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Critique of Battery Powered Flying Cars

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ABSTRACT

This paper analyzes the performance of two different types of battery powered flying cars. The first is a wingless eight rotor version, similar to a scaled-up drone, and projected to be suitable for use as an intracity air-taxi. The second is a winged twelve-propeller version using a long wing and projected to be suitable for use as an intercity air-taxi. In addition to examining the purely battery powered flying cars, a hybrid version is discussed where both electric motors and engines are used as a way to expand utilization beyond that of an air-taxi.

INTRODUCTION

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, that vision has remained unfulfilled for decades despite the availability of


Ehang 184

engines with twenty times the energy per pound compared with batteries. For a VTOL capable flying car to be utilized outside an air-taxi role, it will need to be accessible from a streetside curb. This will require its size to reduce to that of an automobile prior to landing and will limit the swept area of the propellers or rotors. Since power for vertical take-off increases inversely with the square root of the swept area, the power required can become very high as swept area reduces enough to allow flight from the curb. Batteries can produce the high power (Watts/lb.) required to take off vertically while engines can produce the high energy (Watt-hr./lb.) required for increased range and speed. This hybrid approach would allow vertical take-off from a streetside curb.

The first design consideration for both winged and wingless air-taxis powered by batteries is minimizing the power required to takeoff vertically by maximizing the propeller or rotor swept area. This can be accomplished with a single large 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 design consideration is maximizing range by operating at the speed that results in the maximum range (maximum lift to drag ratio)

ANALYSIS


Joby S2

The following equations [1] govern the power required as a function of aircraft speed:

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

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

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

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:

$$W = 33.5(\rho A_{eff})^{1/3}(\text{HP}\eta)^{2/3}$$

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

- Battery storage energy (Wh/kg) is a function of the battery chemistry required to tolerate a given discharge rate (W/hr.) [2]. Batteries in electric cars use a low average discharge rate of less than 0.5 C and can use NCA lithium batteries with a theoretical energy storage of up to 265 Wh/kg. The Joby S2 has a continuous discharge rate of 0.84C and take off discharge rate of 3.5C. The analysis of the Joby S2 assumes that these discharge rates can be tolerated by an NCA battery if it is adequately cooled. For a wingless air-taxi, like the Ehang 184, where the continuous discharge rate exceeds 1.9C, NMC lithium batteries would be needed with a theoretical energy storage of 220 Wh/kg.

- The weight added to cool and package the batteries will significantly lower the net energy stored per kilogram. For example, this added weight in a Tesla automobile reduces its effective stored energy from 265 Wh/kg to 168 Wh/kg. Assuming a similar weight increase with NMC lithium batteries, energy storage will reduce to the 140 Wh/kg for the Ehang 184.

- Propeller efficiency during hover for both the Joby S2 and Ehang 184 will not exceed 80% [3]. During cruise, propeller efficiency of the Joby S2 can exceed 90% through its use of separate propeller/motors for cruise flight. The efficiency of the Ehang 184 propellers in cruise is difficult to determine; however, its power decrease between hover and cruise is predictable.

- The electric motor efficiency for both the winged and wingless air-taxis 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 cruise speed. The Ehang 184, motors/propellers would be designed for maximum efficiency at its cruise speed of 62mph.

- Battery discharge efficiency is a function of the discharge rate and its chemistry. The Ehang 184 has a continuous discharge rate of ~2C where its NMC battery would have a discharge efficiency of approximately 90%. The Joby S2 with its higher internal resistance NCA battery would have a similar 90% efficiency at its lower discharge rate of 0.84C.

- Prior to reaching cruise speed, both the winged and wingless air-taxis will experience a higher discharge rate from the battery. However, if the time to hover, clear the area, and transition to cruising flight is less than one minute (intracity use), the energy consumption can be considered as a small component in the battery discharge efficiency.

Overall energy conversion efficiency between battery and airstream is composed of battery efficiency η_b, motor efficiency η_m, and propeller efficiency η_p.

Ehang 184 during hover $\eta_h = \eta_b \cdot \eta_m \cdot \eta_p = 0.9 \cdot 0.9 \cdot 0.8 = 0.65$

Joby S2 during hover $\eta_h = 0.85 \cdot 0.95 \cdot 0.8 = 0.65$

Joby S2 during cruise $\eta_c = 0.90 \cdot 0.95 \cdot 0.95 = 0.81$

ANALYSIS OF WINGLESS EHANG 184

Design cruise speed = 62 mph (for maximum lift to drag ratio), Design range = 26 miles [4].

