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Critique of Battery Powered Flying Cars

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Flying car advocates are very excited about the attention that battery powered drones have brought to the concept of a VTOL capable flying car. However, the version that most enthusiasts have in mind is a VTOL capable aircraft that can land anywhere with the utility of the automobile. This version includes private ownership and operation from one's home or available curbside near their home. Flying cars powered by state-of-the-art batteries will not be able to provide this capability because of design constraints imposed by a power source with 5% of the energy per lb. of engines.

The first consideration for both winged and wingless versions is how to minimize the power required to takeoff vertically. The best way to accomplish this is to maximize the effective swept area of the propellers (A_{eff}) since power is directly related to the square root of the disc loading (W/A_{eff}). This can be accomplished with a single large propeller (rotor) like the helicopter, or with a number of smaller propellers like the Ehang 184 with its eight counterrotating propellers or the Joby S2 with its twelve lifting propellers.

The second consideration is to minimize power during cruising flight. For the Ehang 184, power will drop by approximately 40%[i] as it reaches its cruising speed of 62 mph. Adding a long wing (high aspect ratio) allows the power to drop by 300%. However, battery power related constraints make both the wingless and winged flying cars unable to be transformed down to the footprint of automobile prior to landing. As a consequence, battery powered flying cars are likely to be used primarily as air taxis between vertiports.

This best-case analysis shows that the wingless Ehang 184 can achieve its design speed of 62 mph for 25 miles if the airframe, powerplant, and necessary ergonomics weigh 70% of the gross weight. For the winged Joby S2 the specified 200 mph speed and 200-mile range can be achieved if the airframe, powerplants, and ergonomics weigh 80% of the gross weight. Achieving these relatively high percentages (about 15% higher than helicopters and airplanes) would be challenging with existing battery energy (Wh/kg). However, by year 2020 when many air-taxi developers expect to enter the market, battery improvements should eliminate this differential.

Equations governing a flying car's power required and hence battery weight and range

The following equations govern the power required as a function of aircraft speed[ii]:

$$\text{Thrust} = \text{Drag} = \rho A_{eff}\left(V_j^2 - V_j V_0\right)$$

$$\text{Drag} = \left(\frac{C_L^2}{\pi AR_E} + C_{DW}\frac{A_W}{S}\right)W$$

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$$\mathrm{Power} = \mathrm{HP} = \frac{\rho A_{\mathrm{eff}}}{1100\eta}\left(V_j^3 - V_j V_0^2\right)$$

Where $C_L = {}^{W}/_{0.5\rho V_0^2 S}$ W = Gross weight, ρ = air density, η = energy conversion efficiency between battery and airstream, V_0 = forward velocity, V_j = exit velocity either downstream of the propeller or at the ducted fan exit, A_{eff} = swept area of propellers/2 or ducted fans exit area.

For V_0=0 the above equation reduces to $W = 35.7(\rho A_{\mathrm{eff}})^{1/3}(\mathrm{HP}\eta)^{2/3}$

The total energy available from the battery to airstream depends on four variables:

- Battery storage energy (Wh/kg) is a function of the battery chemistry required to tolerate a given discharge rate (W/hr.). Batteries in electric cars require a low discharge rate and can use a NCA battery with energy storage up to 280 Wh/kg. For a winged flying car like the Joby S2, if transition to cruising flight occurs in minutes at its initial 2.4C discharge rate followed by 1C during cruising flight, a NMC battery can be used with an energy storage capability up to 220 Wh/kg[iii]. For the wingless flying car like the Ehang 184, the discharge rate during transition will be 3C followed by cruising flight at 2C. In analysis of both the wingless and winged flying cars, the 220 Wh/kg battery energy is used.
- Propeller efficiency can exceed 90% for a winged flying car as in the Joby S2 where separate motors driving propellers are used to generate thrust. In the wingless Ehang 184, the lift/thrust propellers are operating in crossflow and the efficiency is likely to be closer to 85%.
- The electric motor efficiency for both the winged and wingless flying cars can approach 95% if the motor is designed specifically for the cruising flight conditions. In the case of the Joby S2, this is accomplished by having separate thrust motors/propellers designed to operate at the Joby S2's design cruise speed of 200 mph. For the Ehang 184, this suggests that the motors/propellers be designed to operate at a speed where power is a minimum. This is approximately 60% of the power for hover. For the Ehang 184 this minimum power is close to its specified cruise speed of 62 mph.
- Prior to reaching cruise speed, both the winged and wingless flying cars will experience a higher discharge rate from the battery. However, if the time to hover, clear the area, and transition to and from cruising flight and land in less than 2 minutes, the energy consumption for this short high discharge period can be included in the average battery discharge efficiency.

