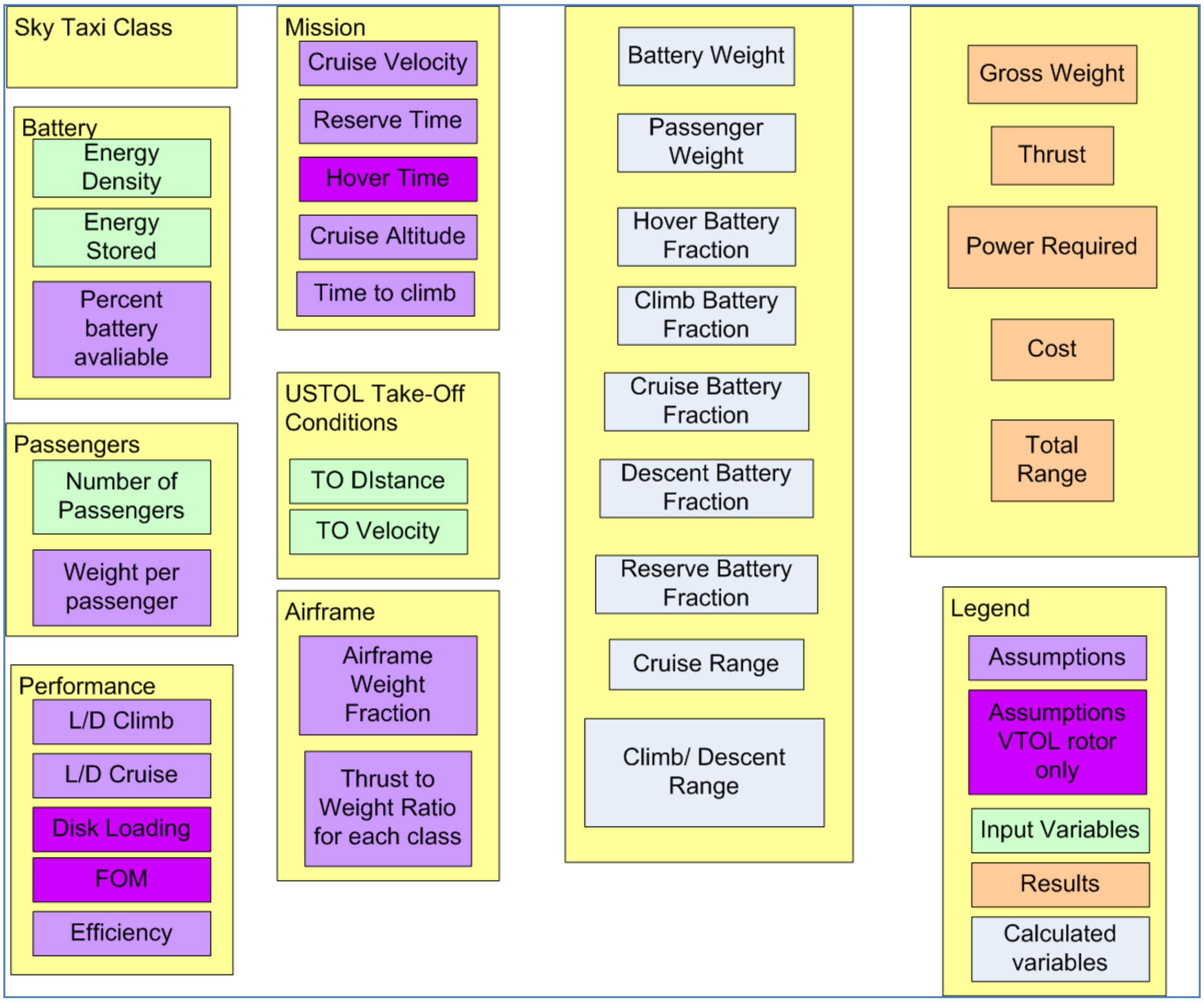

Figure 12: The model variables

Step 2: Calculate the battery weight fractions for taxi/take-off, hover, climb, descent, landing and reserve

The battery's energy is used to power the many segments of the aircraft's mission. The total weight of the battery is composed of:

- Battery weight for taxi and take-off (for USTOL)
- Battery weight for hover during take-off (for VTOL and rotor-craft)
- Battery weight for climb
- Battery weight for cruise
- Battery weight for descent
- Battery weight for hover during landing (for VTOL and rotor-craft)
- Battery weight for landing and taxi (for USTOL)
- Battery weight reserve.

Each of these is briefly discussed here with the exception of cruise which is discussed in the next section. The analysis is actually based on weight fractions, the percentage of the gross weight required for each mission segment. Details on the battery weight fraction derivations are in Reference 6.

The battery weight fraction for taxi and take-off only applies to the USTOL class of sky taxis. While battery energy is used during this phase, the weight fraction (the part of the battery weight used during this phase) is very small, < 1%. So, the weight fraction for taxi and take-off is treated as zero for all sky taxi classes as is that for landing and subsequent taxi. The power needed for the take-off itself (the rate that the energy is extracted from the battery) varies with take-off distance and is discussed in Step 5.

The battery weight for hover (for VTOL and rotor-craft) is dependent on the time for hover, the disk loading, the Factor of Merit and the battery energy density. In the assumptions the disk loading for VTOL was taken as 15 lb/ft^2 consistent with McDonald and German's value for tilt wing or tilt rotor configurations. In the sensitivity analysis below, the effect of changing the disk loading can be seen.

The battery weight fraction needed for climb can be reduced to a direct function of the climb lift to drag ratio (L/D_{climb}) and battery energy density. The higher the climb L/D, the lower the weight fraction needed as expected. The same holds for descent except the L/D was assumed to the same as for cruise.

The battery weight for reserve is based on the need to provide a reserve time aloft. It is assumed that this reserve is used to fly to an alternate airport at cruise conditions. Thus the cruise L/D ratio is used at the cruise velocity.

Step 3: Find the battery weight fraction for cruise.

