7. Benchmarking and Cost Estimation

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eVTOL can Perform Multiple Missions

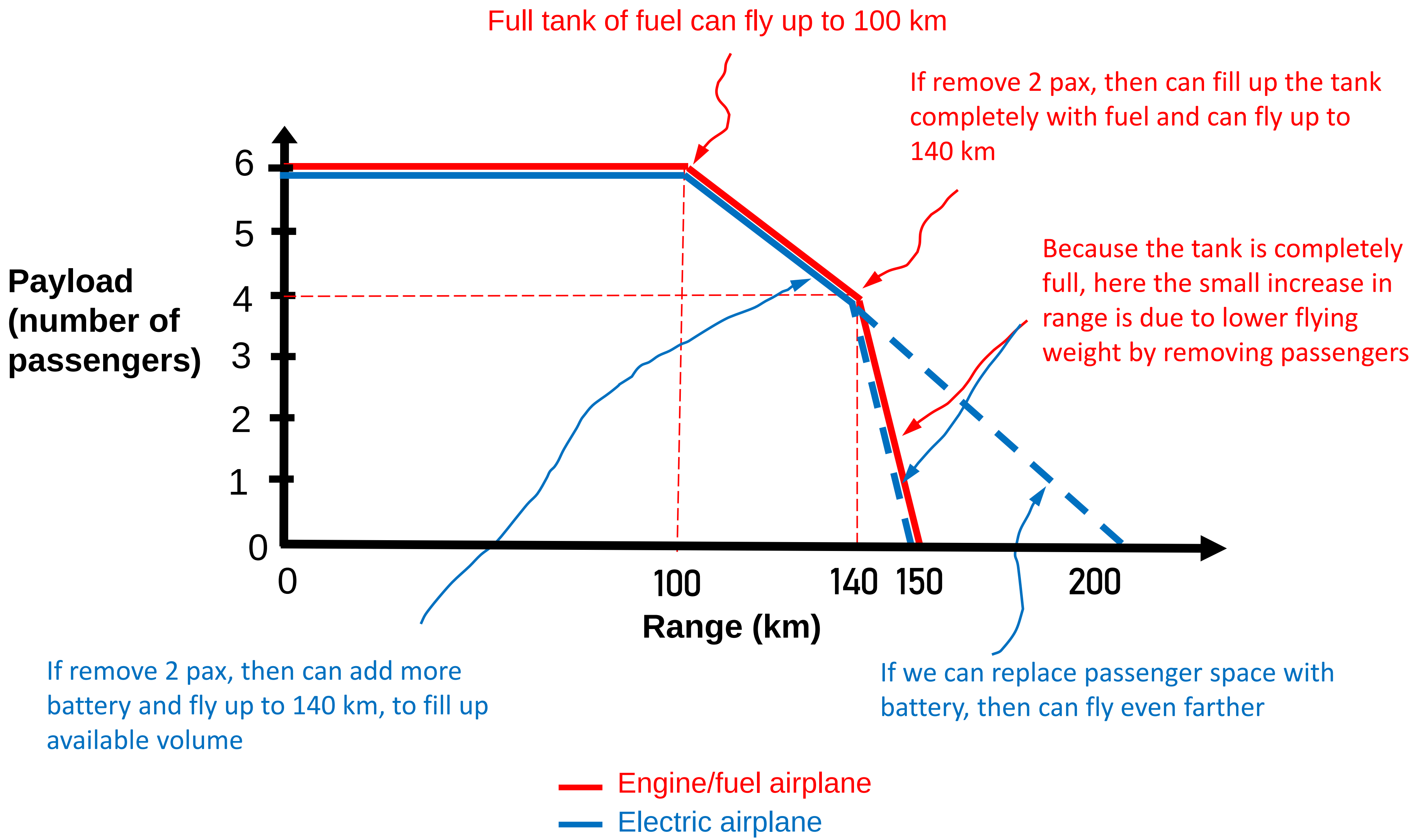
- UAM
- Business travel, VIP transport, luxury Air-taxi
- Private ownership
- EMS (Emergency Medical Service)
- Organ transport
- Cargo delivery
- Disaster relief
- Search and Rescue
- Police, Border patrol
- Logistic, command and control
- Military transport and Commando insertion
- Utility, pipeline surveillance, inspection and repair

Desired Attributes for UAM eVTOL Aircraft

- Electric → Sustainable, lower parts count, lower maintenance, lower manufacturing cost, less noise,
- Recyclability for whole aircraft and batteries
- Configuration takes advantage of distributed electric propulsion & minimize complexity
- >6 lifting rotors, for redundancy, or dual motors per rotor, or dual windings per motor
- Vertical Take-Off & Landing (VTOL) → low infrastructure, no runway
- Possibly allow STOVL (short take-off and vertical landing) → saves power, adds safety
- Efficient cruise → L/D>10 because 90% time will be in cruise, and permits gliding
- Efficient hover → disk loading <15 lb/ft^2 if mission require extended hover
- Autonomous capable or later easily upgradable to level 5
- Safety → 10^{-9}, account for cybersecurity, battery fire, electro-magnetic interference
- Noise → external noise at least 15dB < same weight helicopter
- Cabin comfort → vibration < helicopter, permits conversation without headset
- Emergency → ballistic parachute? autorotation? gliding? Rugged crashworthiness.

Payload-Range Curve for Fuel and Electric Plane

A generic example:



Parametric Study for 13 eVTOLs

Volocopter Volocity
EHang 216
Airbus CityAirbus
Beta Technologies Alia
Cora Kitty Hawk
Hyundai Supernal S-A1
Vertical Aerospace VA-X4
Archer 2-Seat Maker
Kitty Hawk Heavyside
Joby S4
Bell Nexus 4EX
Airbus Vahana
Lilium Jet

I first presented these at Oct 2020 VFS eVTOL Short Course

Parametric Study of 13 Different eVTOLs

Joby S4, USA

Archer Maker, USA

Volocopter Volocity, Germany

Ehang 216, China

Beta Technologies Alia, USA

Hyundai S-A1, Korea

Vertical Aerospace VA-X4, UK

Cora Wisk, USA

Lilium Jet, Germany

Airbus CityAirbus, France

Bell Nexus 4EX, USA

Airbus Vahana, France

Kitty Hawk Heaviside, USA

Volocopter Volocity (multirotor)

EHang 216 (Multirotor)

Airbus CityAirbus (quadcopter)

Beta Technology Alia-250C (lift + cruise)

Wisk Cora (lift + cruise)

Hyundai Supernal S-A1 (vector thrust)

Vertical Aerospace VA-X4 (vector thrust)

Archer Aviation Maker 2-Seat Demonstrator

Kitty Hawk Heaviside demonstrator (vectored thrust)

Joby S4 (vectored thrust)

Bell Nexus 4EX (vectored thrust)

Airbus A^3 Vahana Tiltwing demonstrator (vectored thrust)


Airbus A³ Vahana Tiltwing demonstrator (vectored thrust)

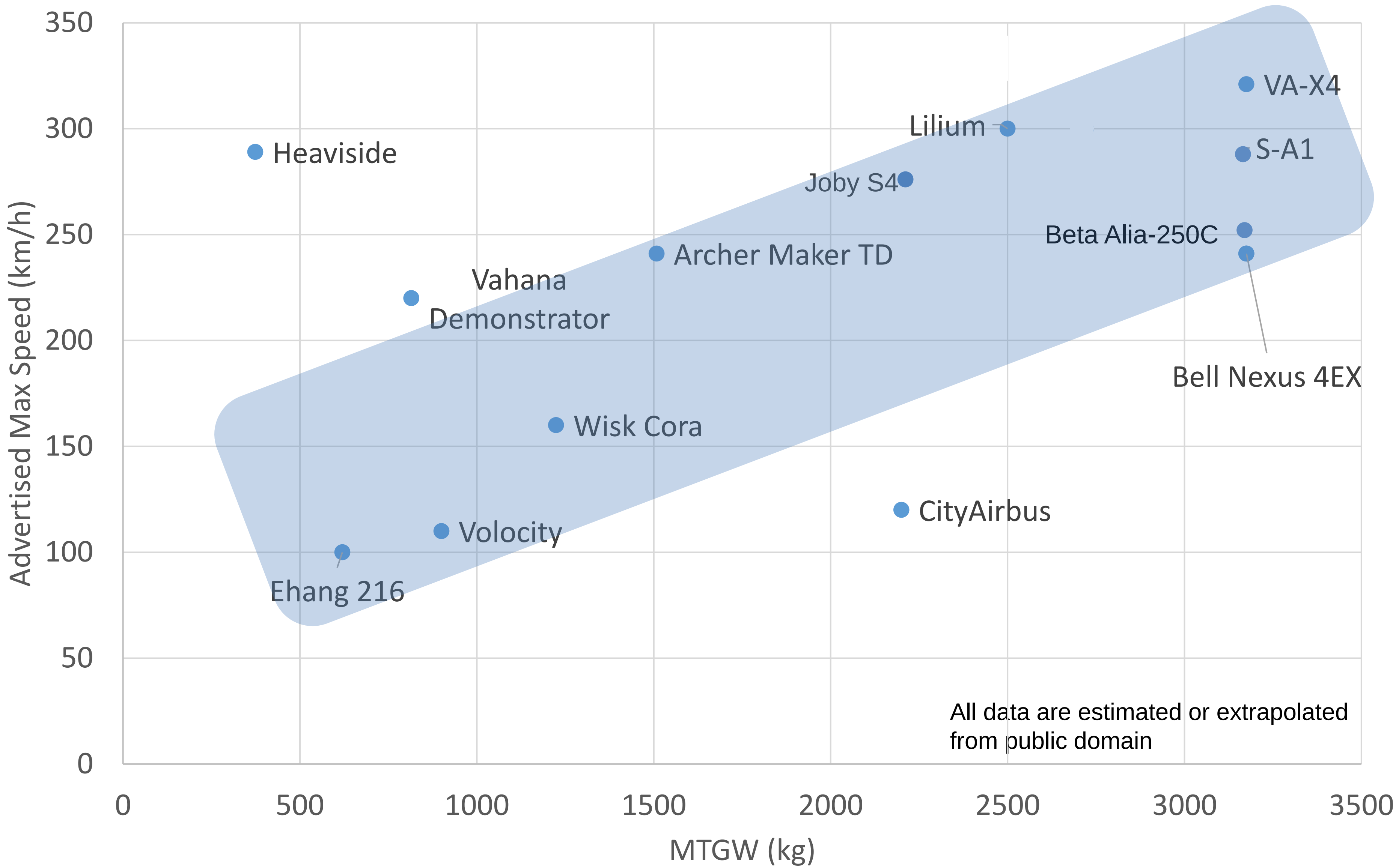
Lilium Jet 5-seat (vectored thrust)

Source: https://techcrunch.com/2019/05/15/lilium-5-seater/?guccounter=1

All data are estimated or obtained from public domain, do not assume they are all accurate. They are only used for teaching purpose in this Short Course !

Advertised or Estimated Max Speed vs MTGW

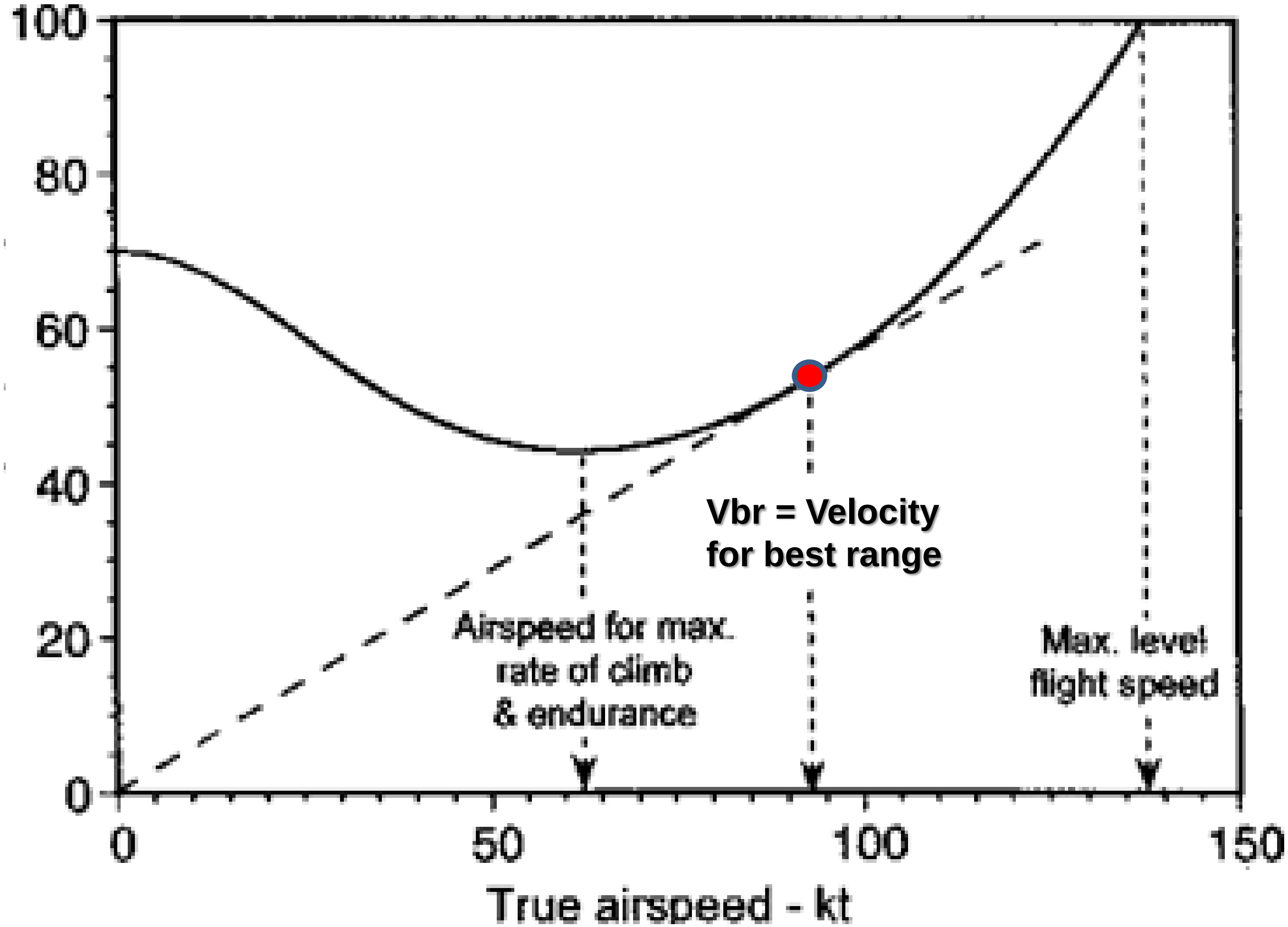
Note, these are max speed, the best range cruise speed should be much lower