Data for light helicopters [5] with a disc loading (gross weight / swept area) similar to the Ehang 184 show that minimum power occurs near 60 mph where it drops to 60% of that required to hover.

Hover power = 80 kW for one minute

Cruising power = 48 kW at 62 mph

Where, ρ = 0.0627 lb./ft³ (100°F day @ 5,000 ft. altitude), A_{eff} = 43.3 ft², W = 792 lbs. With the 20% reserve required to protect the batteries and its 240 lbs. payload, the battery energy is 25 kWh. At 140 Wh/kg the battery pack will weigh 392 lbs. This would leave 160 lbs. for airframe, powerplants, and ergonomics.

ANALYSIS OF THE WINGED JOBY S2

Design cruise speed = 200 mph, Design range = 200 miles [6].

Hover Power = 270 kW for one minute.

Cruising power at 200 mph = 65 kW.

Where S = 56.3 ft^2, A_w = 340 ft^2, C_{DW} = 0.004, A_{RE} = 16.3 W= 2,000 lbs., ρ = 0.0627 lb./ft^3 (100°F day @ 5,000 ft. altitude), A_{eff} = 61.4 ft^2.

If minimum retained battery energy is 20% for protection of batteries and its 390 lbs. payload, the battery energy is 77.5 kWh. At 168 Wh/kg, the battery pack weighs 1,014 lbs. This would leave 596 lbs. for airframe, powerplants, and ergonomics.

HYBRID APPROACH EXPANDS FLYING CAR PERFORMANCE AND UTILITY

For the foreseeable future, a VTOL capable flying car with sufficient capability to personalize versus commercialize airborne transportation, engines will be needed for aerodynamic flight supplemented by battery power during VTOL flight. This hybrid approach could make the following performance possible:

- Intercity range over 500 miles.
- Cruise speed over 250 mph.
- Expanded payload capability.
- Can land curbside with wings folded and with the size and stowability of a large automobile.
- Fuel economy near 100 passenger miles per gallon.

Skycar® 200 (hybrid)

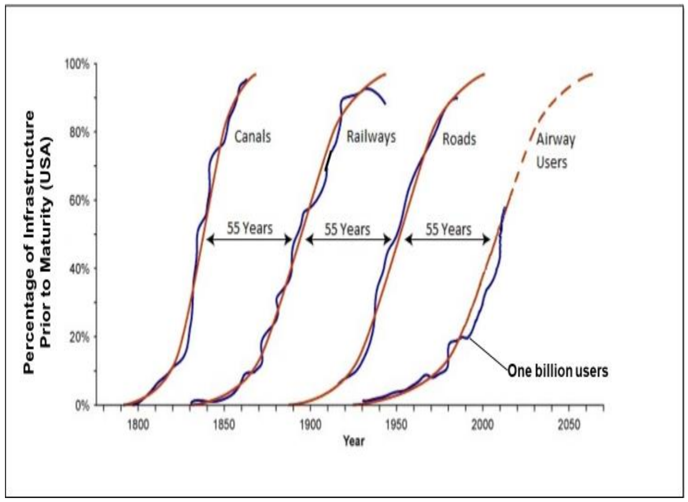
Analysis shows that to meet these objectives, a hybrid flying car would derive most of its power during vertical takeoff from batteries. To be landable at the curb it must reduce its size prior to landing. This will limit the size of the propulsion system's sweep area and increase the short-term power required (watts/lb.) to take off vertically. Consequently, the discharge rate from the batteries will be high (~30 C) requiring the use of a LFP lithium type battery where the energy storage per kilogram is significantly lower than that used in an air- taxi application. The VTOL flight time including transition to aerodynamic flight will need to be measured in seconds to minimize battery weight and maximize its life.

FUTURE PERSONAL AIRBORNE TRANSPORTATION

If all the cars on the road in the US were airborne and evenly spaced, they would be over two miles apart. This benign environment will make pilotless flying cars far easier to implement than the ground-based driverless cars currently under development.