Since the total battery weight fraction is known from Step 1 and the battery weight fractions for all mission phases except cruise are found in Step 2, the difference is the cruise battery fraction. If positive there is sufficient battery for time at the cruise altitude and velocity. If negative, then the mission cannot be accomplished.

Step 4: Calculate the range.

The range is the sum of the climb, descent and cruise ranges. The climb and descent ranges can be easily found from the cruise velocity and time to climb. As mentioned earlier, a 500 ft/min climb rate has been assumed and, with the cruise velocity of 150 mph, the distance covered during climb and descent is 2.5 miles each for all classes of sky taxis.

The cruise range, assuming a positive cruise battery weight fraction, is a function of the percent battery capacity available, the battery energy density, the cruise L/D, and the electrical and propulsor efficiency. The higher each of these is, the longer the range.

Step 5: Calculate the needed maximum thrust and power.

The needed maximum thrust needed is a direct function of weight for all classes of vehicle. It is substantially less for USTOL than for rotor-craft and VTOL as explained in the assumptions.

The maximum power for VTOL and rotor-craft is that used to hover and is a function of the weight, Figure of Merit (FOM) and Disk Loading (DL). For USTOL the maximum power required is that needed for take-off acceleration. The shorter the take-off run, the more power needed.

Step 6: Estimate the aircraft unit cost.

The cost estimate was made using standard general aviation cost estimation methods from Gudmundsson[15] plus an estimate on the cost of batteries. The former is dependent solely on the gross weight. While Gudmundsson provides equations to estimate many different cost factors, only those for material and manufacturing have been included here. It is assumed that any error with these estimates is uniform across all the classes of aircraft considered.

The cost for the batteries is based on the calculated weight of the batteries and the assumed cost per kwh discussed earlier.

Results

For each sky taxi class, and each combination of battery densities and number of passengers (1 - 3), the model was run across a range of different size batteries (the kwh stored). The class, battery density and number of passengers are indicated in a short-hand notation as, for example, VTOL- NF-3, is a VTOL craft with Near Future Batteries and 3 passengers.

For each run the gross weight, total range, thrust required, maximum power required and cost was calculated. For example, the range for a USTOL with 2 passengers is shown in Figure 13 for two different battery densities, Current (150 wh/kg) and Near Future (300 wh/kg). Note that as the size of the batteries increases so does the range. A currently available 120 kwh battery weighs 800 kg (1760 lbs) and the gross weight of the aircraft needed to carry it is 2000 kg (4400 lbs). This is very large for a 2 passenger aircraft.

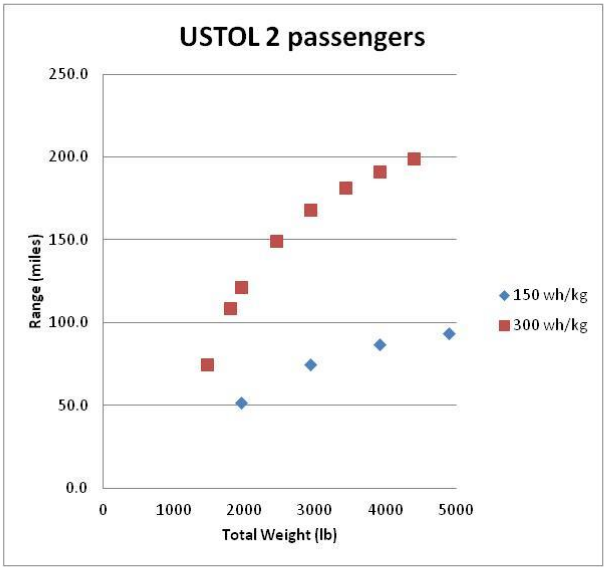

Figure 13: USTOL range with 2 passengers

A representative sample of the results is shown in Table 2. For each aircraft class and number of passengers, the result shown in the table is a compromise “best case”. A judgment was made based on total weight and range achieved with eye on lighter-is-better. The gross weight was capped at 5000 lb (2272 kg) as this was considered to be a very large and expensive aircraft. Anything larger requires unrealistically big batteries (>1500 lb (700 kg). Note that all VTOL craft were limited by this cap as were some rotor-craft. UBER is only considering 5000 lb VTOL vehicles. The results here show they must look only at these larger vehicles to achieve useful range.

Range versus gross weight is shown on Figure 14. The green lines show a range of USTOL aircraft with near-future batteries (300 wh/kg).