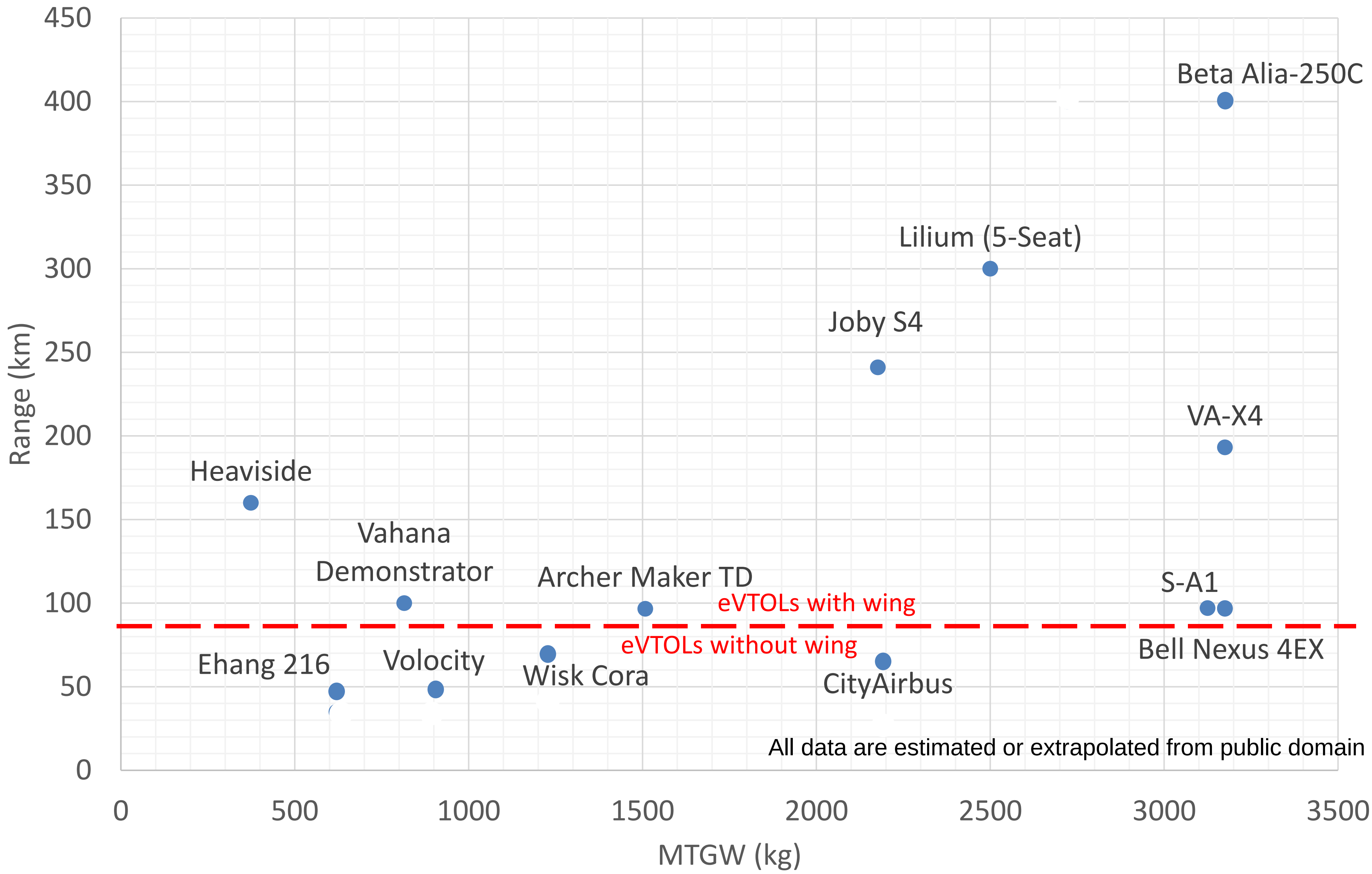
Note, Most Rotorcraft Will Cruise at Vbr

Typical power required curve shape for helicopters

% hp required from the engine



Claimed Range vs MTGW, With What Reserve?



Trend is Multirotor Replaced by Lift+Cruise

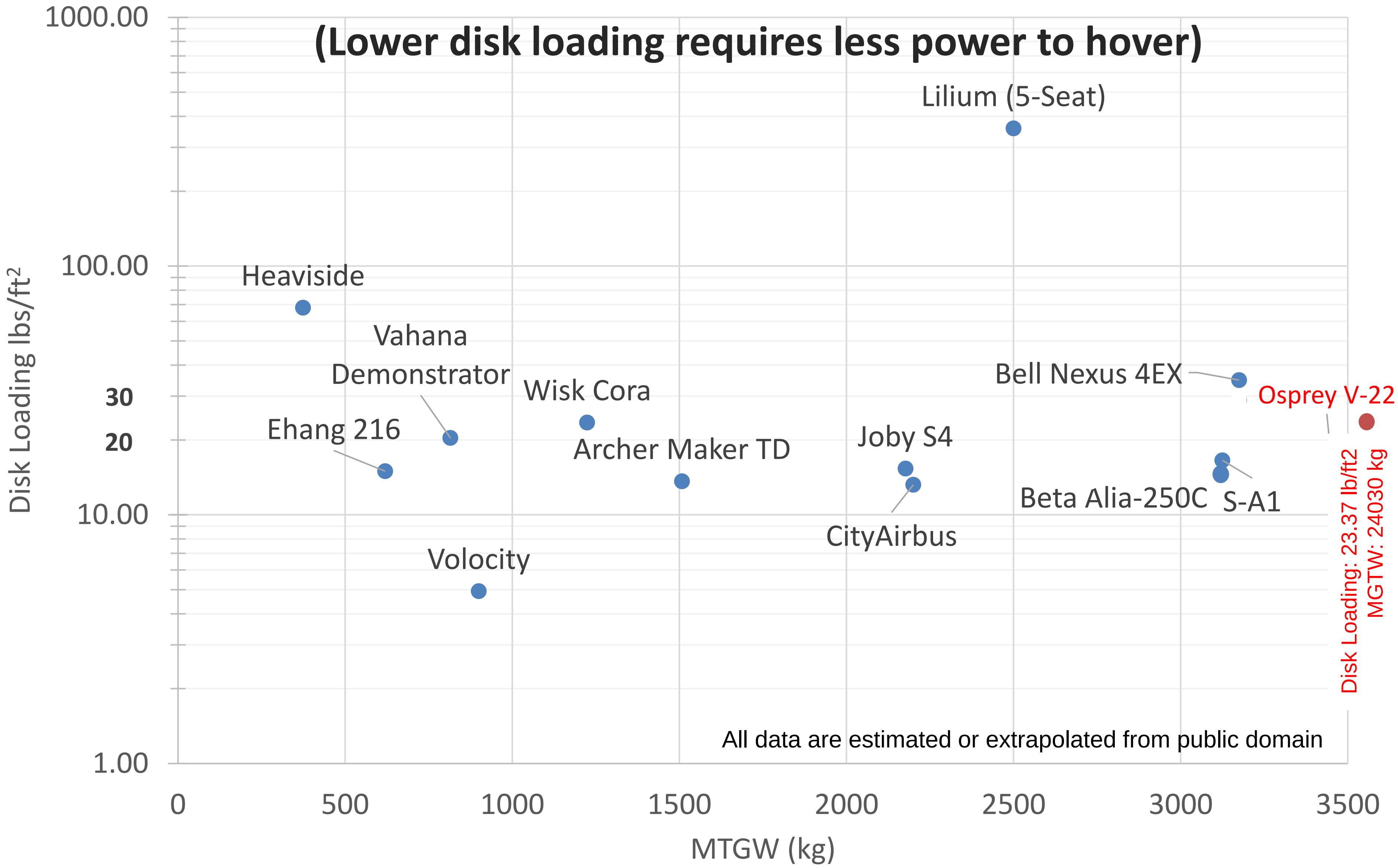

Volocity 2019


Voloconnect
May 2021


EHang 216 2019

Ehang VT-30
May 2021

Estimated Disk Loading vs Estimated MTGW



What Rotor Diameter and rpm?

Target: We want to keep the disk loading at around 15 to 25 lb/ft^2. The lower the disk loading the more efficient the aerodynamics and the less power required for hover and cruise, and also quieter. Fullsize helicopters are 4 to 10 lbs/ft^2 .

Target: To keep noise down, we want to keep the blade tip speed at under 556 km/h (about Mach 0.45 because the speed of sound is 1235 km/h).

Exercise Question

Let's say our MTGW is 7000 lbs and we have 6 rotors and our target disk loading is 15 lb/ft^2, what should be our rotor diameter?

Answer:

Disk loading = thrust per rotor / rotor area

$$15\ lb/ft^2 = 7000\ lbs / 6 / (3.1415 \times radius^2)$$

$$radius = 4.98\ ft\ (1.52\ meter)$$

(By the way, this is roughly the radius of Joby S4, and the S4 has advertised lighter MGTW, too)

What Rotor RPM to Chose for this eVTOL?

Answer: To keep the rotor noise reasonable and stress reasonable, let's keep the blade tipspeed at 556 km/h.

556 km/h for a 1.52 meter radius means 970 rpm

Let this rpm provide 1G thrust

Here is the formula: Tipspeed = ΩR

Tipspeed (km/h) = 2x3.1415 x rpm x 60 x radius (meter)/1000

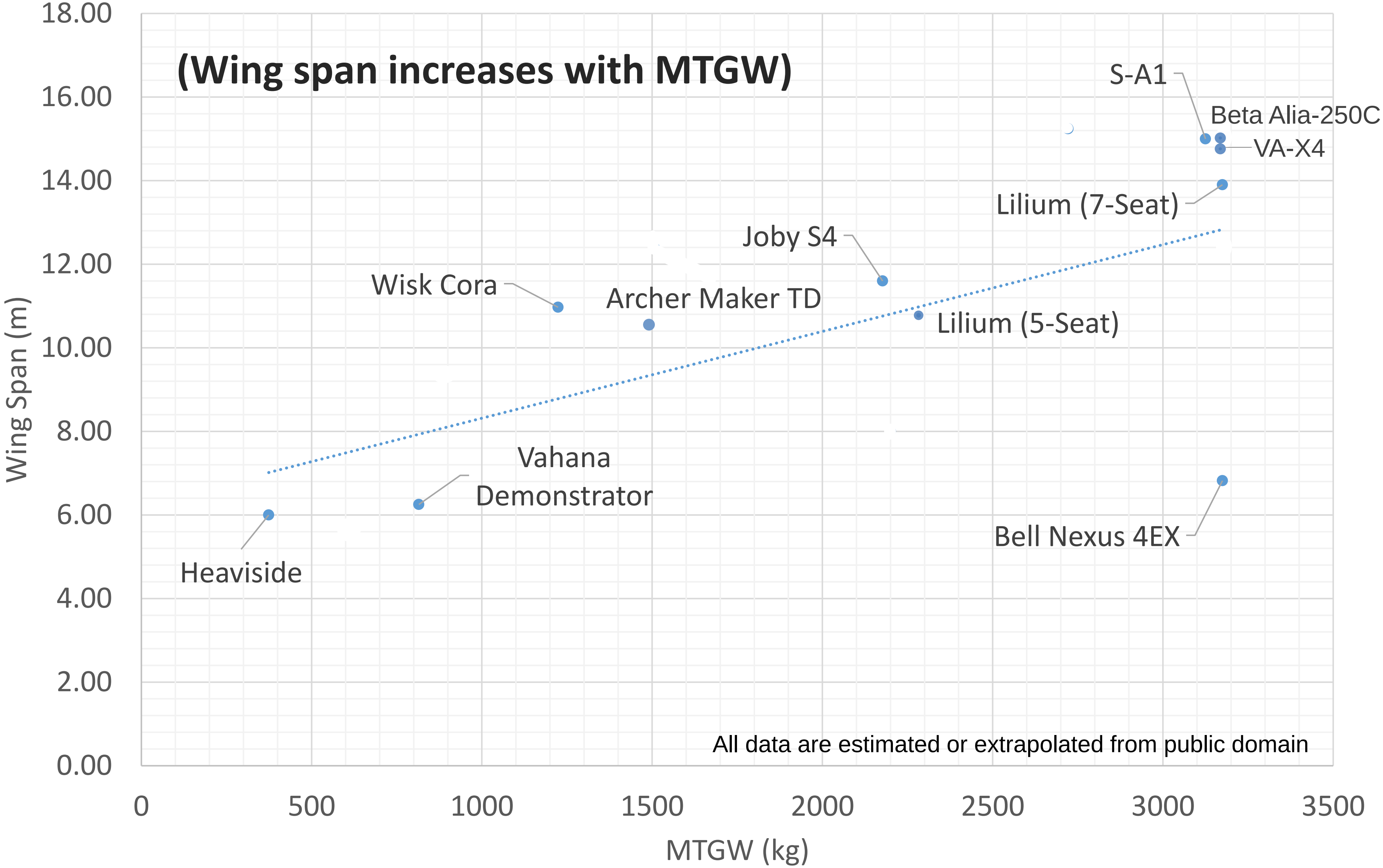
$$\text{rpm} = \frac{\text{Tipspeed (km/h)} \times 1000}{2 \times 3.1415 \times 60 \times \text{radius (meter)}}$$

To improve control response and flight performance, may want to consider raising the tip Mach No. to 0.5 and recalculate rpm. It also depends on using variable pitch or variable rpm for control.

Key design requirements for minimum noise can be summarized as follows:

1. Low disk loading
2. Low tip speed
3. If possible, use more than 2 blades per rotor
4. Minimize interference with rotor flow, both upstream and downstream
5. Minimize what can contribute to high-frequency airload fluctuations