For wingless flying car $\eta = \eta_b \cdot \eta_m \cdot \eta_p = 0.93 \cdot 0.95 \cdot 0.85 = 0.75$
For winged flying car $\eta = 0.95 \cdot 0.95 \cdot 0.92 = 0.83$

Analysis of wingless Ehang 184 flying car[iv] (Best Case)

It is assumed that the time to takeoff, transition to cruising speed of 62 mph, and land requires 2 minutes. Data from helicopters during transition indicate that as speed increases, the power reduces to 60% of that for hover at the least power condition (very near 62 mph).

Hover power = 57.8 kW for two minutes

Cruising power = 34.7 kW at 62 mph

Where η = 0.75, ρ = 0.0627 lb./ft^3 (100°F day @ 5,000 ft. altitude)

A_{eff} = 43.3 ft^2, W = 748 lbs

Range = 25.7 miles where battery energy used is specified at 14.4 kWh.

This range and speed agree with Ehang specifications. With the 20% reserve required to protect the battery and 220 lb. payload, the battery will weigh 174 lbs. This would leave 354 lbs for airframe, powerplants, and the ergonomics needed to make the Ehang 184 commercially viable.

http://www.popularmechanics.com/flight/drones/a18865/ehang-184-fly-in-autonomous-drone/

Analysis of the <u>winged</u> Joby S2 flying car[v] (Best Case)

http://hiconsumption.com/2015/12/joby-s2-vtol-personal-electric-airplane/

Hover Power = 181 kW for two minutes. Cruising power at 200 mph = 62.9 kW.

Where S = 56.3 ft^2, A_w = 340 ft^2, C_{DW} = 0.004, AR_E = 16.3, η = 0.83, W = 2,000 lbs, ρ = 0.0627 lb./ft^3 (100°F day @ 5,000 ft. altitude), A_{eff} = 68.75 ft^2 (motor failed), Range = 200 miles.

If minimum retained battery energy is 20% for protection of batteries and 390 lb. payload, the battery energy capacity required is 75.5 kWh. With a battery energy of 220 Wh/kg, the battery would weigh 755 lbs. This would leave 855 lbs. for airframe, powerplants, and the ergonomics needed to make the Joby S2 commercially viable.

Battery Powered Flying Car Limitations

The Joby S2 and Ehang are state-of-the-art designs however, certain limitations were inevitable when batteries are the sole source of energy:

- The FAA will impose requirements that will compromise these best-case results for both the <u>winged</u> and <u>wingless</u> flying cars. For example, protection of some sort will be needed for personnel in this world of rotating propellers.
- Size of <u>winged</u> flying cars like the Joby S2 will limit their stowability, maneuverability, and the number of vertiports available in an urban environment.
- Neither the <u>winged</u> Joby S2 or <u>wingless</u> Ehang 184 are suitable for a broad range of personal useage.

- The winged Joby S2 appears able to fly at 200 mph for 200 miles. Achieving this range with existing batteries would be challenging in this design with its highly-articulated lift and propulsion systems, high aspect ratio wing, and retractable undercarriage.
- The wingless Ehang 184 appears able to fly at 62 mph for 25 miles. Since this was a best-case analysis, it will be challenging to achieve this range with existing batteries.

The energy available from batteries will improve and expand the role air-taxis play in future airborne transportation, however, the enormous difference in the energy available from batteries versus engines will continue to put limits on the performance of battery powered flying cars until a major breakthrough in battery energy storage occurs.

Hybrid Approach Expands Flying Car Performance and Utility

For some time into the future, a VTOL capable flying car with sufficient performance to personalize versus commercialize airborne transportation will need engines for aerodynamic flight supplemented by battery power during VTOL flight. This hybrid approach makes the following performance possible[vi]:

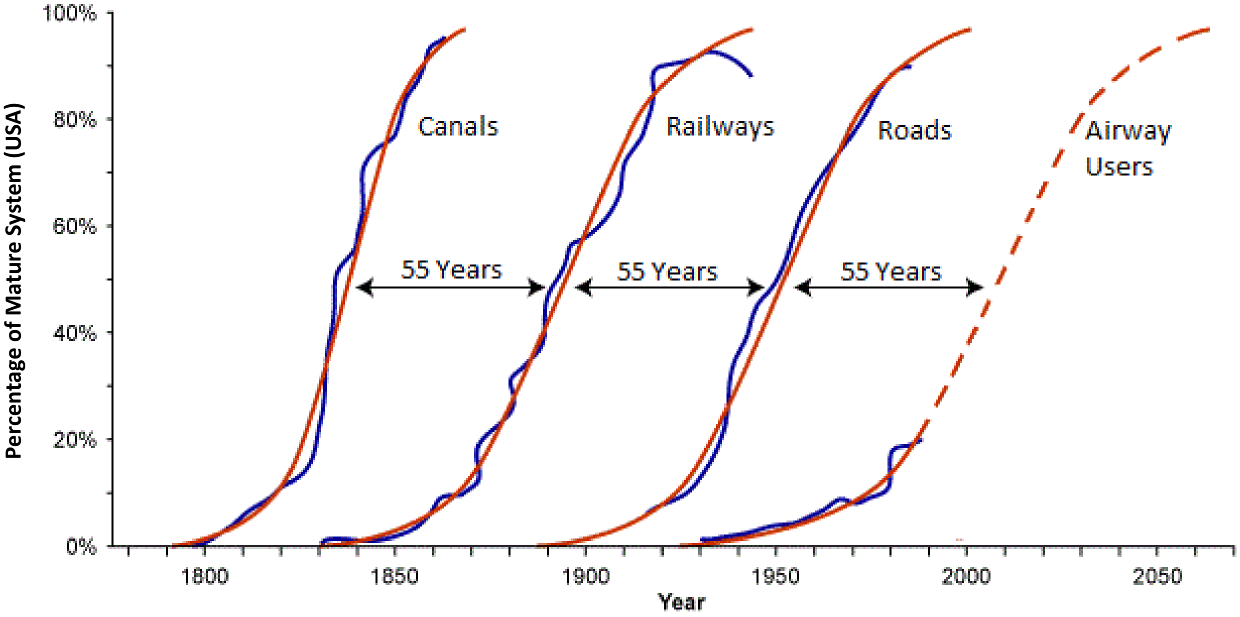
- Intercity range (at least 500 miles).
- Cruise speed over 300 mph.
- Payload capability from one to six passengers.
- Streetable, landable, and stowable with a size comparable to a large automobile (wings folded).
- Fuel economy exceeding 100 passenger miles per gallon.

Wind tunnel tests along with fluid dynamic computer modeling suggest that a hybrid flying car can meet these objectives, where most of the power during vertical takeoff will be provided by batteries. A streetable hybrid version like the Skycar® 200 will, because of size constraints, have a much higher disc loading than the state-of-the-art Joby S2 ($W/A_{eff} > 125$ lb./ft^2 versus 25 lb./ft^2). As a consequence, the batteries will need to tolerate a very high discharge rate (>50C). This could require the use of a LFP lithium type battery where the energy is significantly lower than 220 Wh/kg. For a streetable VTOL aircraft like the Skycar® volantor, the VTOL flight time including transition to aerodynamic flight will need to be measured in seconds to minimize battery weight and maximize its life.