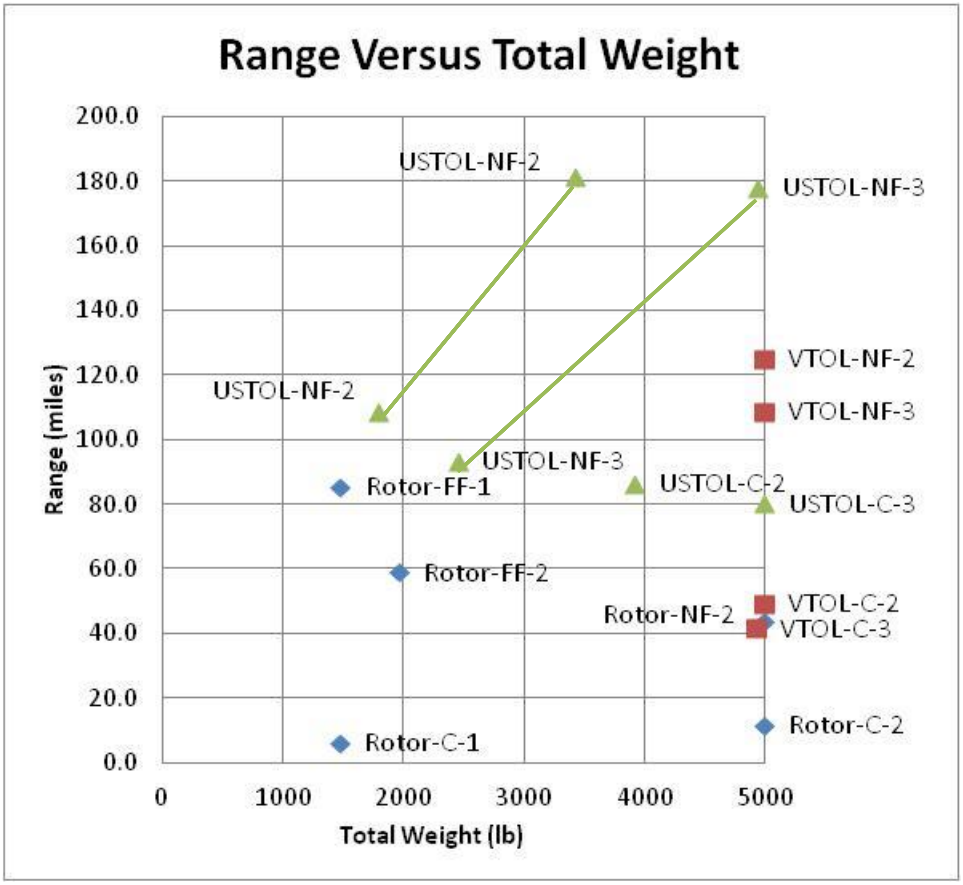

Figure 14: Range versus total weight

Observations based on these results follow the table on the next page. Do note that the sensitivity of them is addressed in the next section of this paper.

Config.	Type	Battery	Pass	Total weight (lb/kg)	Range (mi/km)	Thrust Req (lbs / kg)	Max Power (HP / kw)	Cost k$
Rotor-C-1	Rotor	Current 150 wh/kg	1	1467 / 667	6 / 10	1833 / 833	57 / 43	183
Rotor-FF-1	Rotor	Far Future 600 wh/kg	1	1467 / 667	86 / 138	1833 / 833	57 / 43	201
Rotor-C-2	Rotor	Current 150 wh/kg	2	5000 / 2272	12 / 19	6233 / 2833	195 / 146	442
Rotor-NF-2	Rotor	Near Future 300 wh/kg	2	5000 / 2272	44 / 70	6233 / 2833	195 / 146	499
Rotor-FF-2	Rotor	Far Future 600 wh/kg	2	1956 / 889	59 / 95	2444 / 1111	77 / 57	243
VTOL-C-2	VTOL	Current 150 wh/kg	2	5000 / 2272	49 / 74	6233 / 2833	195 / 146	496
VTOL-NF-2	VTOL	Near Future 300 wh/kg	2	5000 / 2272	125 / 202	6233 / 2833	195 / 146	500
VTOL-C-3	VTOL	Current 150 wh/kg	3	5000 /2272	42 / 67	6152 / 2796	193 / 144	485
VTOL-NF-3	VTOL	Near Future 300 wh/kg	3	5000 /2272	109 / 176	6254 / 2842	196 /146	497
USTOL –C-2	USTOL	Current 150 wh/kg	2	3911 / 1777	87/139	1067 / 485	100 / 74	374
USTOL –NF-2	USTOL	Near Future 300 wh/kg	2	1793 / 815	109/175	489 / 222	46 /34	210
USTOL –NF-2	USTOL	Near Future 300 wh/kg	2	3422 / 1555	181/292	934 / 424	87 / 65	346
USTOL -C-3	USTOL	Current 150 wh/kg	3	5000 / 2272	80/130	1361 / 618	127 / 95	473
USTOL -NF-3	USTOL	Near Future 300 wh/kg	3	2444 / 1111	94/151	667/ 303	62 / 46	264
USTOL -NF-3	USTOL	Near Future 300 wh/kg	3	5000 / 2272	178 / 287	1348 / 613	126 / 94	451

Table 2: Representative results

Range Observations:

Current batteries (150 wh/kg) and 2 passengers (XXXX-C-2):

- VTOLs have range of less than 50 miles (70km) with 5000 lb (2272 kg) aircraft. (VTOL-C-2)
- USTOLs can achieve 87 miles (139 km) with 3911lb (1777kg) vehicle. This aircraft will need 1320 lb (600 kg) batteries (not shown). (USTOL-C-2).
- Rotor-craft have a range of 12 miles (19 km) and require very high thrust and power. (Rotor-C-2).

Near Future batteries (300 wh/kg) and 2 passengers (XXXX-NF-2):

- VTOLs can achieve 125 miles (202 km) with a 5000 lb (2272 kg) vehicle. This will require 1804 lb (820 kg) of batteries. (VTOL-NF-2).
- USTOLs can achieve 109 miles (175 km) with a 1793lb (815 kg) vehicle, or 181 miles (292 km) with a 3422 lb (1555kg) vehicle. (USTOL-NF-2). Note that the battery weight increases from 367 lb (167 kg) to 1100 lb (500kg) to get the added range. A green line on the plot shows a range of vehicles in between these two.
- Rotor-craft are limited to 44 miles (70 km) (Rotor-NF-2).

Current batteries and 3 passengers (XXXX-C-3):

- VTOLs have a range 42 miles (74 km) for a 5000 lbs (2272 kg) vehicle (VTOL-C-3).
- USTOLs can achieve 80 miles (130 KM) (USTOL-C-3).

Near Future batteries (300 wh/kg) and 3 passengers:

- VTOL can achieve 109 miles (176 km) with a 5000 lb (2272 kg) vehicle. (VTOL-NF-3).
- USTOL can achieve 178 miles (287 km) with a 5000 lb (2272 kg) vehicle (1540 lb in batteries). At half the vehicle weight the range is 94 mi (1151 km). (USTOL-NF-3). A green line on the plot shows a range of vehicles in between these two.

VTOL in general (VTOL-XX-X)

- VTOLs require vehicle weights >5000 lb (2272 kg) for Current and Near Future batteries flying 2 or 3 passengers.

Rotor-craft in general (Rotor-XX-X)

- Only Far Future batteries (600 wh/kg) give useful range for these craft.