Estimated Wing Span vs Estimated MTGW

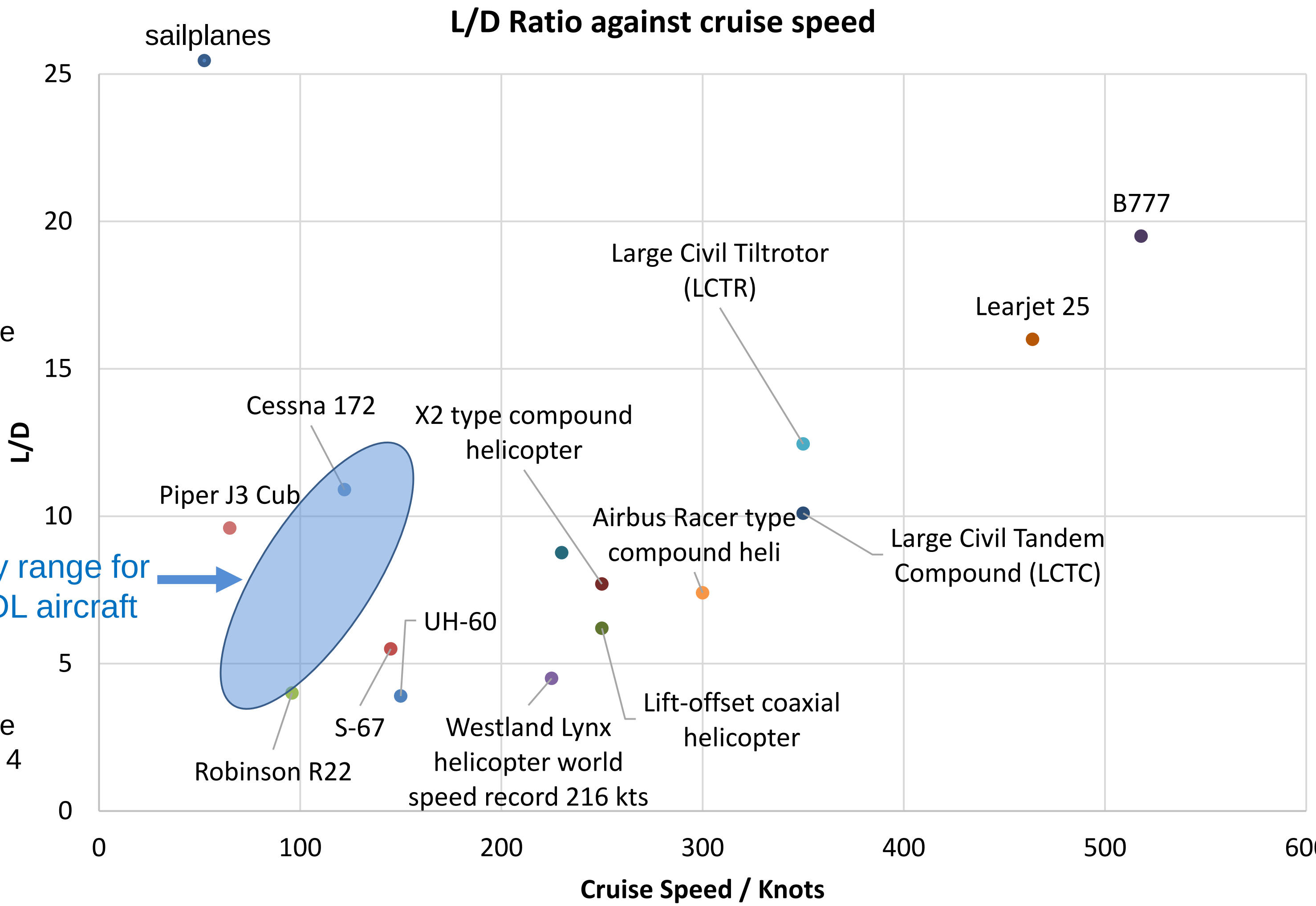


Total Aircraft L/D versus Cruise Speed

Airplane usually have L/D around 10-20

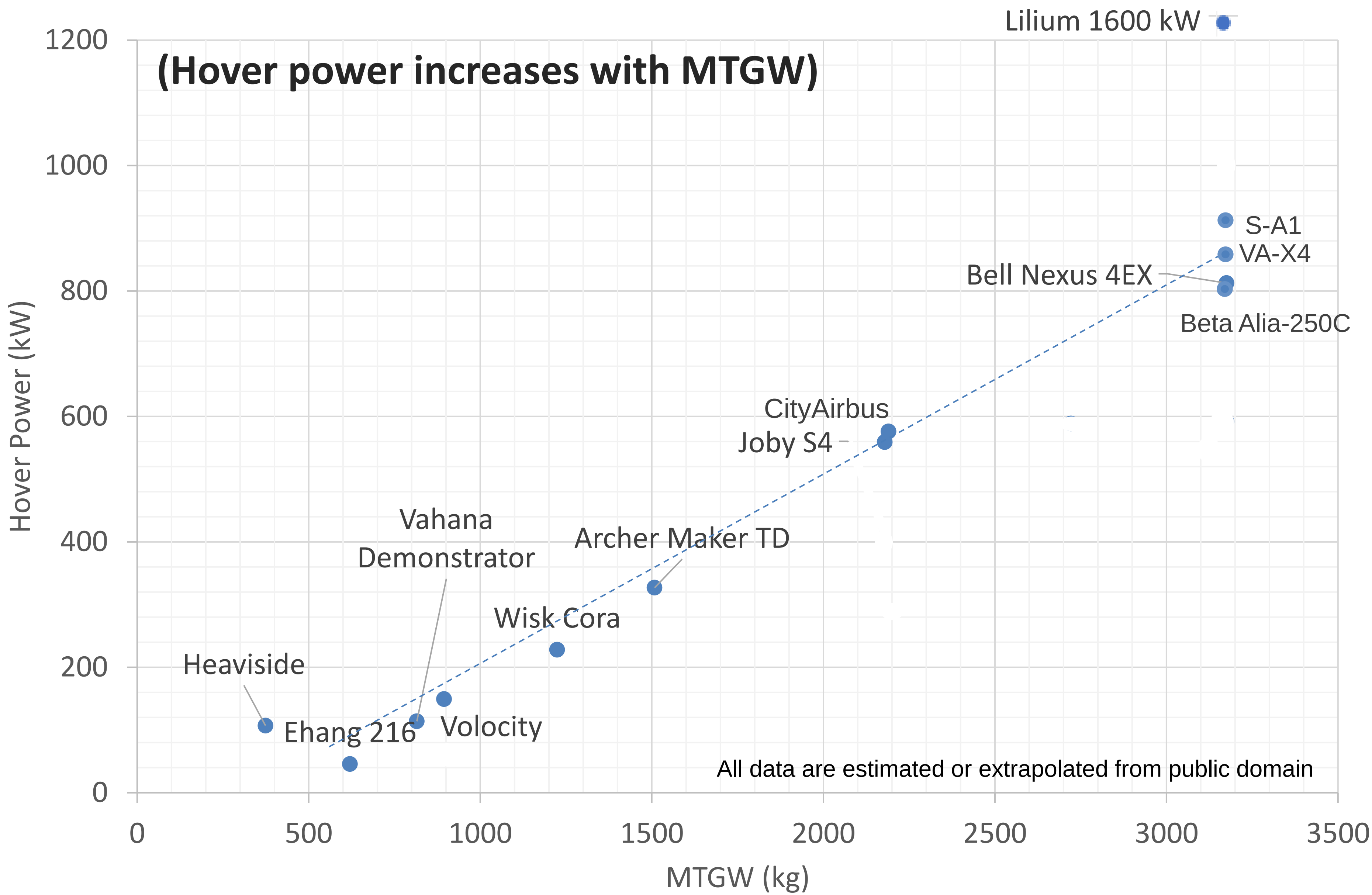
Likely range for eVTOL aircraft

Helicopters usually have L/D around 4



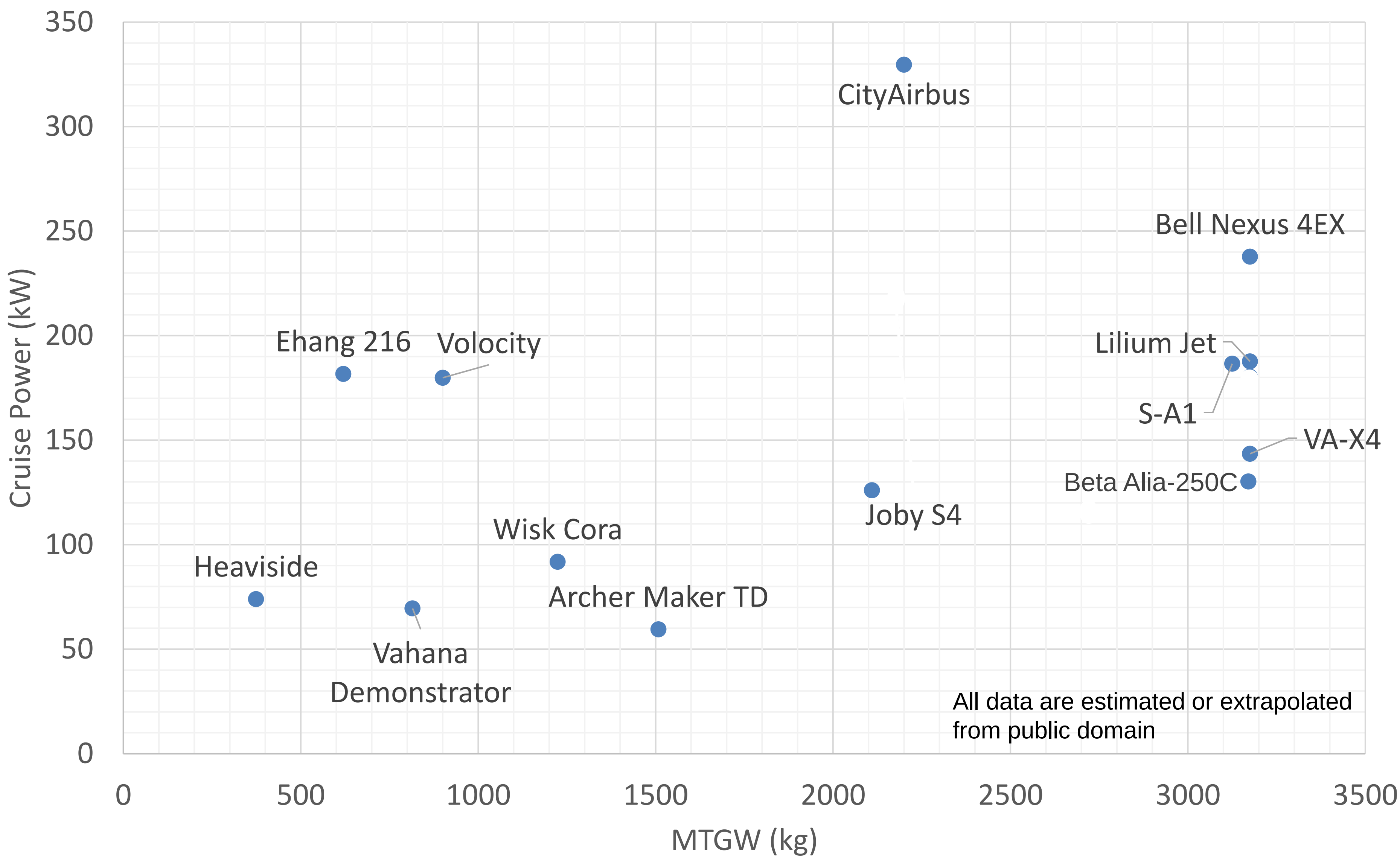
Source: Johnson, W., H. Yeo, and C. Acree Jr, *Performance of Advanced Heavy-Lift, High-Speed Rotorcraft Configurations*. 2007

Estimated Hover Power vs MTGW



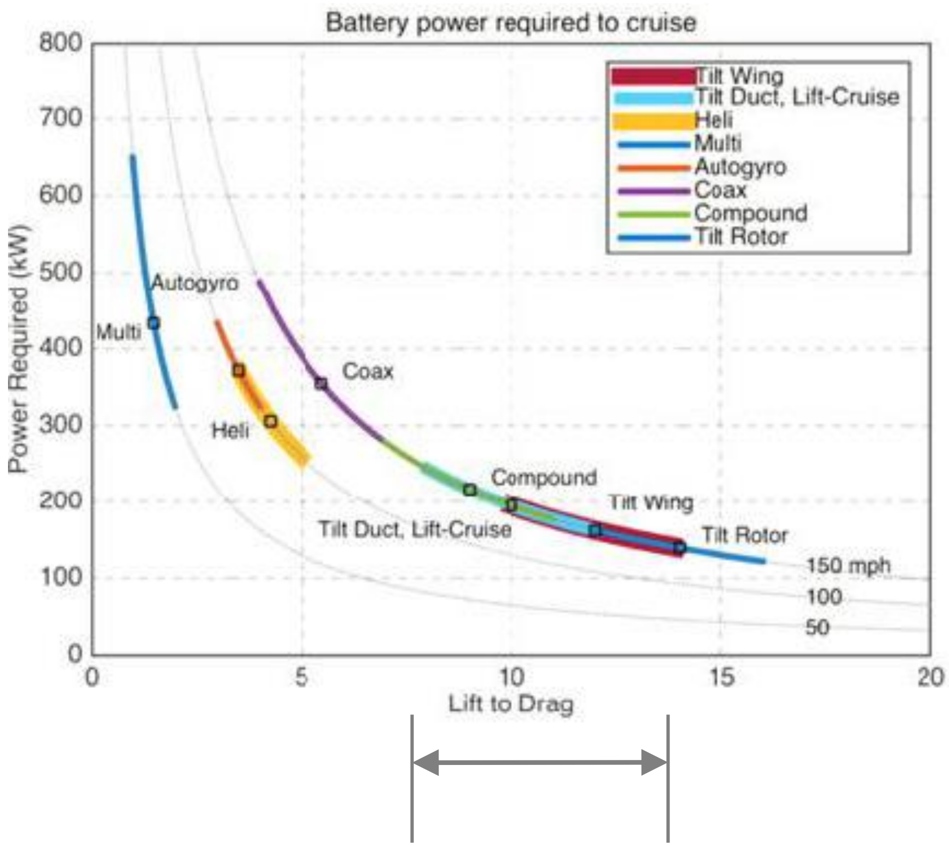
Estimated Cruise Power at V_{br} vs MTGW

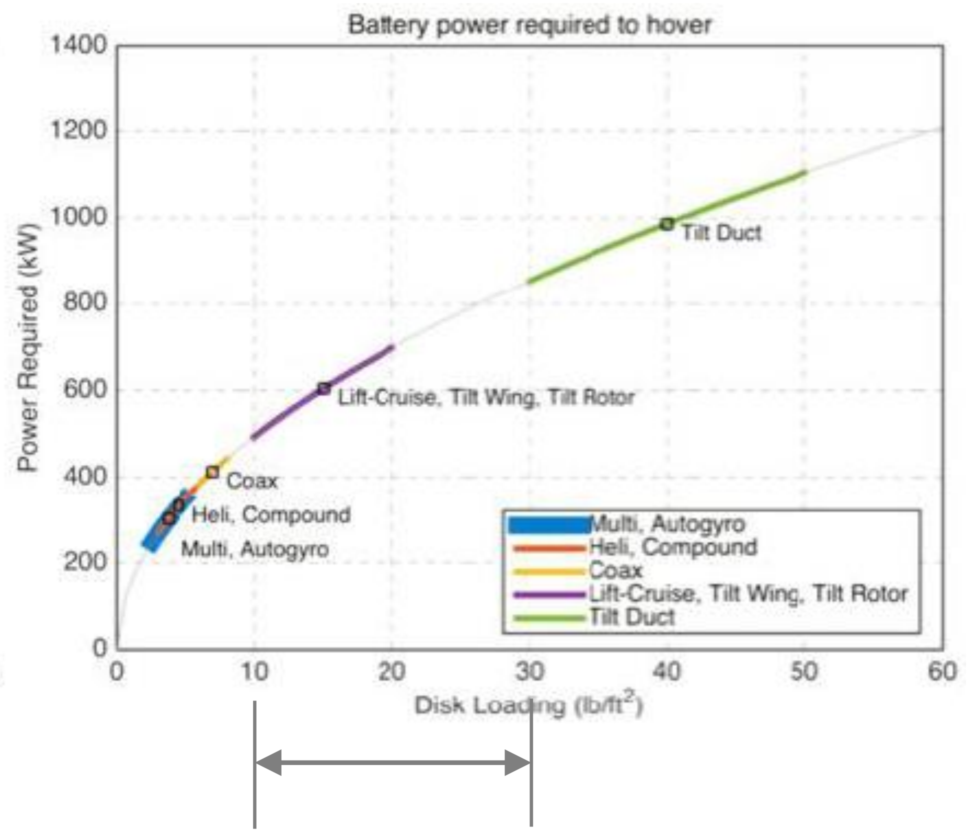
(Lower cruise power = longer range)



Example: Comparing Hover and Cruise Power Required for Different VTOL Designs,

(assume all have a MTGW = 5000 pounds)