Skycar® 200

Future of Personalized Airborne Transportation

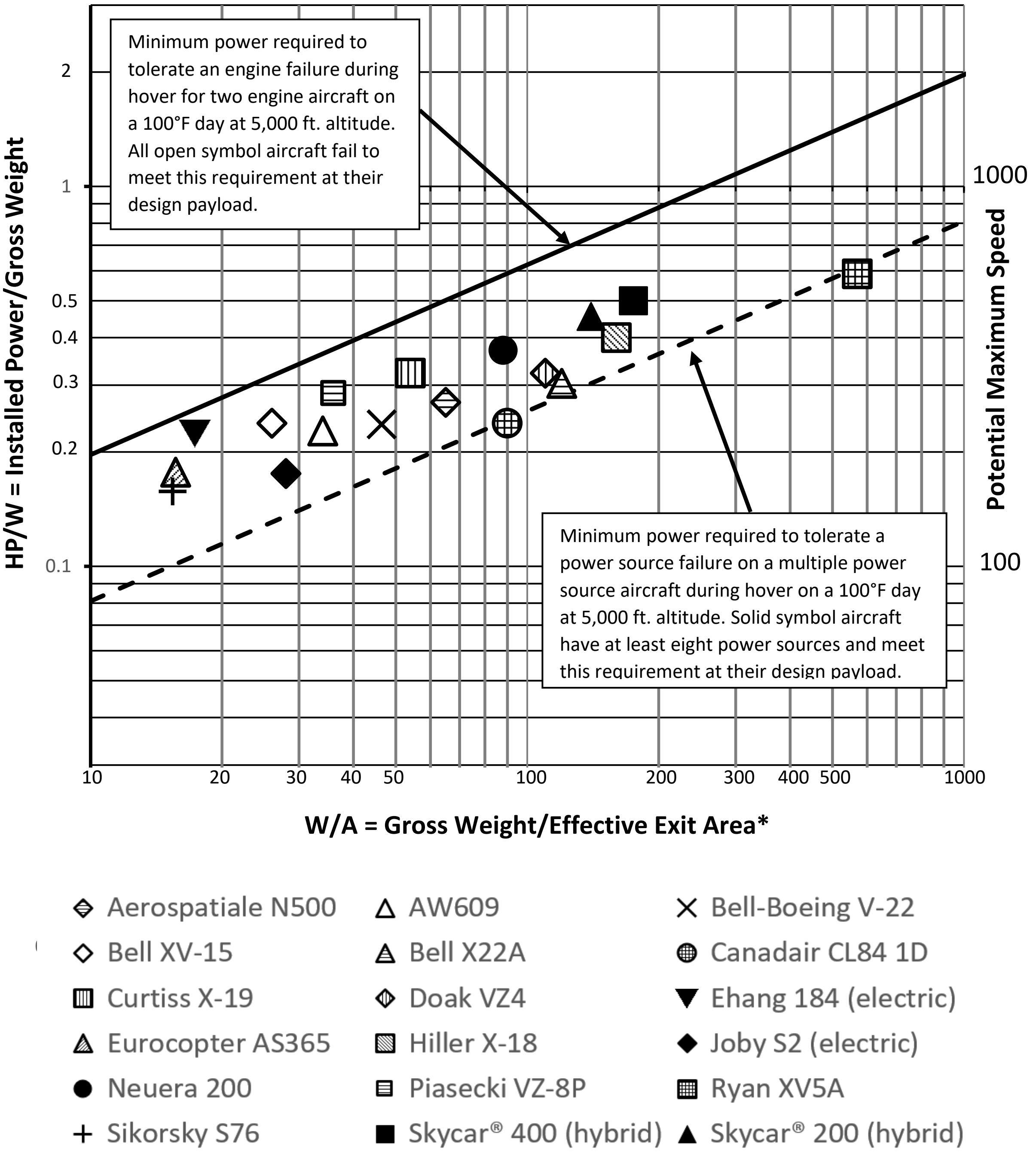
The following figure shows a future where personal travel will be mostly done by air utilizing the relatively unused airspace above us. Future airborne private travel could demand far more performance than can be provided by flying cars powered only by batteries.



If all the cars on the road in the US were evenly airborne they would be over 2 miles apart. This benign environment will make pilotless flying cars far easier to implement than the already underway driverless cars.

Inherent in any VTOL capable aircraft is the need to have sufficient power and number of power sources to tolerate an engine or electric motor failure at altitude on a hot day. The best way to achieve this is by maximizing the number of electric motors and engines used as shown in the following figure. From 1950 through the 1970's over fifty different VTOL aircraft configurations were demonstrated. Many had a single engine while none had more than two engines. Many lives were lost due to engine or single component failure. Fool-proof redundancy is the key to building confidence in the public's eyes through experience. Using at least eight powerplants and a number of independent flight control systems (FCS), is the first step towards building a safety record that will provide confidence in commuting by flying cars.

VTOL Aircraft Power Required for Safe Operation



Minimum power required to tolerate an engine failure during hover for two engine aircraft on a 100°F day at 5,000 ft. altitude. All open symbol aircraft fail to meet this requirement at their design payload.

Minimum power required to tolerate a power source failure on a multiple power source aircraft during hover on a 100°F day at 5,000 ft. altitude. Solid symbol aircraft have at least eight power sources and meet this requirement at their design payload.

***With unducted fans, propellers, or rotors the effective exit area in ft^2 is one half the swept area.**

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[i] Rinddell “Advancing Blade Concept (ABC) Development” JAH, 22-1, 1997.

[ii] Moller, Paul “Airborne Personalized Travel Using ‘Powered Lift Aircraft’”, (SAE Paper #985533) presented at the joint AIAA/SAE World Aviation Congress & Exposition, September 1998, Anaheim, CA.

[iii] http://batteryuniversity.com/learn/article/types_of_lithium_ion

[iv] http://www.ehang.com/ehang184/

[v] http://www.jobyaviation.com/S2/

[vi] Moller, Paul “A Hybrid Powerplant for Powered Lift Aircraft, Flying Cars”, 2007 SAE AeroTech Congress & Exhibition, September 2007, Los Angeles, CA.