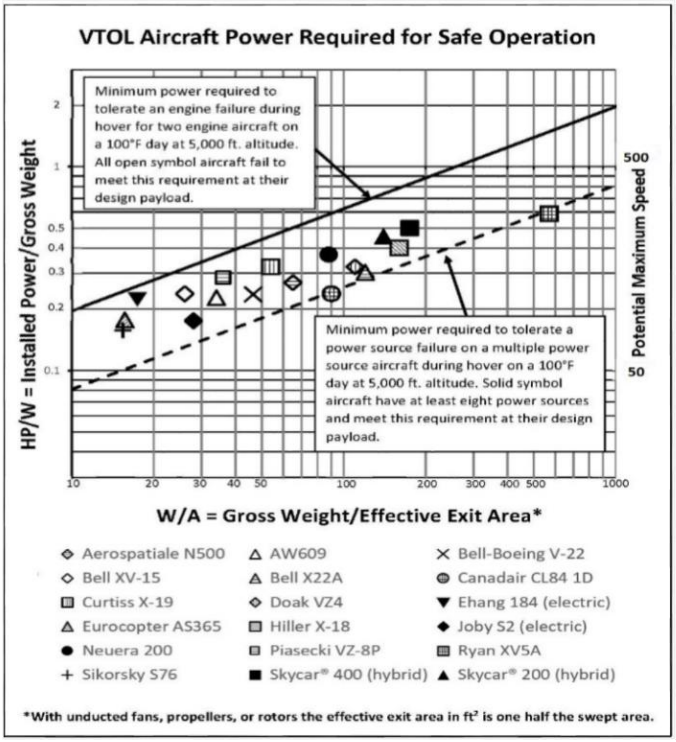
The following figure shows a future where personal travel could be done mostly by air utilizing the relatively unused airspace above us.

The status of airway infrastructure is not quantifiable like canals, railways, and highways. However, passenger usage has historically followed the infrastructure status of the other transportation modes. For that reason, passenger usage is used as a surrogate for airway infrastructure status. Airborne private travel could demand far more performance than can be provided by flying cars powered by batteries unless an unexpected breakthrough in battery chemistry occurs.



From 1950 through the 1970's over fifty different VTOL aircraft were demonstrated. Most had a single engine while none had more than two engines. Many lives were lost due to engine or the failure of a critical component. Inherent in any VTOL capable aircraft is the need to have enough total installed power, which when distributed will allow a powerplant failure on a hot day at altitude. The following figure shows that all two-engine prototype and production VTOL aircraft are or were unable to hover at altitude on a hot day while carrying their design payload. This would require operating above the solid line. VTOL aircraft with eight or more powerplants (solid symbols) could operate safely above the dotted line.

Achieving fool-proof redundancy of both powerplants and flight control systems will be the key to establishing public confidence in pilotless personal use flying cars.



CONCLUSIONS

- The wingless Ehang 184 and the winged Joby S2 cannot meet their design speed and range due to the low weight available for airframe, lift/propulsion and ergonomics.
- The Ehang 184 could achieve a range of 15 miles at 62 mph. This would provide a barely adequte 322 lbs. for airframe, lift/propulsion and ergonomics.
- The Joby S2 could meet the much more realistic performance goals set by the Airbus Vahana flying car with a design speed of 140 mph and range of 50 miles.
- Using as many powerplant/propellers as possible will minimize the installed power and maximize occupant safety.
- If the growth of airway infrastructure follows the historic path of canals, railroads, and roads, then air-taxis will make up only a small portion of future airborne trips by the public. To achieve widespread personal use, the flying car will need to land at a street curb. This will require its size to reduce to that of a large automobile prior to landing and the propellers will need to be ducted for safety and increased lift.
- Until the energy storage capacity of batteries increases by an order of magnitude, curbside operations will make it necessary for the flying car to operate in a hybrid mode where during takeoff and landing most of the power is derived from batteries while engines provide the energy during cruise.
- Projecting the airway infrastructure growth using the number of users as a surrogate indicates that the airway infrastructure will mature about 2050 or when the number of users reaches five billion per year.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

NCA: Lithium Nickel Cobalt Aluminum Oxide
NMC: Lithium Nickel Manganese Cobalt Oxide
LFP: Lithium Iron Phosphate

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