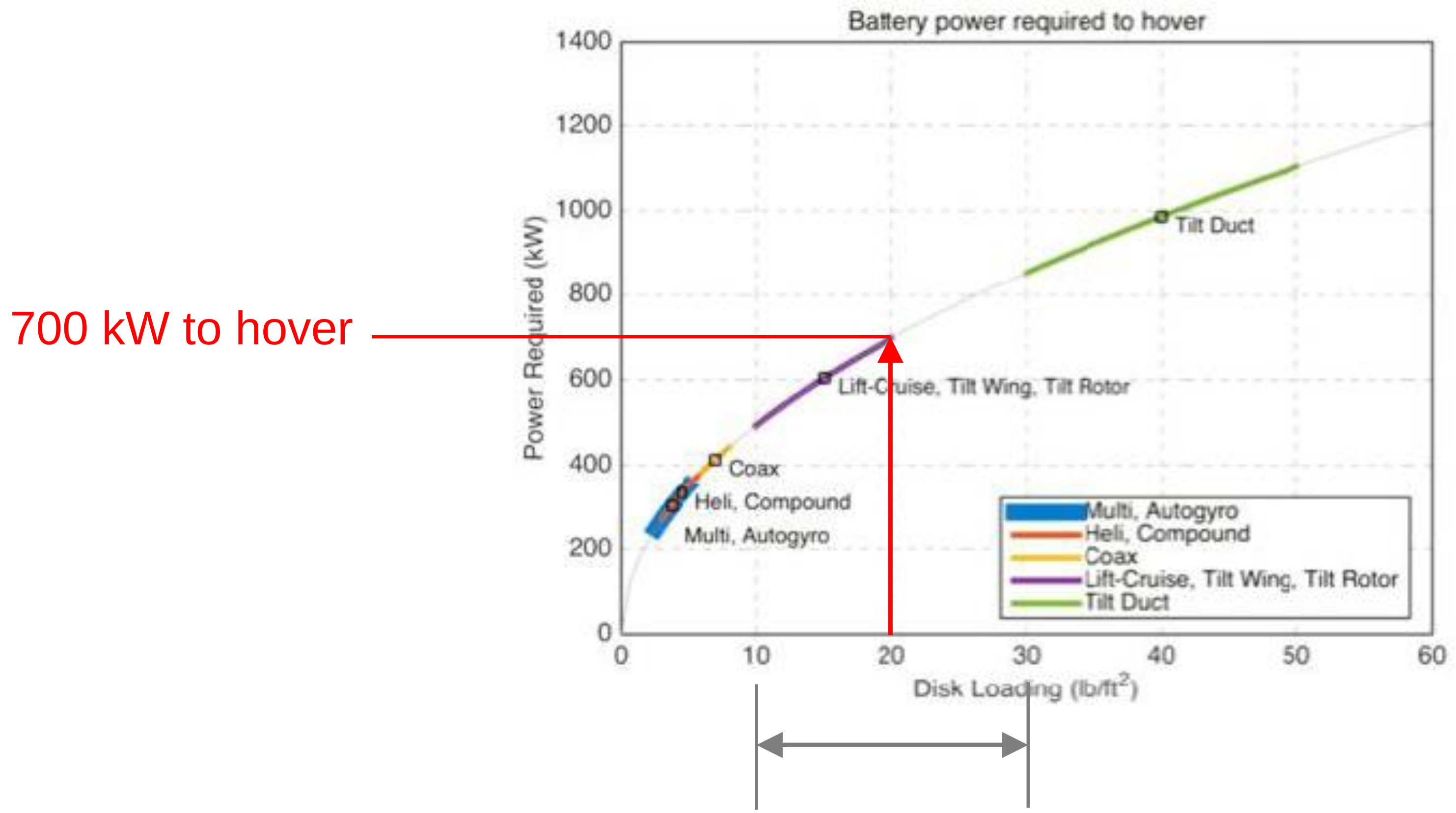


Likely range for most eVTOL aircraft. The higher the L/D, the more efficient for forward flight.

Likely range for most eVTOL aircraft. The lower the disk loading, the more efficient for hover.

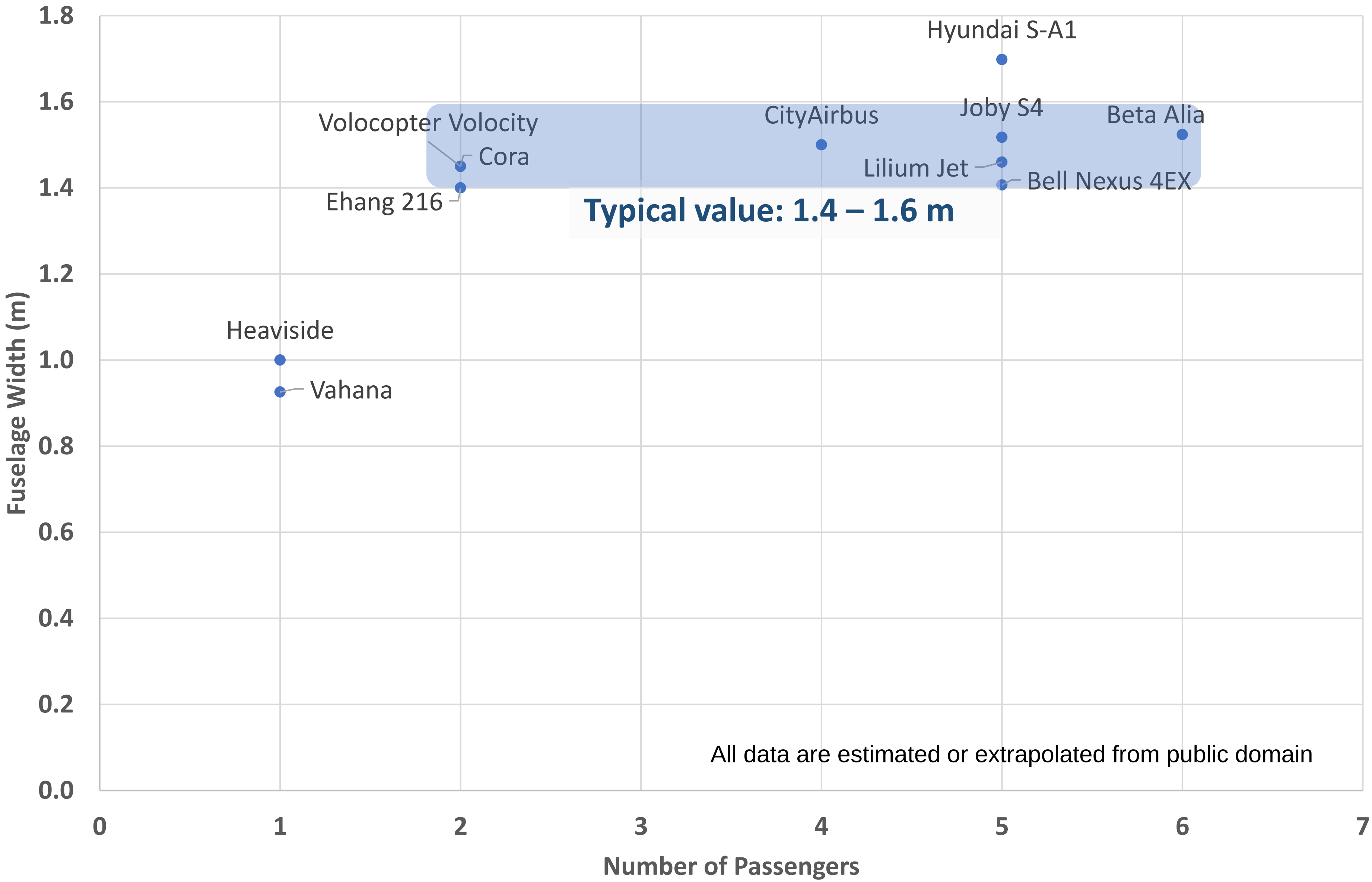
Example: Comparing Hover and Cruise Power Required for Different VTOL Designs,

(assume all have a MTGW = 5000 pounds)

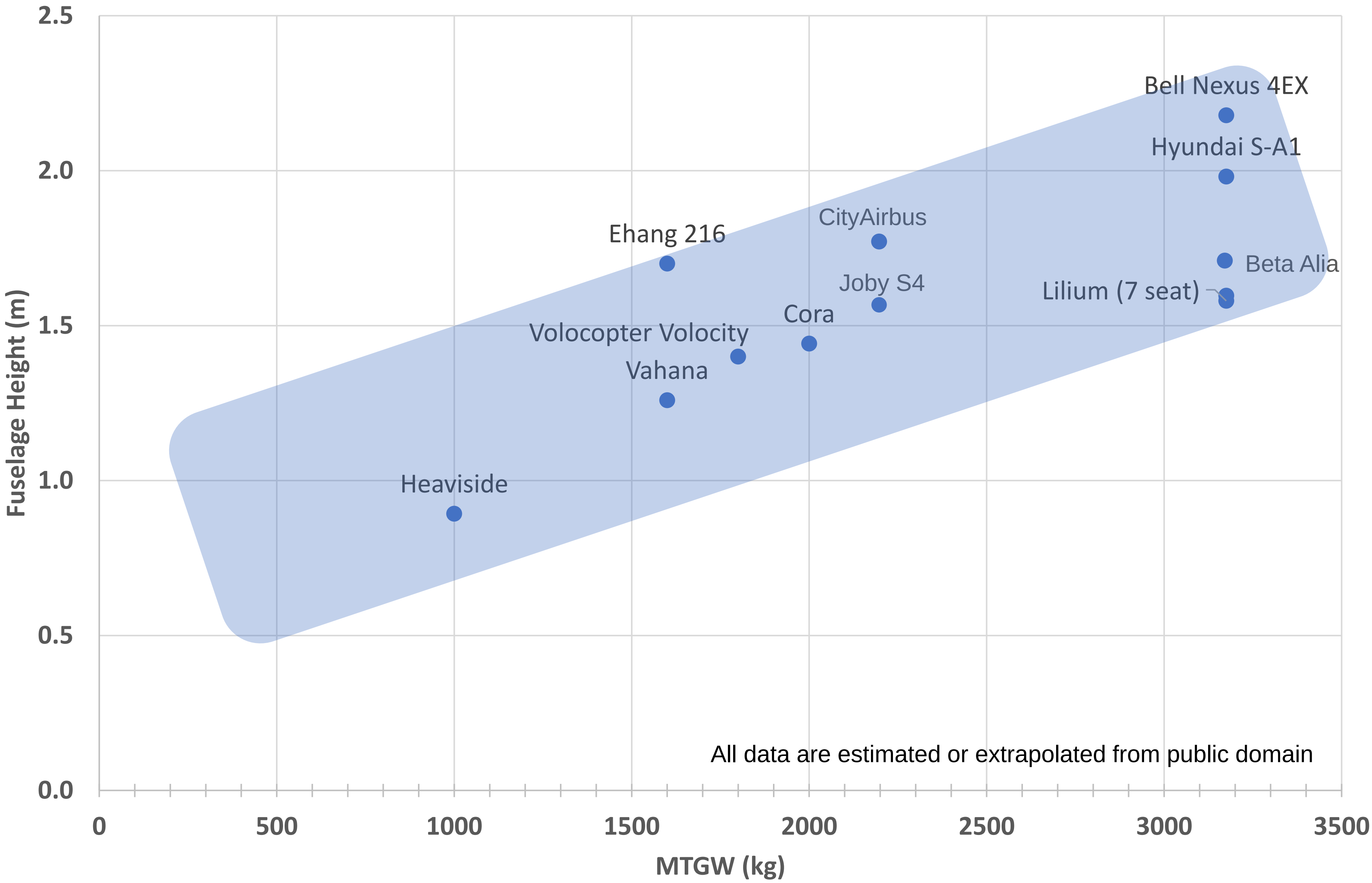


Likely range for most eVTOL aircraft. The lower the disk loading, the more efficient for hover.