USTOL in general: (USTOL-XX-X)

- For all cases USTOL has range significantly better than the other classes.
- For all cases USTOL requires about one half the power of the other classes.

General observations about range:

- VTOL aircraft are challenged when using Near Future batteries. They will need hybrid or other systems for electric energy at least for the near term.

- Rotor-craft like Ehang and Volocopter will always be very limited in range. It will take very large machines with Far Future batteries to achieve useful ranges.
- USTOLs have the potential to achieve ranges to over 20 miles with Near Future batteries.

Battery observations:

Battery weight fractions are not shown in Table 2, but in Figure 15. Here the hatching indicates the number of passengers. The results show:

- Battery weight fractions range from 17% to 36%. The battery weight is a sizeable proportion of the aircraft weight regardless of class.
- Only Near Future batteries can reduce the weight fraction below 20% and then only for USTOLs.

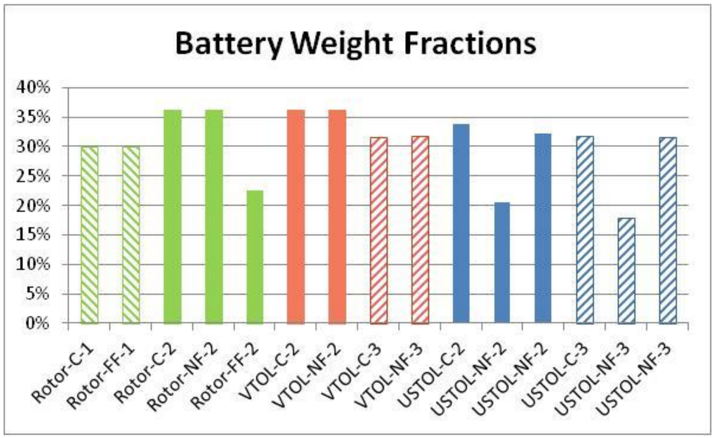

Figure 15: Battery weight fractions

Thrust and Power Observations:

As seen in Table 2:

- USTOLs require much less thrust of the other types of sky taxis as shown in the table. VTOL and Rotor-craft require Thrusts equal to 125% of their weight to lift off the ground. For the USTOLs the thrust and power are directly proportional to the take-off distance desired as a vast majority of the thrust goes to accelerating the mass of the aircraft. passengers and batteries. For these simulations a USTOL take-off distance of 150ft was assumed (see sensitivity analysis for the effect of distance).
- The power required for the 5000 lb (2,272 kg) VTOLs and the rotor-craft are in all cases about double that needed for USTOL. In fact, the weight penalty for higher power is not reflected in this model as the weight of motors and controllers is absorbed in the airframe weight fraction. If it had been included the range of the VTOL and rotor-craft would have been reduced further relative to USTOL.

Cost Observations:

Cost is proportional to weight and all the VTOLs and Rotor-craft need heavy vehicles to achieve significant range. In general, USTOLs are less expensive to manufacture than VTOLs and Rotor-craft.

Ground and Air Space

An important measure for comparing options is the amount of ground and air space needed for operations. While VTOL and rotor-craft offer the vision of very small ground footprints - taking off and landing on rooftops - it isn't that simple.

Sky taxis, regardless of class, will most likely be governed by current helicopter regulations, codes, advisory circulars and industry best practices; or their descendents. With this in mind and leveraging off the current visions for ski taxi operations a weak comparison of classes is possible.

Ground Space

The air taxi ports of the future will clearly be different from current airports and helipads. Exactly what form these "vertiports" (UBER) or "pocket airparks" (Seeley) will take is unclear. Under consideration is to place these ports on building tops, structures over throughways (travel plazas), on barges, on top levels of parking garages or high rises, mall parking lots and even in the non-used areas of clover leafs. Regardless of what they are called or where they are placed, some options can be compared sufficiently for this paper.

FAA Circular "Heliport design" [16] defines the ground areas needed for helicopter operations. These requirements have been used to design VTOL vertiports by Rex Alexander of HeliExperts International for the UBER Summit [17]. Based on current helicopter requirements each Touchdown and LiftOFf area (TLOF) is surrounded by a Final Approach and Takeoff Area (FATO) and further by a Flight Safety Area (FSA). Alexander assumed a 45' (13.7m) VTOL span since these will probably be multi-rotor machines. So, based on the FAA requirements the diameter of areas needed for each sky taxi pad is as shown in Figure 16.

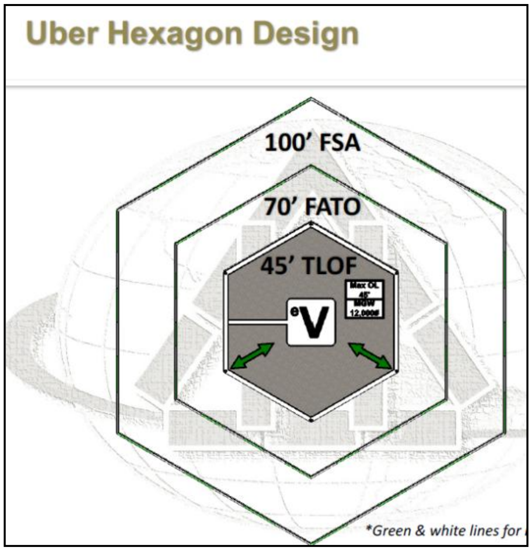

Figure 16: A vertiport operations footprint

For a full vertiport, at least one of these areas would need to be linked to parking areas for loading and unloading in some form. One such configuration proposed by Alexander (Figure 17) is to have multiple loading areas (in gray) connected to a single TLOF area as shown. Even without space for amenities like passenger lounges and auxiliary facilities, this configuration would require about 300' x 200' (90m x 60m) ground space. Many other proposed configurations are under consideration.