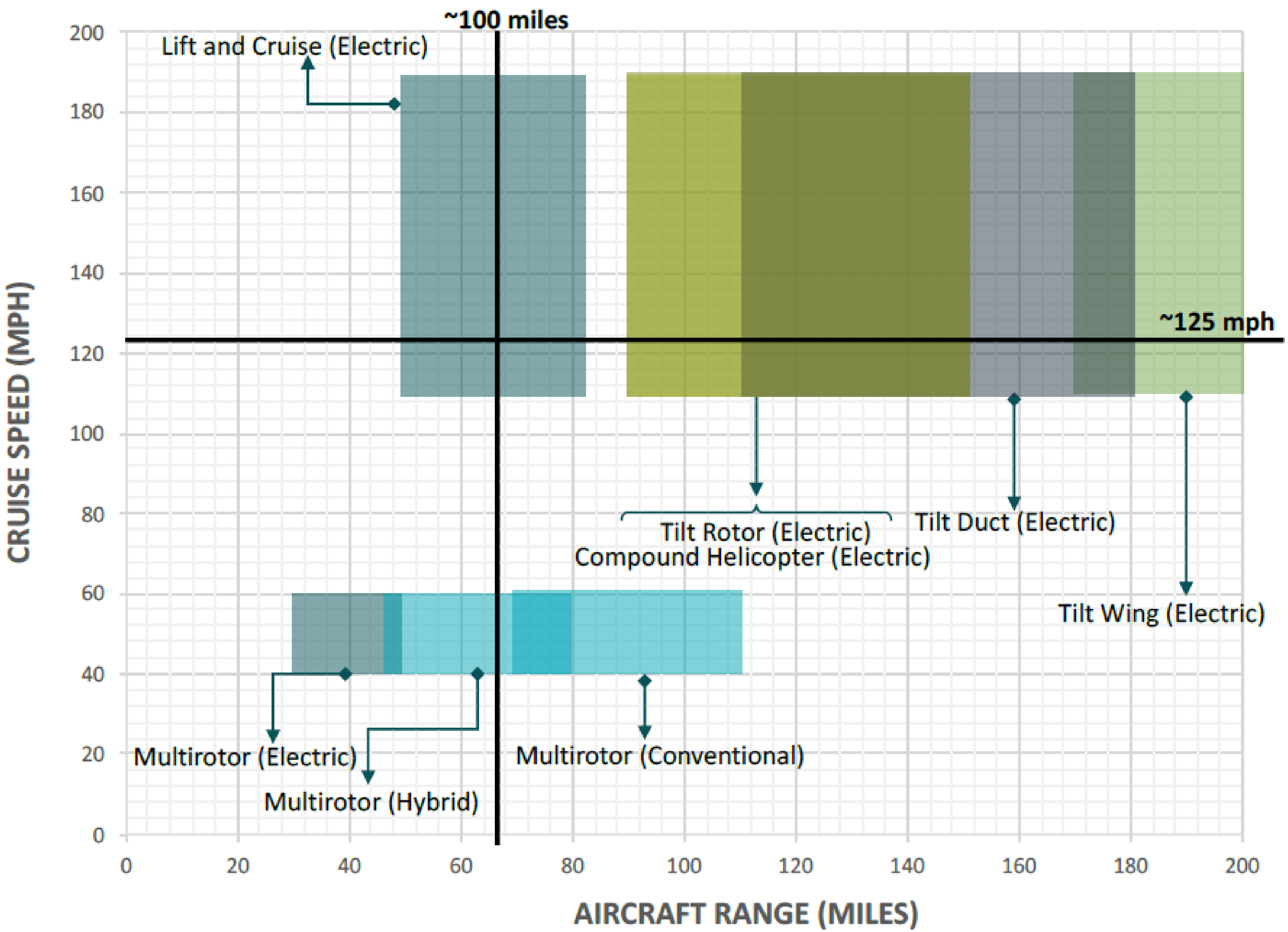
Extrapolated Fuselage Width vs Pax



Extrapolated Fuselage Height vs MTGW



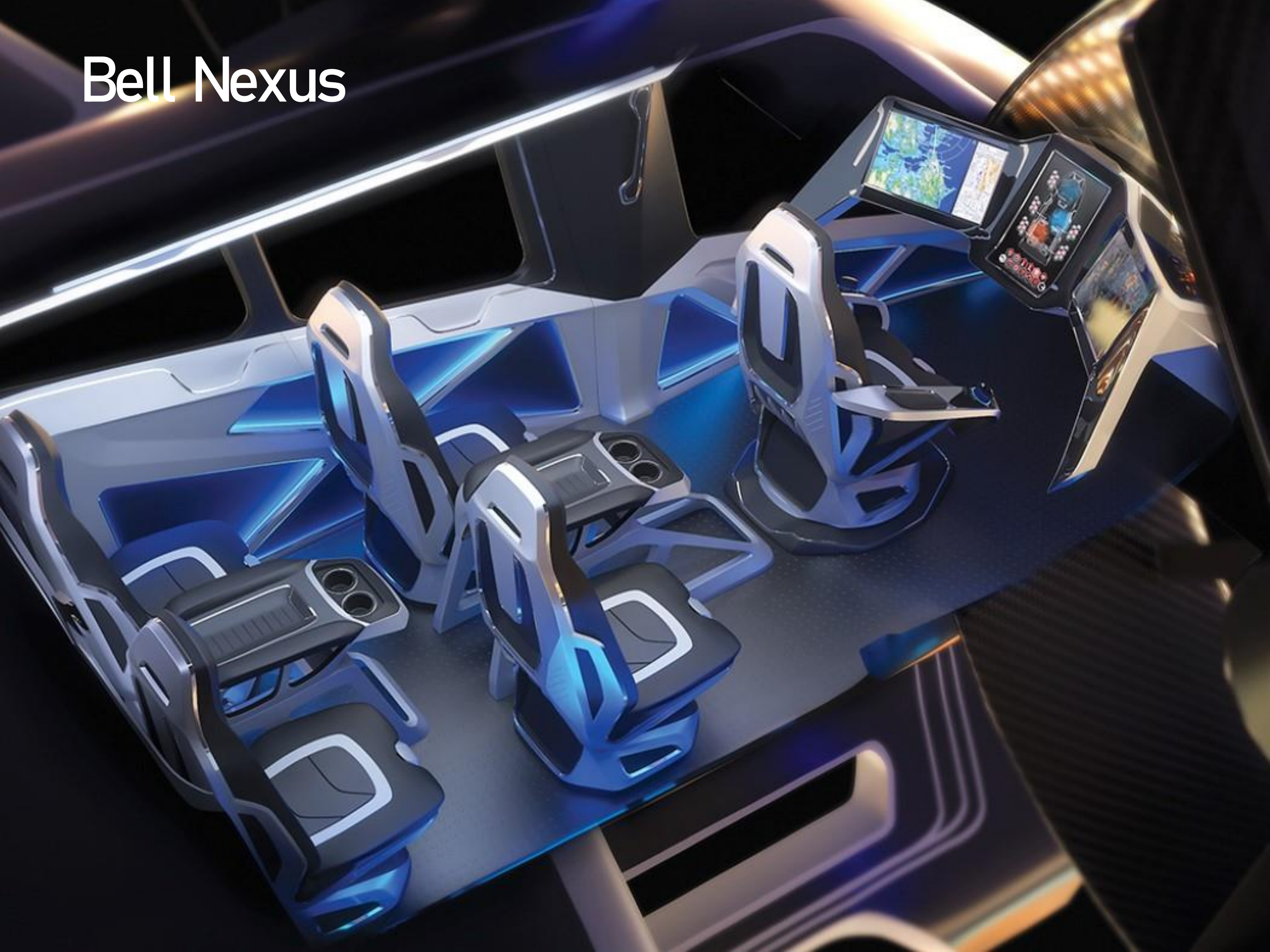
Cruise Speed and Range vs Configuration



Source: 2019-11-21 BAH report

Cabin Interior Design

Bell Nexus



Joby S4 Cockpit

Source: Joby brief https://youtu.be/F49BuJsUH-w

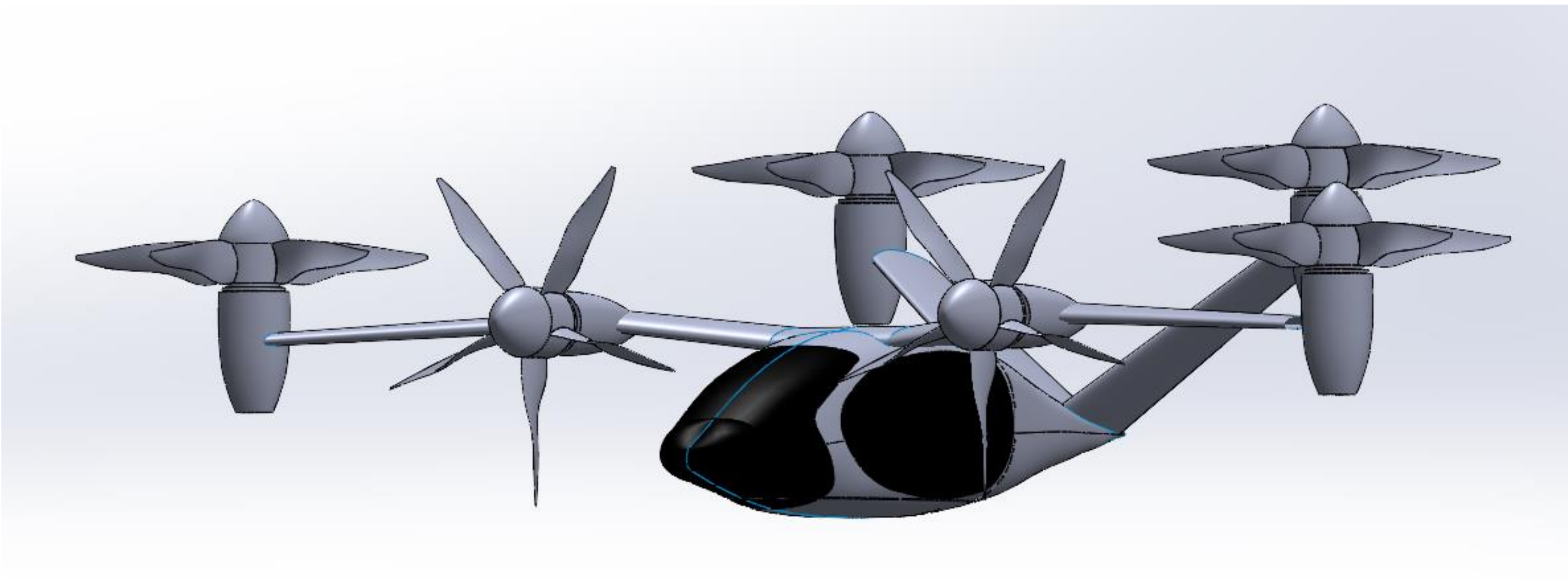
Vertical VX4 Cabin

Source:

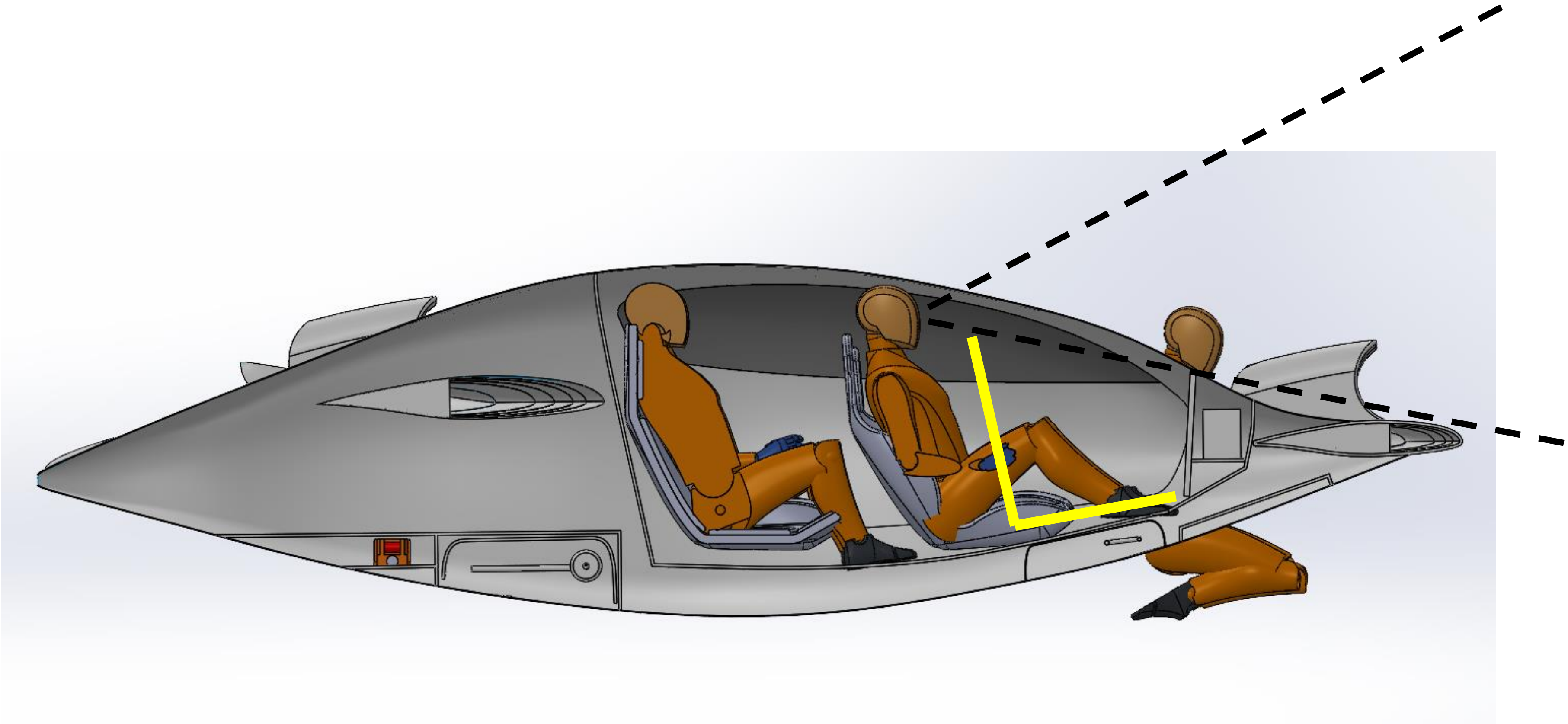
Vertical VX4 Cabin

Source:

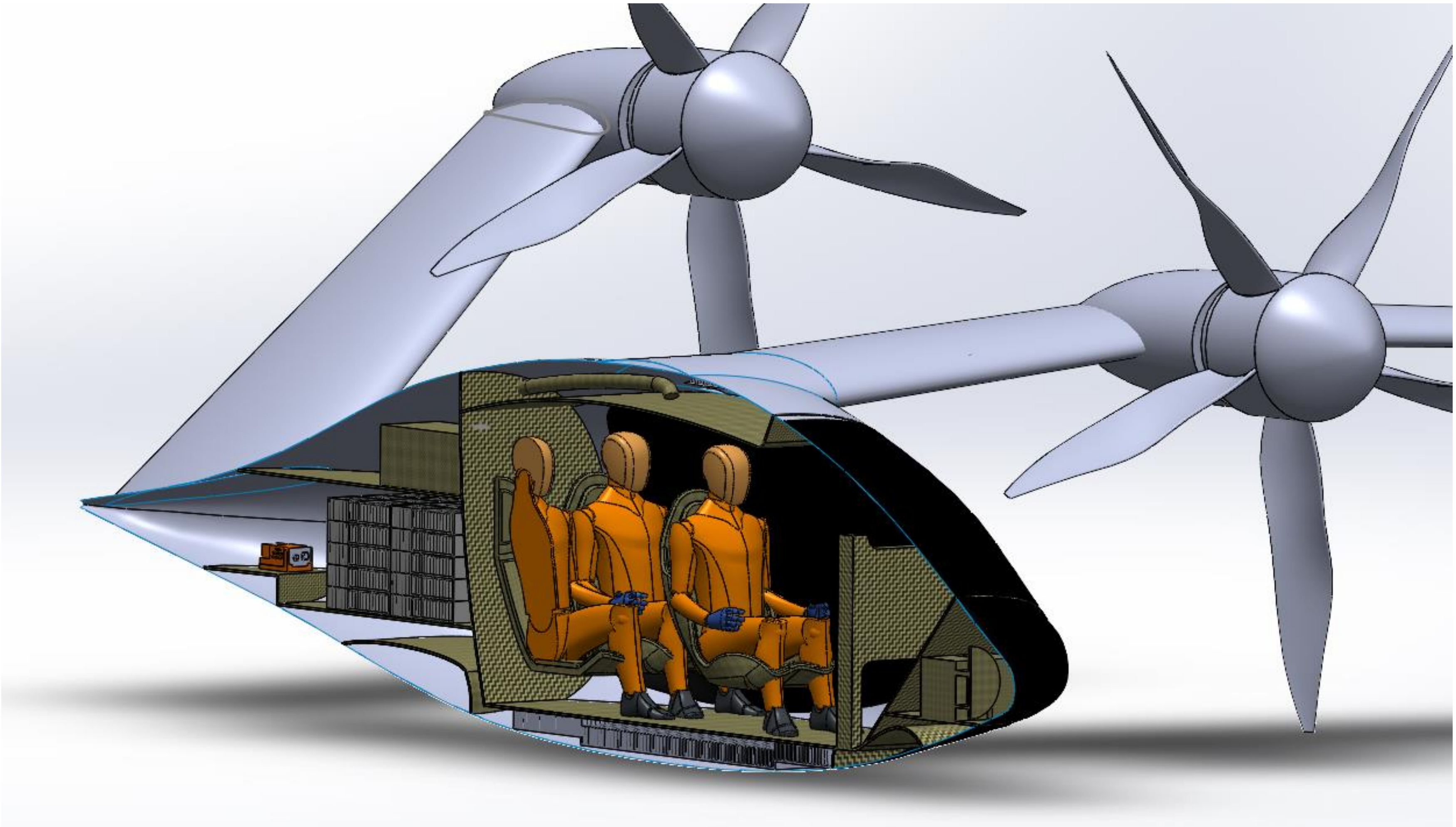
Use glass and doors judiciously, they are heavy