Seeley has spent much time designing pocket airports. Figure 18 shows one of his concepts complete with 13 docking stations for loading and unloading, and development of traffic flow. Note that the “rose” patterns on the diagram are part of his noise studies. The main runway is over 500 ft long which is greater than needed for a USTOL (see Sensitivity and Assumptions, USTOL). In fact, based on the analysis, a USTOL airport may be somewhat smaller than Seeley envisions.

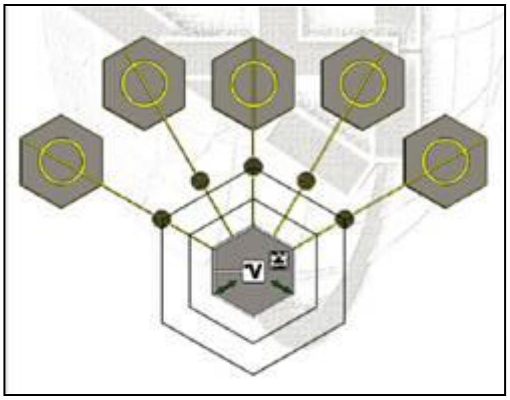

Figure 17: A proposed Vertiport

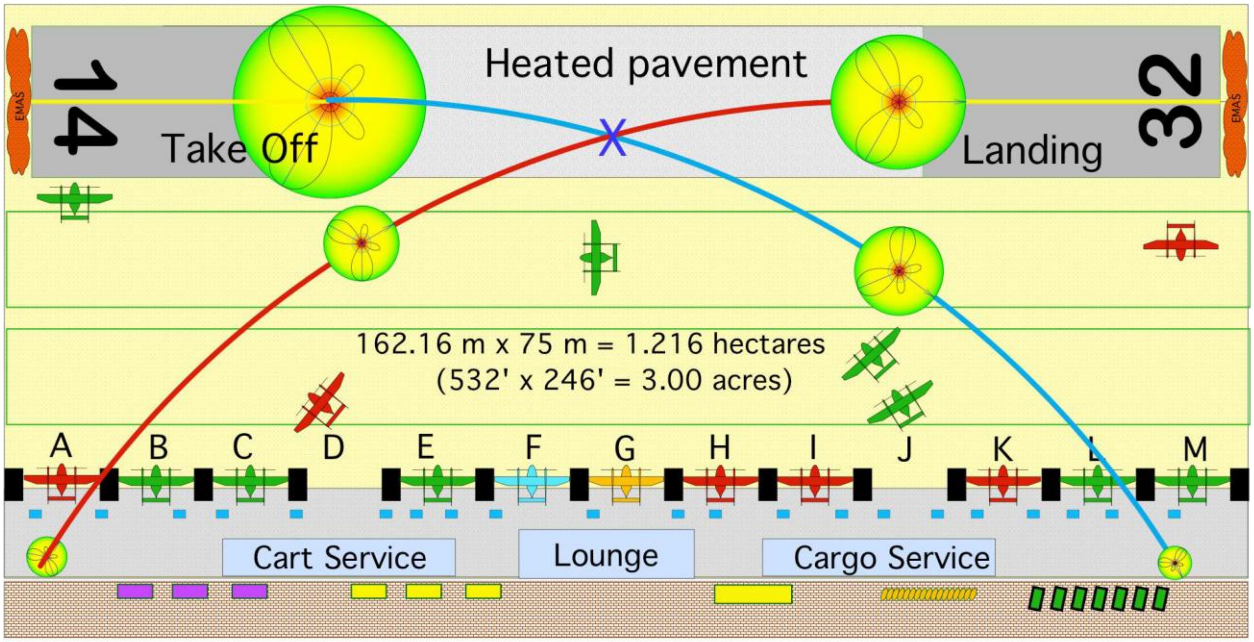

Figure 18: Proposed Pocket Airport

Both of these concepts are immature and there is clearly much more work to be done to define the needed ground space for air taxi operations. What is evident is that:

1. Regardless of configuration all types of sky-taxis will be hard pressed to be placed on building tops and other very small spaces. A minimal size ground space will co-evolve with the vehicles being developed.
2. The Ground space needed for USTOL operations, while larger than that for rotor-craft and VTOL, is not much greater. If the vertiport described above is expanded to handle thirteen docking stations, all surrounding the TLOF and passenger amenities added, to be comparable with the USTOL example, then the footprint of the vertiport would be at least 300’ x 375’ (90m x 114m) or 2.6 acres (1 hectares).

Air Space

The airspace around the air taxi ports of the future will similarly be based on current regulations and co-evolve with the development of the vehicles. The FAA Circular on heliport design AC 150/5390-2C specifies the approach/departure surfaces as shown in Figure 19. Here, the 500' (152m) altitude at 4000 ft (1220m) defines an 8:1 surface (7.1^o). Helicopters normal operation is above this surface with a 12^o glide slope and 15^o deemed "steep". It is safe to assume that rotor-craft and VTOL will at least be adhering to these values, at least initially.

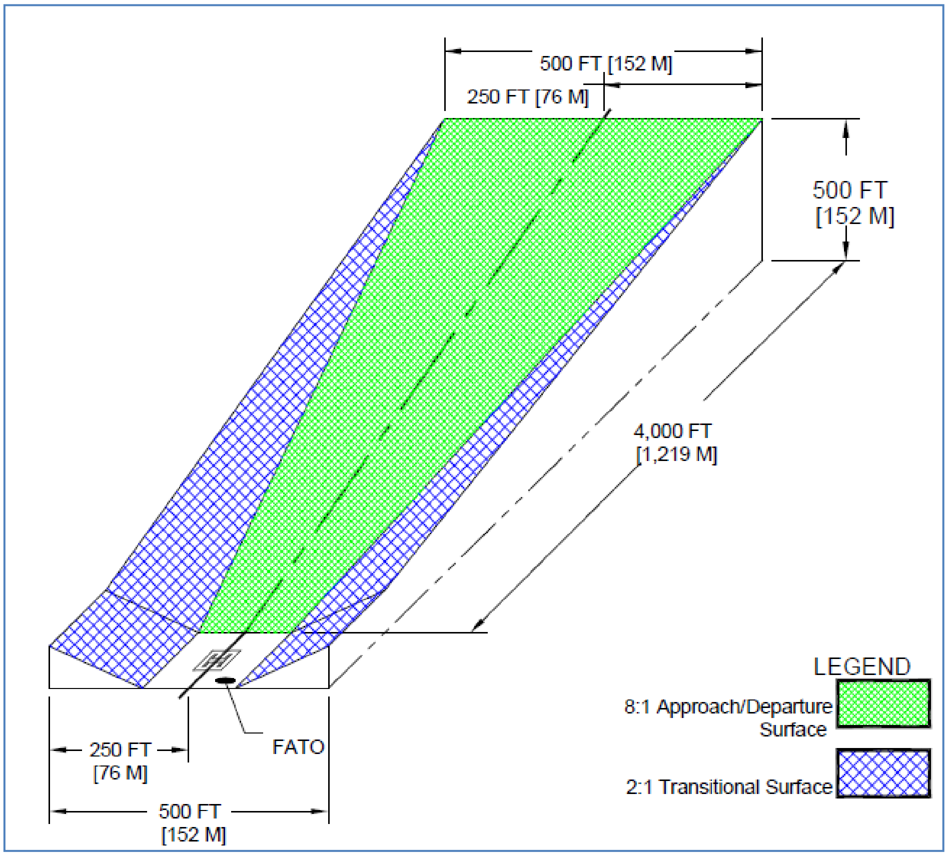

Figure 19: From Figure 2-7 "VFR Heliport Approach/Departure and Transitional Surfaces: General Aviation." AC 150/5390-2C

For comparison consider current STOL aircraft performance. A CubCrafters Carbon Cub(a two place STOL aircraft) has a 1500+ft/min climb rate at Vy = 71 mph (62 kts). This gives a climb angle of 13^o. It is expected that a USTOL could even perform better than this.

On landing, a Cessna 172 with the engine at idle and 40^o of flaps descends at about 10^o. The Boeing YC-14, a large STOL transport, achieved a controlled descent rate of 2500 ft/min (30 mps) resulting in a 23^o descent angle[18]. Further, CubCrafters tests to the FAA standard 3^o glide slope and that is all they publish. However, many pilots have demonstrated descent rates at over 2000 ft/min. At 60mph (52 kts) the XCub can descend at as much as 21^o. The velocity used is based on the published Vso = 46 mph and using the FAA mandated 1.3 factor for approach speed,

Ground and Air Space Summary

It is hard to predict the ground and airspace requirements for the different classes of air taxis. These will co-evolve with the aircraft and the FAA effort to ensure safety. What is clear is:

1. Vertiports will be larger than many envision. This precludes most roof tops and many parking garages.
2. Pocket airports for USTOLs will be larger than what is required for vertiports, but not by much.
3. Rotor-craft, VTOL and USTOL can all easily meet the current FAA heliport approach/departure surface requirement of 8:1 (7.1^o).

Confirmation of Model Fidelity

Since there are no sky taxis, the best that can be calculated is a relative fidelity to what is known. Here, comparison is made to existing information, both the models of others and what flight data there is. In some ways, confirmation is also found through the sensitivity to assumptions which is covered in the next section.

Comparison to McDonald and German's Model

Since many of the VTOL and rotor-craft assumptions were based on the work of McDonald and German, it is worth comparing the results here with those of their simulation:

- For rotor-craft with Near Future (300wh/kg) batteries and 4 passengers, McDonald and German found a range of 75 miles, the model here gives 95 miles. This result implies that the L/D ratios for rotor-craft used here are too generous.
- For tilt rotor VTOL with Near Future batteries and 4 passengers, McDonald and German found a range of 78 miles, the model here gives 87. Still acceptable with the model here being slightly more generous for VTOL aircraft.

Comparison to eHang

The Ehang 184, introduced earlier, is a rotor-craft. Data on it is murky as it is still under development. Best data shows:

- Gross weight 750 lb (340 kg)
- Batteries 140 wh/kg and 17 kwh
- One 100 kg (220 lb) passenger
- Cruise speed 55 ft/sec

The model over-estimates the total weight at 1083 lbs and gives a range of 15 miles. If the airframe weight fraction is lowered to 35% (from the assumed 50% for winged vehicles) then the weight estimate is 750 lbs and the range is 24 miles. This airframe weight fraction of 35% is not unrealistic as the Ehang is just a pod with rotors on stalks. The sensitivity to airframe weight fraction will be addressed below.

Comparison to EPSAROD

EPSAROD is an electrically powered helicopter. Without any change to the assumptions, the model gives:

- Weight = 2933 lbs (Actual 2500 lb)
- Battery weight fraction 37.5% (Actual 44%)
- Cruise time 33 minutes (Actual 30 min)

These are excellent comparisons for the only real data available.

All-in-all, for a relatively simple model, this is very good and can easily be used to assess different classes of air-taxis. Further, it can easily be extended for other sets of assumptions or technologies.

Sensitivity to the Assumptions

In the results shown in Table 2, the VTOL class of aircraft does not look very good in comparison to the USTOL potential. Obvious questions are; What if the assumptions are wrong? Will the VTOL look more promising? To explore these questions the L/Ds, disk loading, hover time and other assumptions on VTOLs will be varied, as will those for USTOL.

The configuration VTOL-NF-3 (near future batteries (300 wh/kg) and 3 passengers) will be used for this sensitivity analysis. UBER, in its original report proposed craft with 4 passengers, but in a presentation[19] at the UBER Summit in April 2017, a more optimum number of 3 passengers was found. A gross weight limit of 5000 lbs was put on each vehicle for this study as larger vehicles seemed unrealistic to the authors.

VTOL Sensitivity

Figure 20 shows the sensitivity of the range to changes in key assumptions about the base range in Table 1. Changing the L/D ratio for climb has a very small effect which is as expected as only a small portion of the mission is spent climbing. Changing the L/D for cruise by +50% (from 10 to 8 and 12) changes the base range of 82 miles to 130 miles and 59 miles respectively.