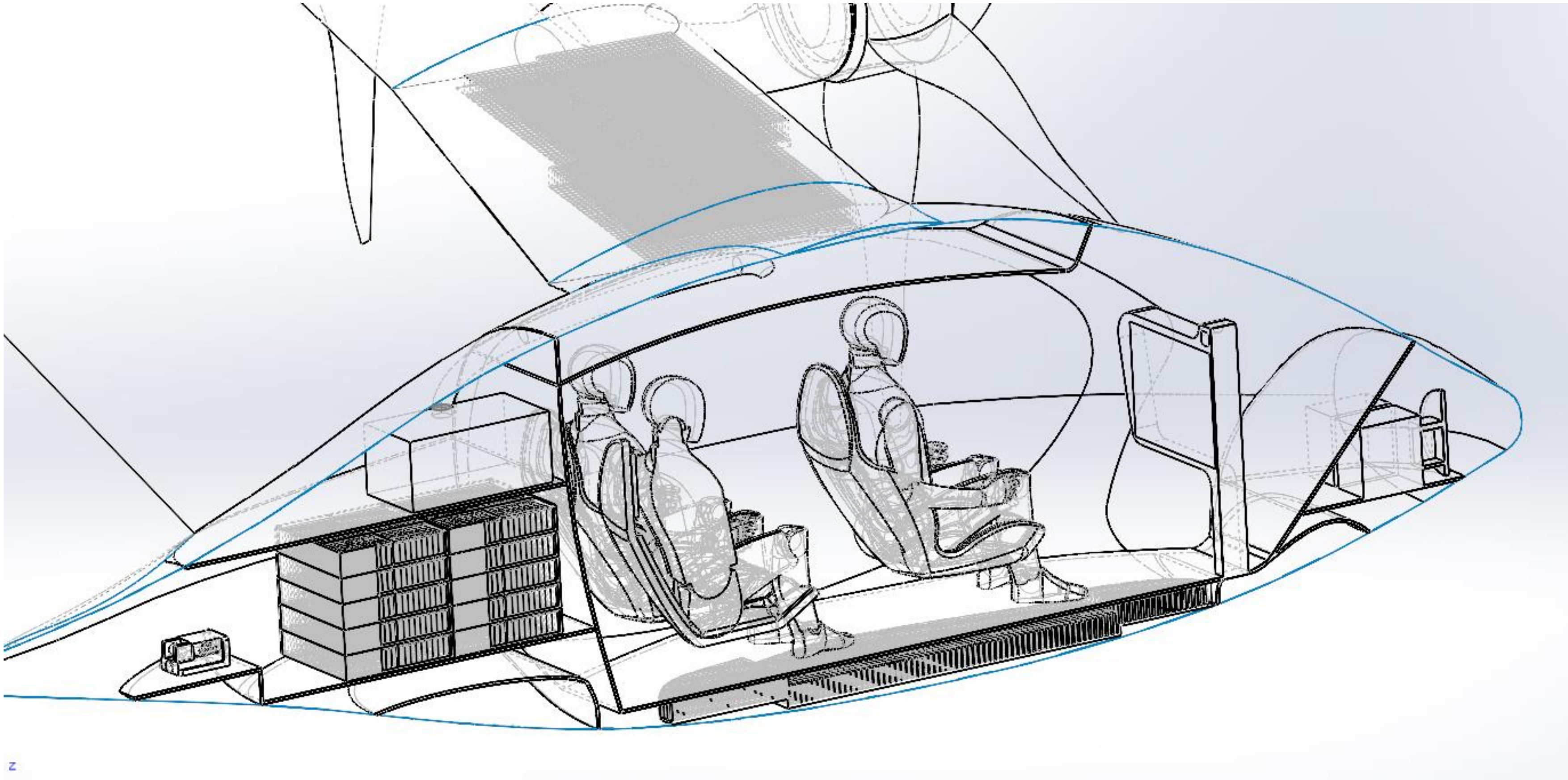
Check Visibility for Pilot



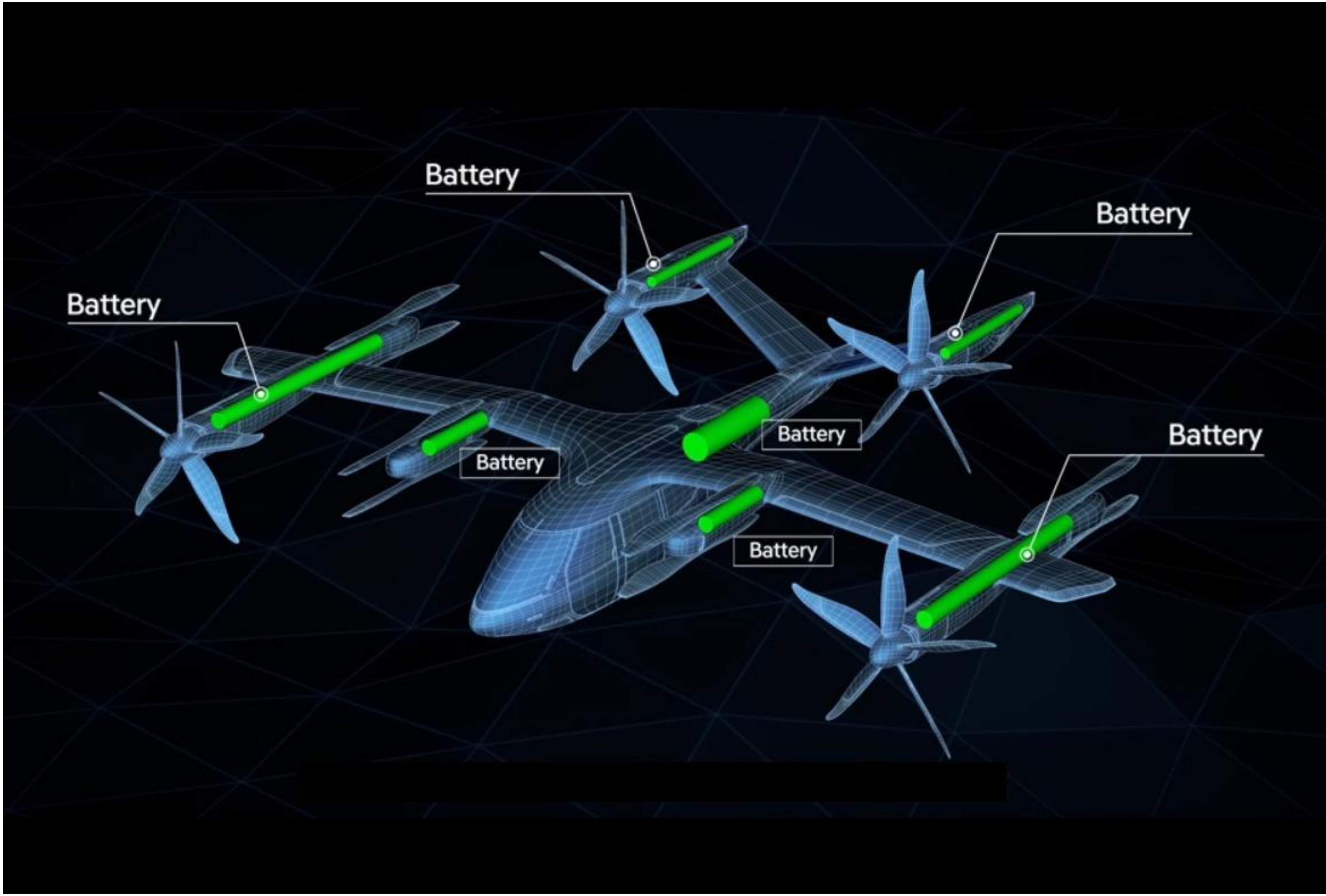
Make Sure Passengers are Comfortable



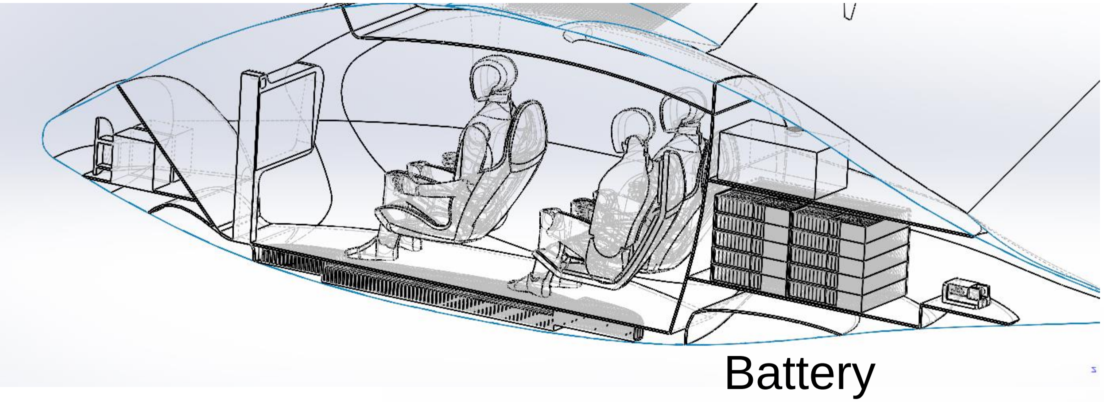
Packaging

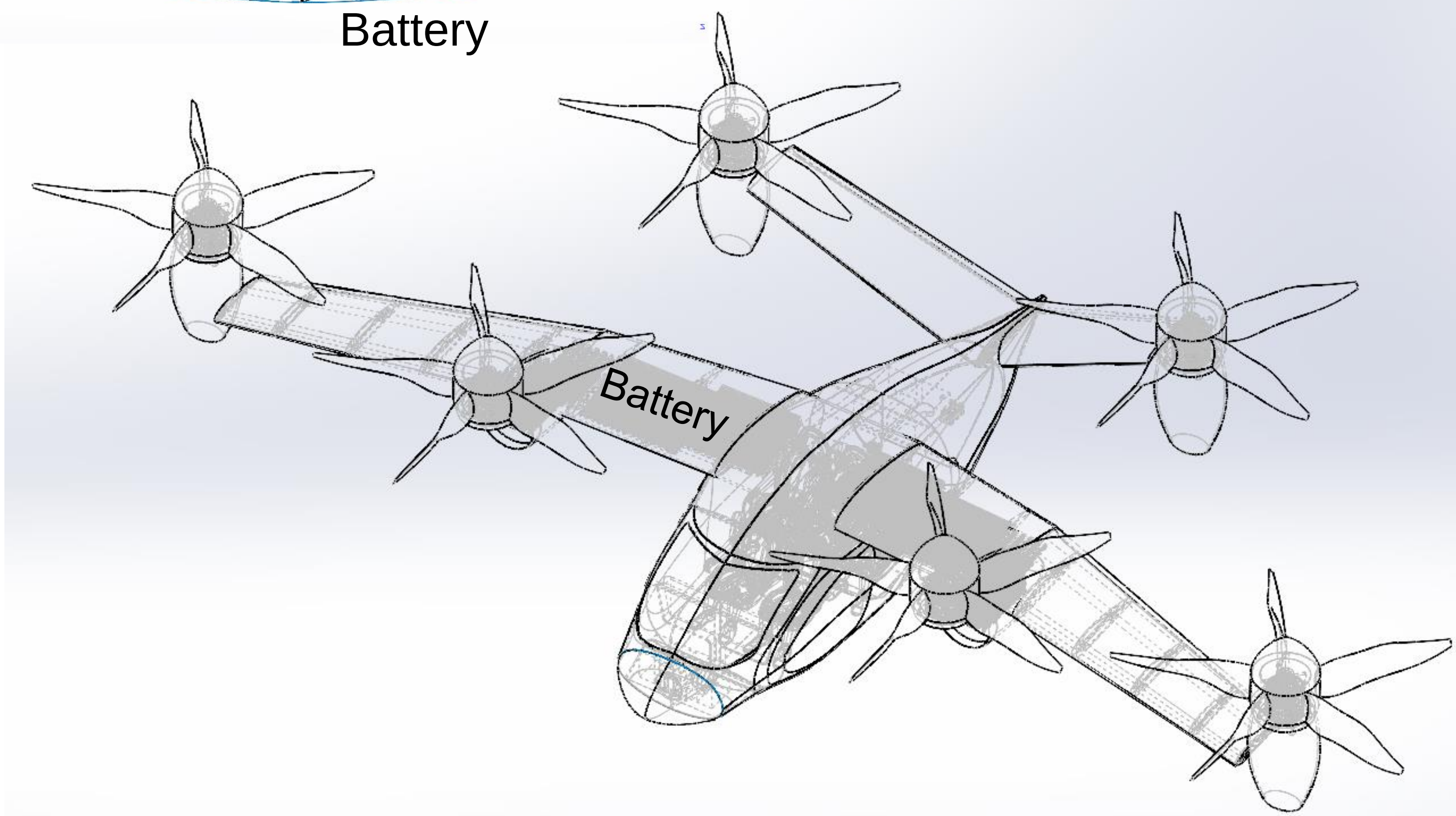


Think about Battery Placement

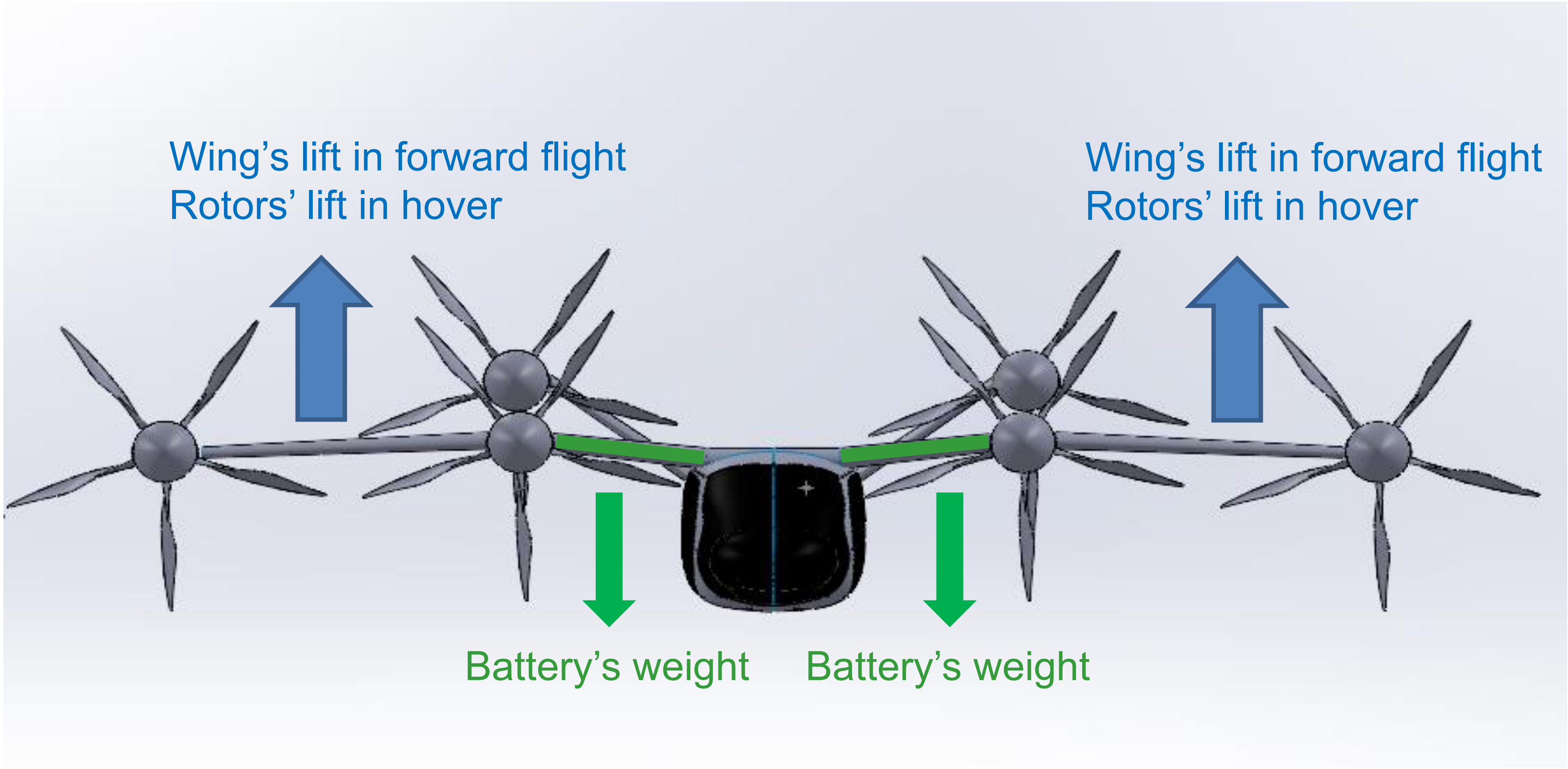


Put Battery in Fuselage or in Wing?