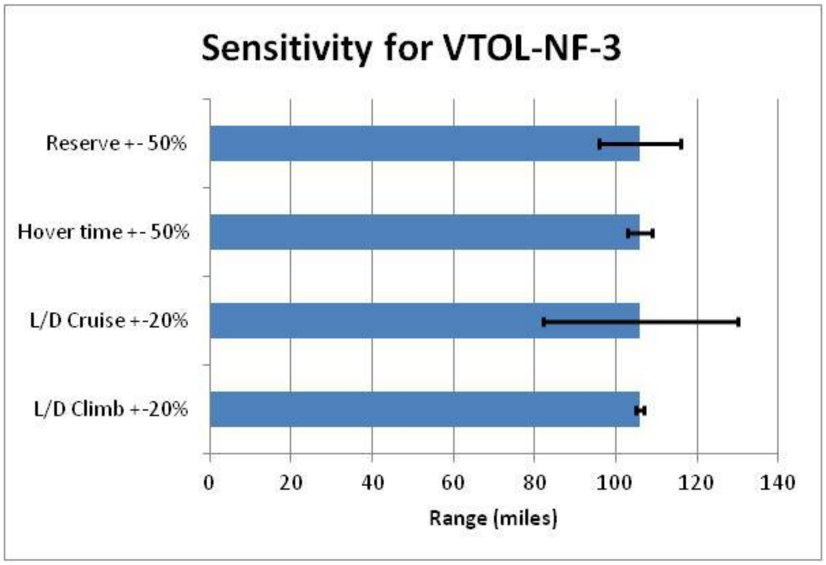

Figure 20: Sensitivity analysis forVTOL-NF-3

Hover time for the base case is 60 seconds after take-off and before landing. Raising this by 50% (90sec) or lowering it to 30 sec only changes the range by + 3 miles.

Finally, raising the 10 minute reserve to 15 minutes reduces the range by 10 miles, lowering it to 96 miles, and lowering the reserve to 5 minutes raises the range by 10 miles to 116 miles.

Another look at sensitivity can be had by varying the size of the battery. In Figure 21 the kilowatt hours for the batteries is varied. As can be seen in the plot, smaller batteries result in smaller vehicles with shorter range. To achieve a 106 mile range (the base case) requires 1580 lb (720 kg) of batteries. Reducing the size of the batteries rapidly kills the range. This plot clearly shows the relationship between the size of the battery and gross weight of the aircraft. Doubling the size of the battery from 100kwh to 200 kwh increases the gross weight of the aircraft by 53% (from 3096 lb to 4726 lb).

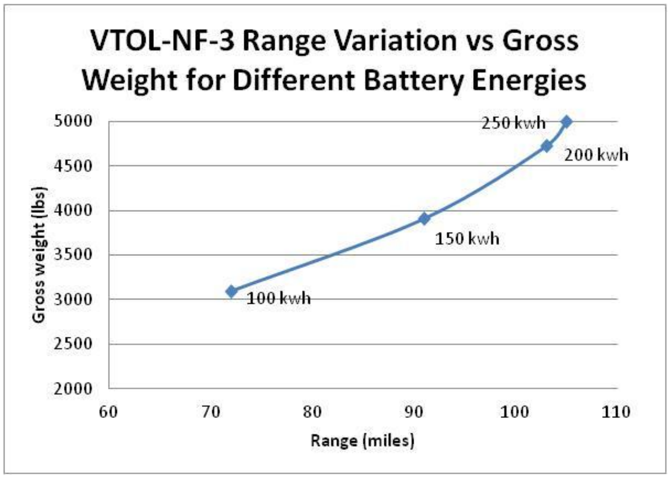

Figure 21: Sensitivity to battery size

The assumed thrust to weight ratio (T/W =1.25) for VTOLs may be too low. It has been suggested that values of 1.35-1.5 due to ground effects, suck-down, thrust recovery, yaw recovery, and other factors) may be more accurate. Changing this will have a secondary effect on range and gross weight in that it mainly affects the thrust needed and thus more power (T/W), more weight, more energy, and more noise. A value of

1.25 was used in the model. An increase in T/W of 10% will increase the needed thrust by 10%.

The model has no mechanism for reflecting how this will affect gross weight, range or cost. However, batteries with good energy characteristics will usually have poor power features. Using batteries designed to provide energy for high power consumption will result in faster battery drain, and hurt battery life cycle raising the costs for more frequent battery replacements.

USTOL

A similar study can be done for USTOL. Here the obvious question is: What if the L/D ratios assumed cannot be achieved? Figure 22 shows what happens if the base assumption of the L/D for cruise (15) is reduced to as low as 10. While the range is significantly decreased, it is still higher at 120 miles than that of the VTOL with similar passenger carrying capability (106 miles). Thus, the USTOL range, even if the L/D is not as good as is hoped is still superior to that offered by VTOLs.

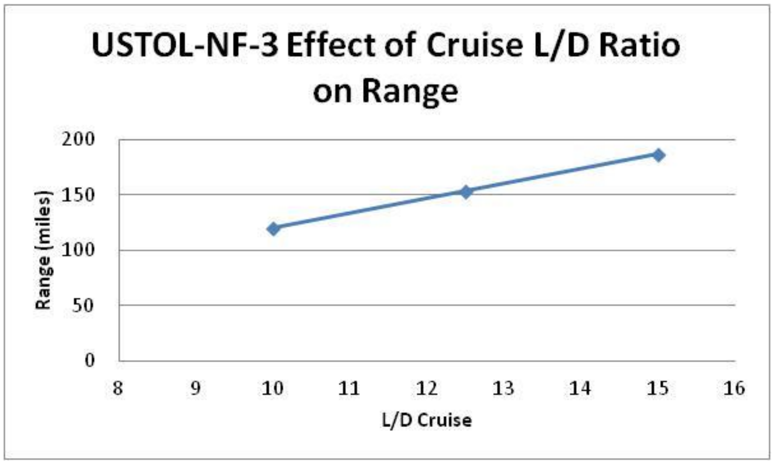

Figure 22: USTOL sensitivity to L/D ratio

The battery size sensitivity is shown reduced from its base value in the plot on the right. The gross weight of the aircraft and its range is represented. A 50kwh battery (24% the size of the base 210kwh) results in a 2000 lb aircraft which has a range of 93 miles. This is nearly equivalent to the 5000 lb VTOL with 250 kwh batteries.

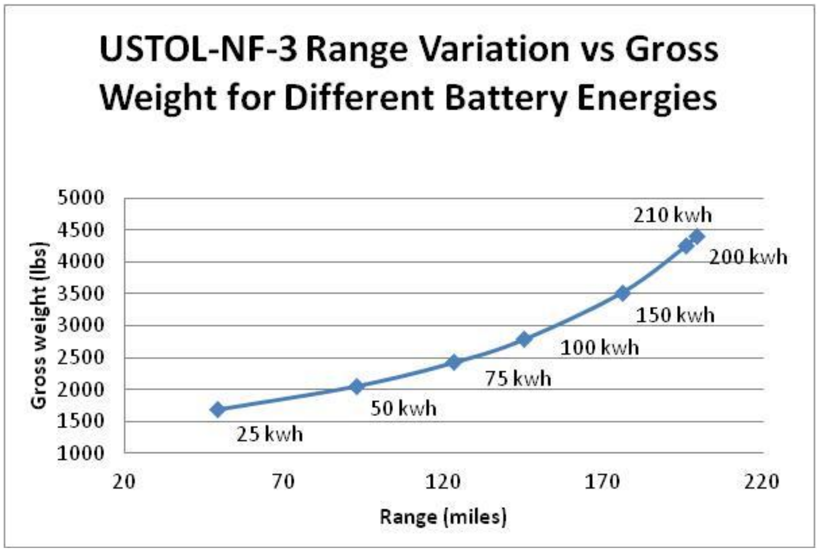

Figure 23: USTOL sensitivity to battery energy stored

While the power for a VTOL or rotor-craft is directly proportional to the vehicle weight, the power for a USTOL is directly proportional to the ground roll distance as seen in Figure 24. While the power required does not affect the battery weight, it does affect the size of the motors, wiring and controllers which is not taken into account here. Further, the use of wheel motors could greatly improve the acceleration force alleviating some of the propulsion thrust needed. This is not accounted for in this study. What is clear is that USTOL can be built that can get off the ground in 100 ft or less requiring half the power of the VTOL even without wheel motors.

General Sensitivity

If the percent battery capacity and/or the electrical and propulsor efficiency are assumed too high (which they may well be) all the ranges estimated in this model will be reduced proportionally. In the development of these aircraft, these values are bound to decrease. If true, this further degrades the range of rotor-craft and VTOL faster than it does USTOLs.

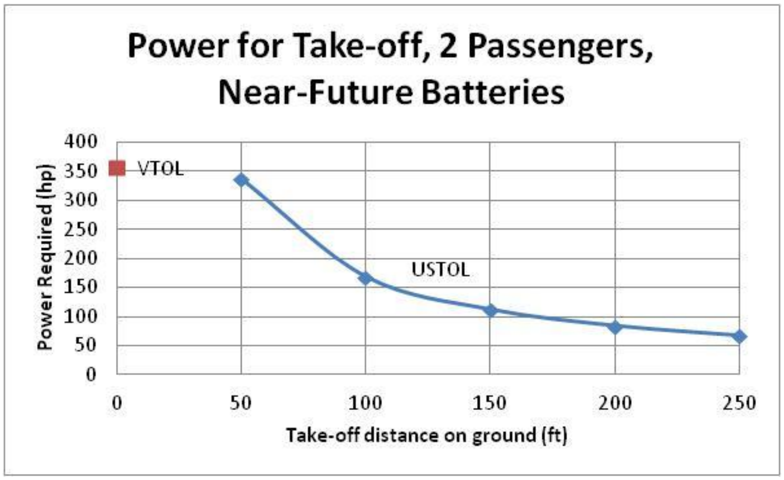

Figure 24: Power for Take-off

Conclusions

This study gives a basis for decisions and investments in the development of sky taxis. The development of sky taxis today is much like the development of the airplane in 1909, with many people trying many different configurations with the outcome unclear. Hopefully, this study has helped in giving some supportable evidence to the path forward. What has been shown here is:

1. It is possible to use a fairly simple model to compare and contrast different classes of air vehicles without getting caught up in the details.
2. Electric rotor-craft have very limited range. While the EPSAROD, an electric helicopter, has stayed aloft for 30 minutes, and the eHang 184 and Volocopter 2x have both made flights, the potential for significant range, even with the most optimistic, far-future batteries is in doubt. Further, their power to weight ratio is high indicating significant noise and energy efficiency issues.
3. VTOL aircraft need to be very large to be effective. UBER studies assumed 5000 lb (2,272 kg) vehicles. As shown here, for sky taxis of this size, Near Future batteries (300 wh/kg) are needed to achieve ranges of more than a few miles. Further, the high power needed, as with the rotor-craft, imply inefficiencies that may not be overcome. We find it interesting and curious that UBER has focused solely on the large VTOL aircraft.
4. USTOL aircraft have high potential. They are perhaps the least developed of the three classes considered. While studies going back into the 1950s have been made on the interaction of propulsion and aerodynamics, the advent of DEP gives this technology new life. Current STOL aircraft that almost meet the sky-taxi needs are in production by companies like CubCrafters. Leveraging PAI with

these lighter craft can possibly produce sky-taxi configurations more rapidly than is possible with the other classes and result in aircraft that are lighter and more realizable. This is the IDEAL that the authors are studying.

5. Clearly the use of batteries for air taxis is problematic. Other forms of energy storage need to be explored and developed.

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