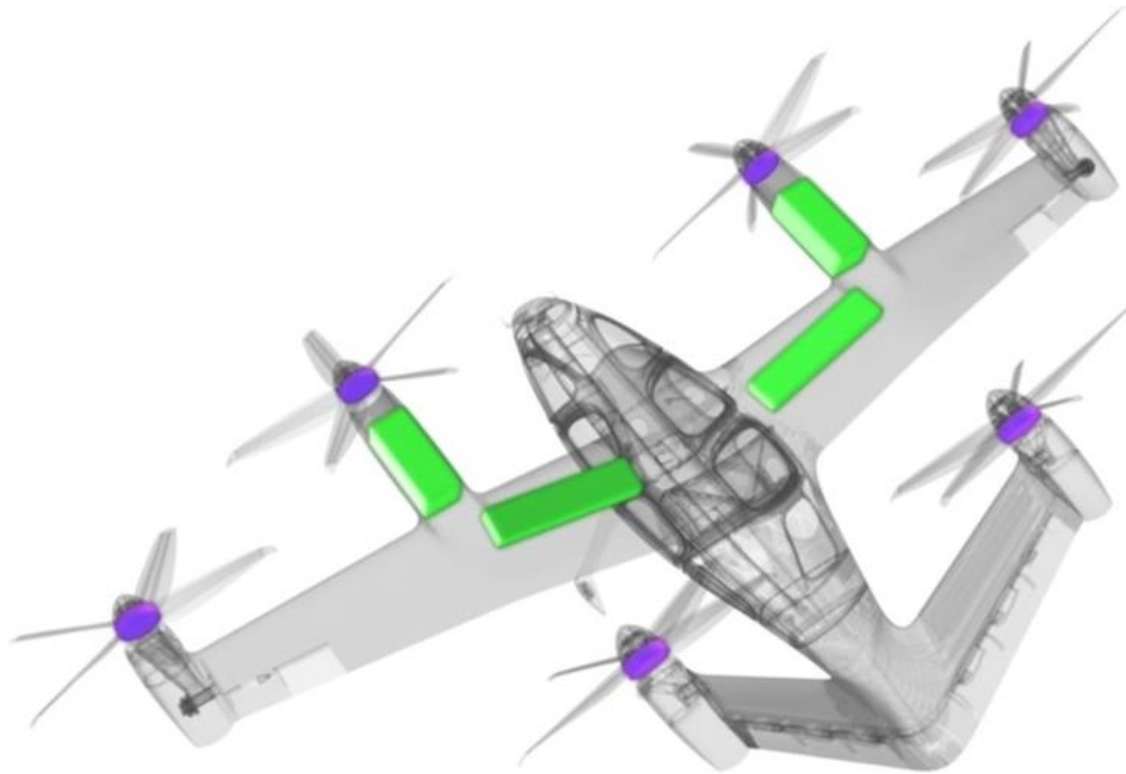


Consider Bending Moment in Wing



Joby S4 Uses 4 Battery Packs in Wing Only

- 6 propellors – can fly safely with the loss of any one propellor
- Each motor is redundant and powered by two separate inverters
- Each inverter is wired to a separate battery pack
- 4 isolated and redundant battery packs on board
- Motor continues to function if an inverter or pack fails

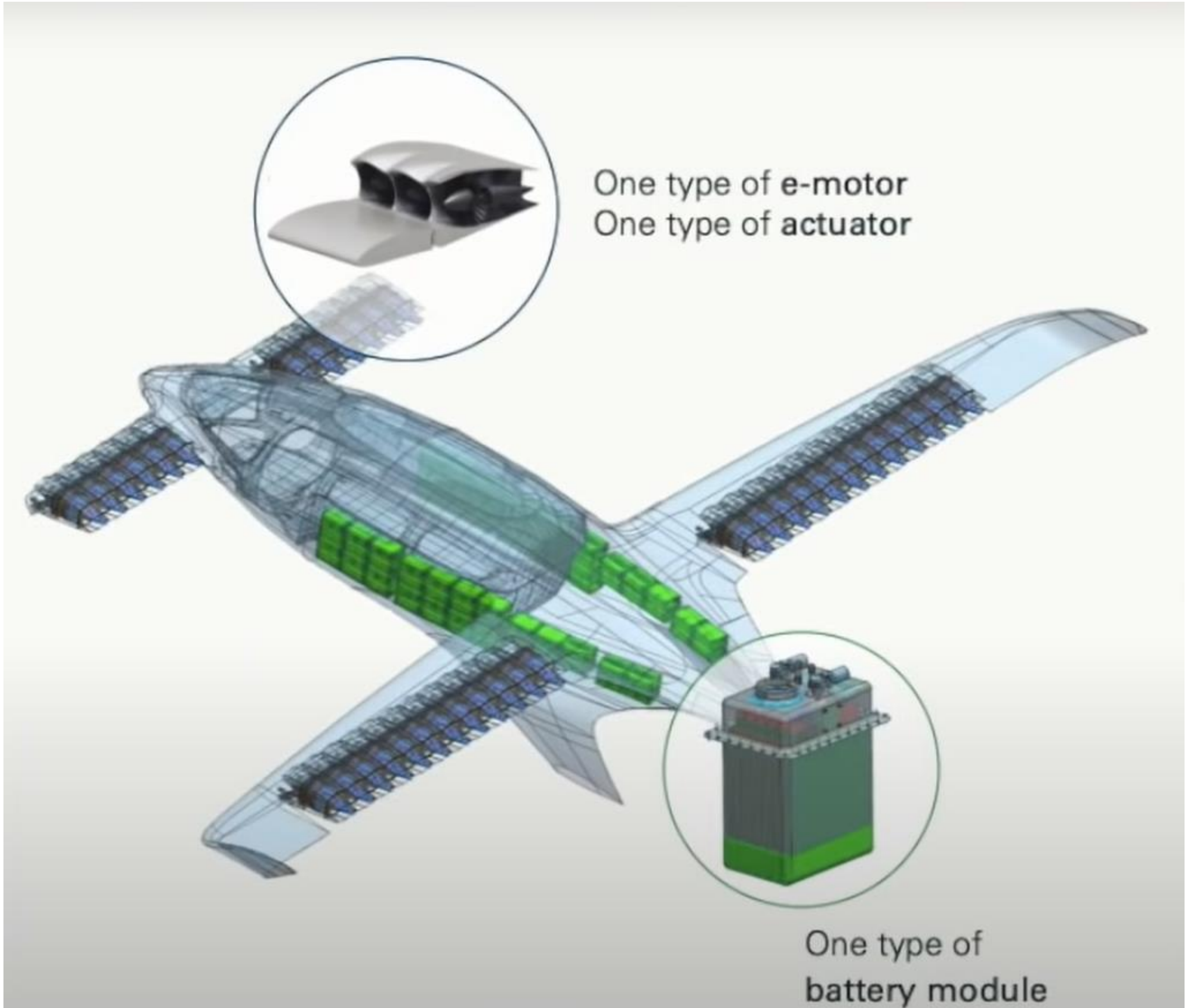


Source: Joby brief https://youtu.be/F49BuJsUH-w

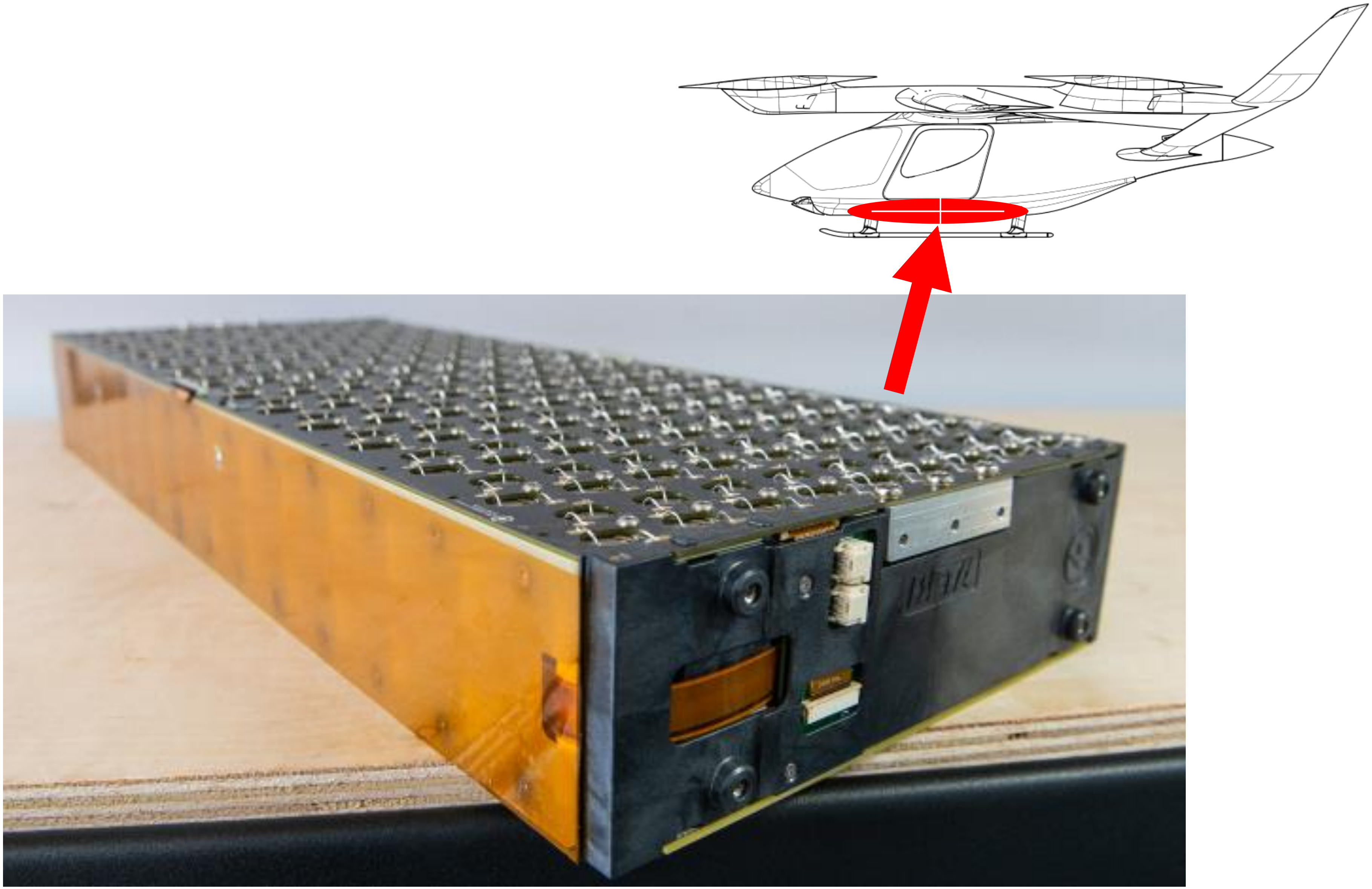
Joby S4 Uses 4 Battery Packs in Wing Only

Source: Joby brief https://youtu.be/F49BuJsUH-w

Battery on Sides of Fuselage

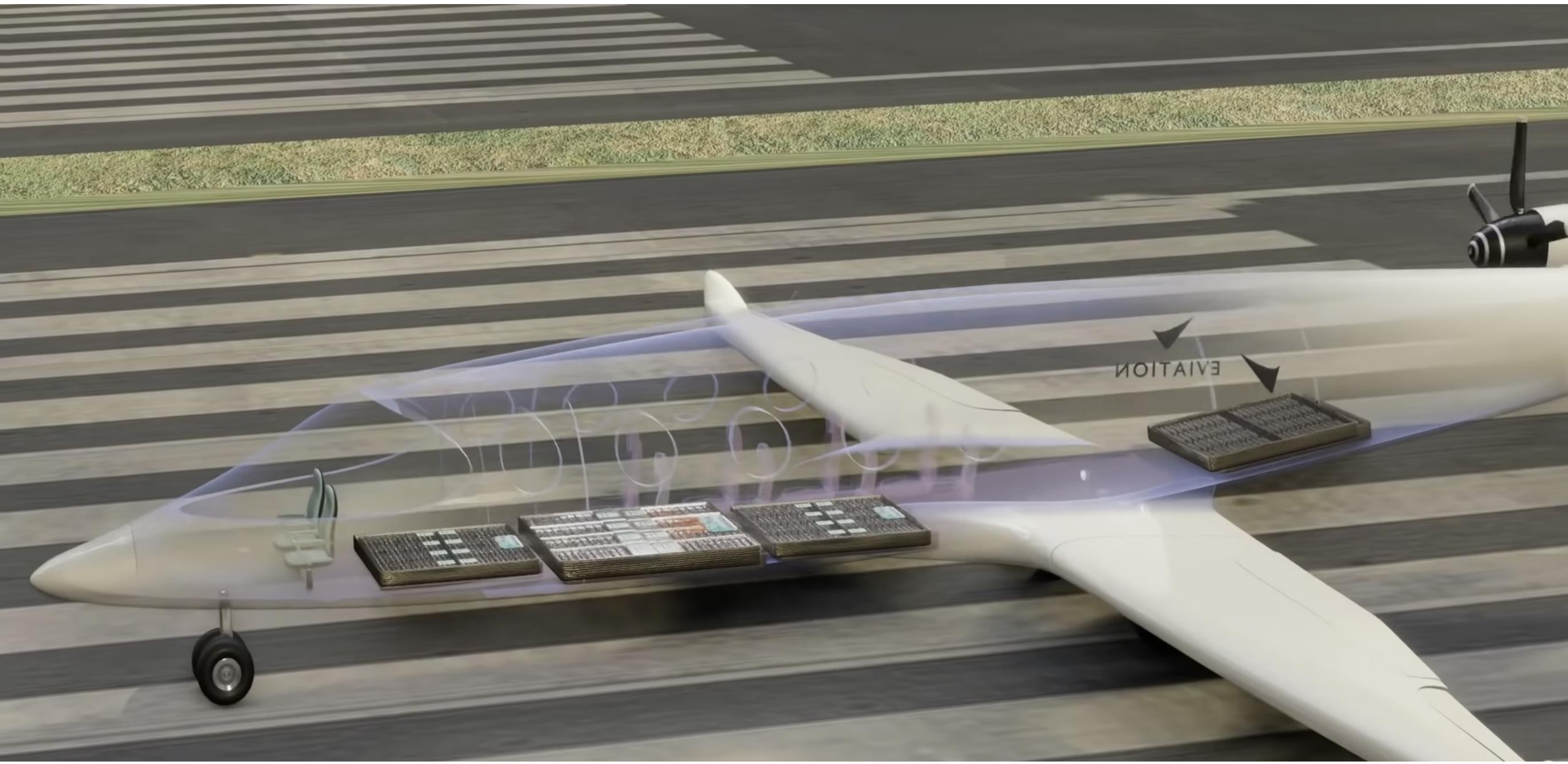


Think about Battery Placement

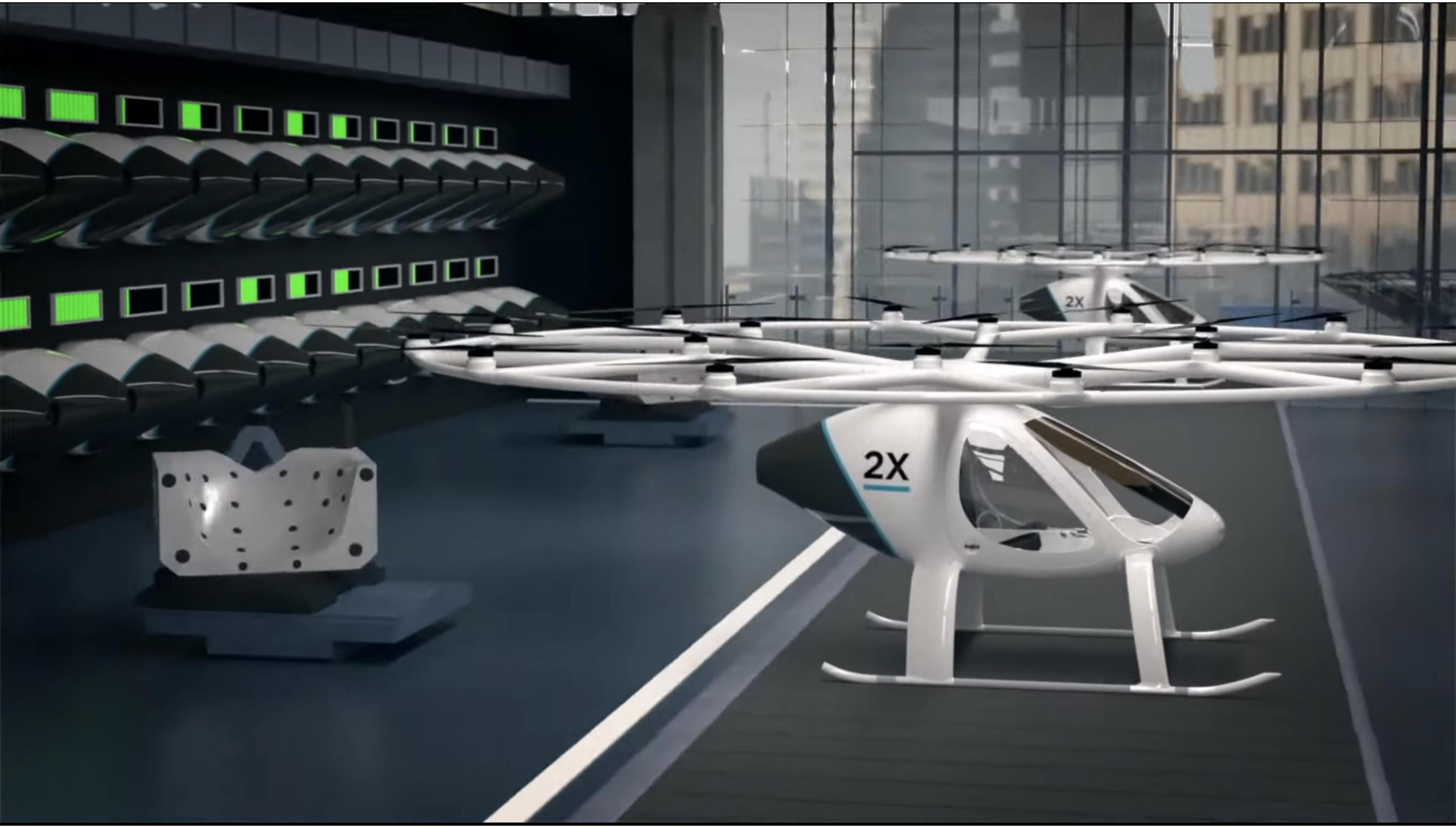


Source: https://www.beta.team/aircraft/

Batteries Are Placed in the Belly for Eviation

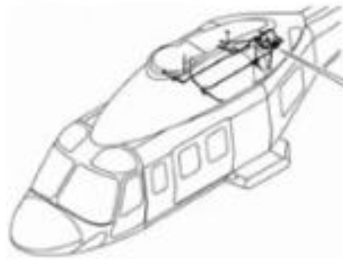


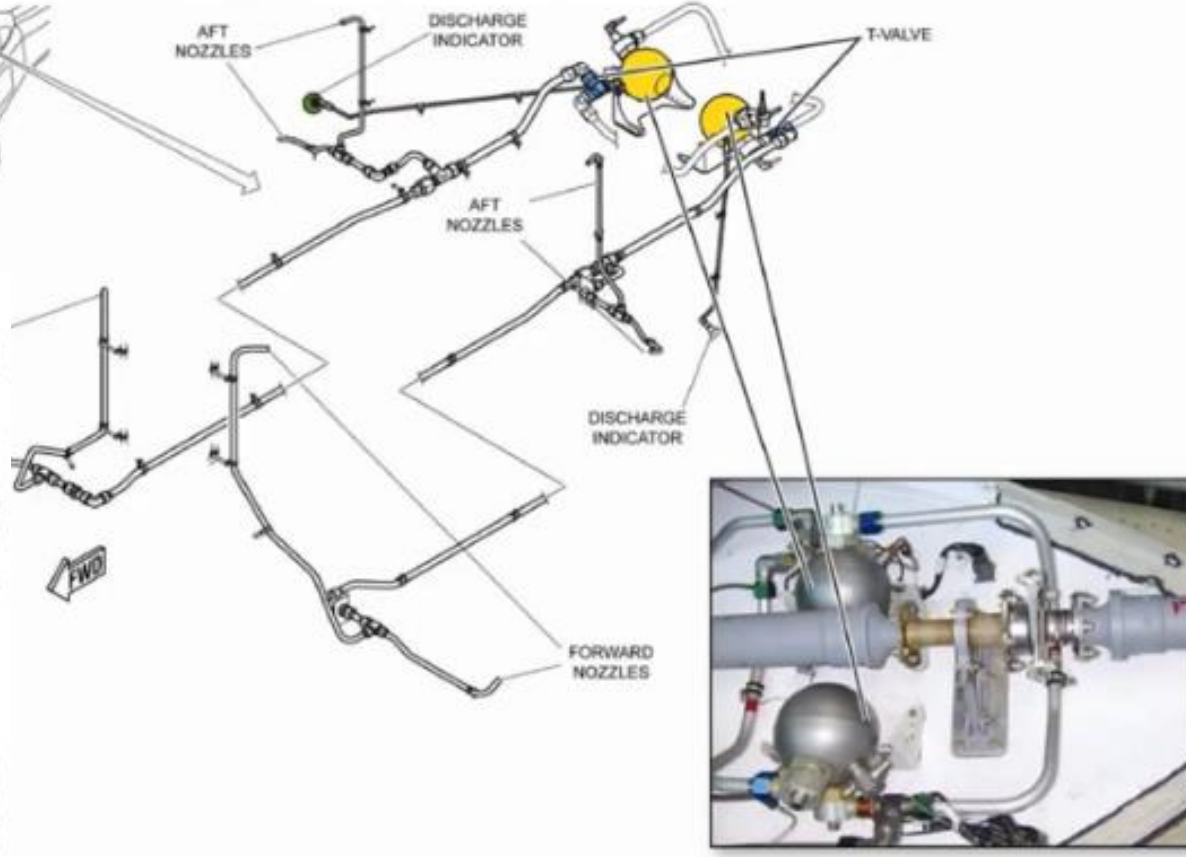
Volocopter's Automatic Battery Swapping



Detecting and Extinguishing Fire

Example: AW139 helicopter engine bay fire extinguishing system





FIRE EXTINGUISHING - GENERAL

The purpose of the fire extinguishing system is to protect the engine compartment from fire. The fire extinguisher system is composed by two identical and interconnected sub-systems one for each engine compartment. Each system comprises a fire extinguisher bottle and double-check T-valves. The extinguisher bottles are operated manually by the pilot on the FIRE EXTING control panel. When the pilot operates the system, the double-check T-valves make sure that only one of the two extinguisher bottles is operated. If the pilot operates the system a second time, the second bottle will be operated.
In addition two hand-held fire extinguishers are located in the cockpit and in the passenger cabin.

FIRE EXTINGUISHING SYSTEM – MAIN COMPONENTS

EXTINGUISHING BOTTLE

There are two 72 cubic inches extinguishing bottles filled with halon and pressurized with nitrogen gas. The bottles are installed on either side of the engine compartment and are cross-connected so that the content of any one of the two bottle can be discharged into any one engine bay and/or both bottles can be discharged into any one engine bay.
Each bottle is provided with a device which acts as a primary safety relief device. In case of overpressure, the halon agent is fully discharged outside the helicopter through the discharge indicator.
Upon discharge, the outer green disc is fired and a red circular band is displayed providing a visual indication during on ground inspection.

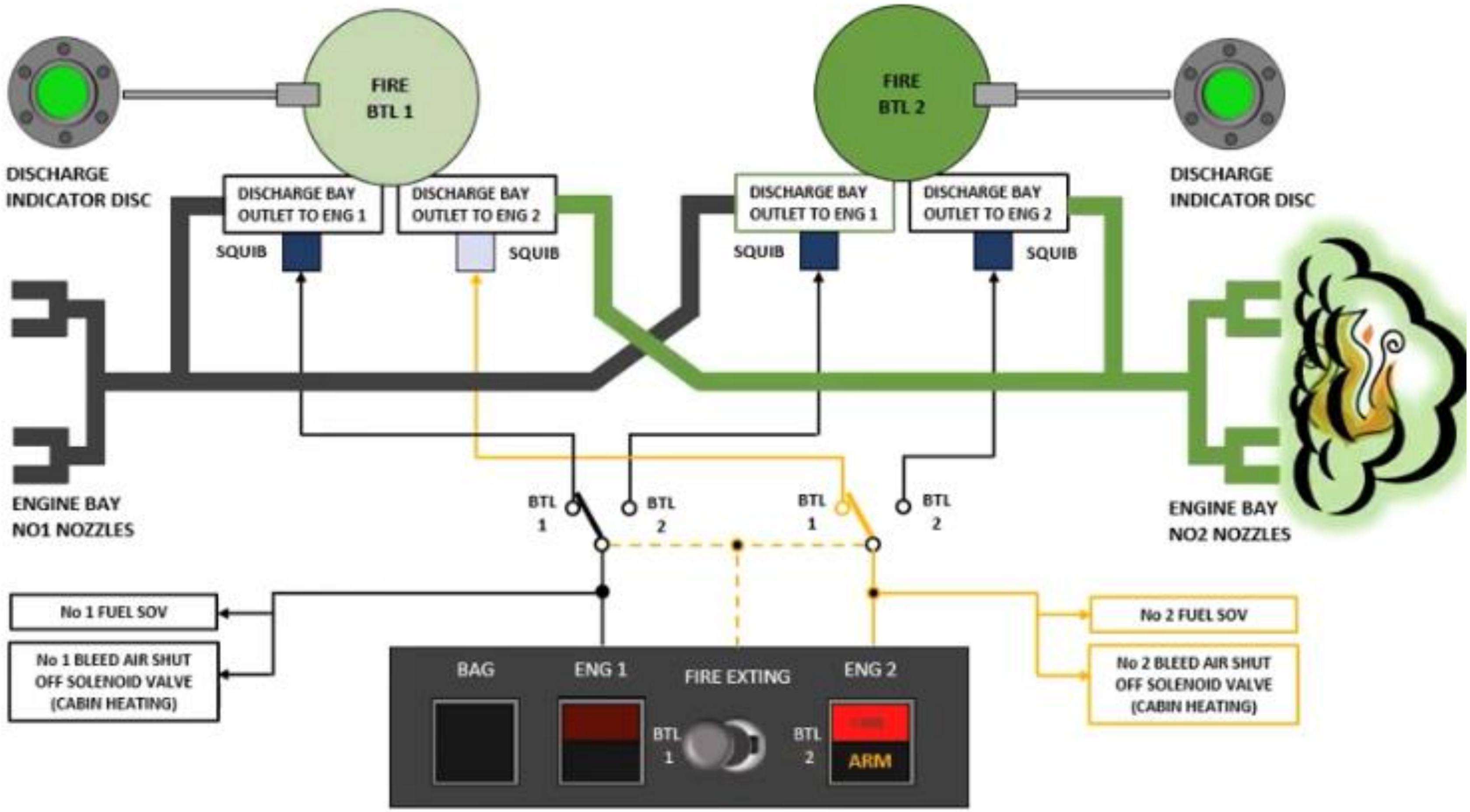
DOUBLE CHECK T-VALVE

Double-check T-valves interconnect the two sub-systems allowing to discharge halon into anyone of the two engine compartments.

Source: www.youtube.com/watch?v=02awRrNXqMc
Radial Solution Systems produces good training videos on AW139 helicopter

Detecting and Extinguishing Fire

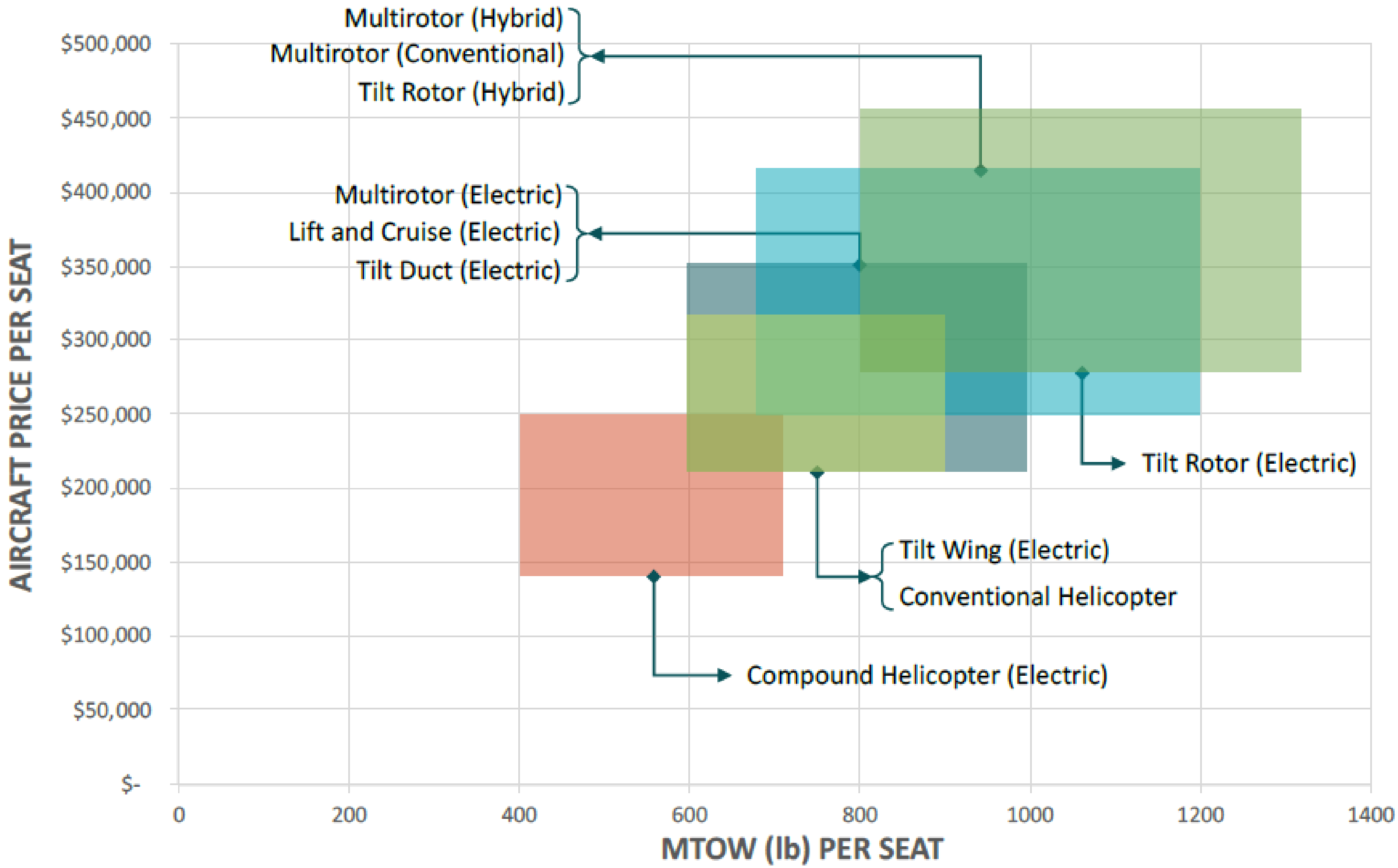
Example: AW139 helicopter engine bay fire extinguishing system



Source: www.youtube.com/watch?v=02awRrNXqMc
Radial Solution Systems produces good training videos on AW139 helicopter

Cost and Selling Price

Aircraft Price vs MTOW/Seat vs Configuration



Technical specifications of the vehicle types with uncertainty ranges; (top) Cruise Speed (mph) vs Range (miles), (bottom) Aircraft Price vs MTOW (lbs.)

Source: 2019-11-21 BAH report

One Way to Estimate Selling Price is by Using Price-per-Pound for Empty Weight

Vehicle	Vehicle type	Empty weight (lbf)	Price ($US)	Price per unit empty weight
Cessna Citation Mustang	Very light jet	5,600	$3,350,000	$598.2
Robinson R44	Light helicopter	1,450	$425,000	$293.1
Cessna 172R	General-aviation aircraft	1,691	$274,900	$162.6
Ferrari 488	Sports car	3,362	$272,700	$81.1
Tesla Model S (75D)	Electric car	3,549	$48,182	$13.6
Honda Accord	Sedan	3,170	$22,455	$7.1

Source: https://convex.mit.edu/publications/arthur_ondemand.pdf

The $/lb will for eVTOL aircraft will depend on the design's complexity, business model and volume. Example: for a MTGW=7000 lbs (empty weight = 5900 lbs) eVTOL aircraft, the selling price could be

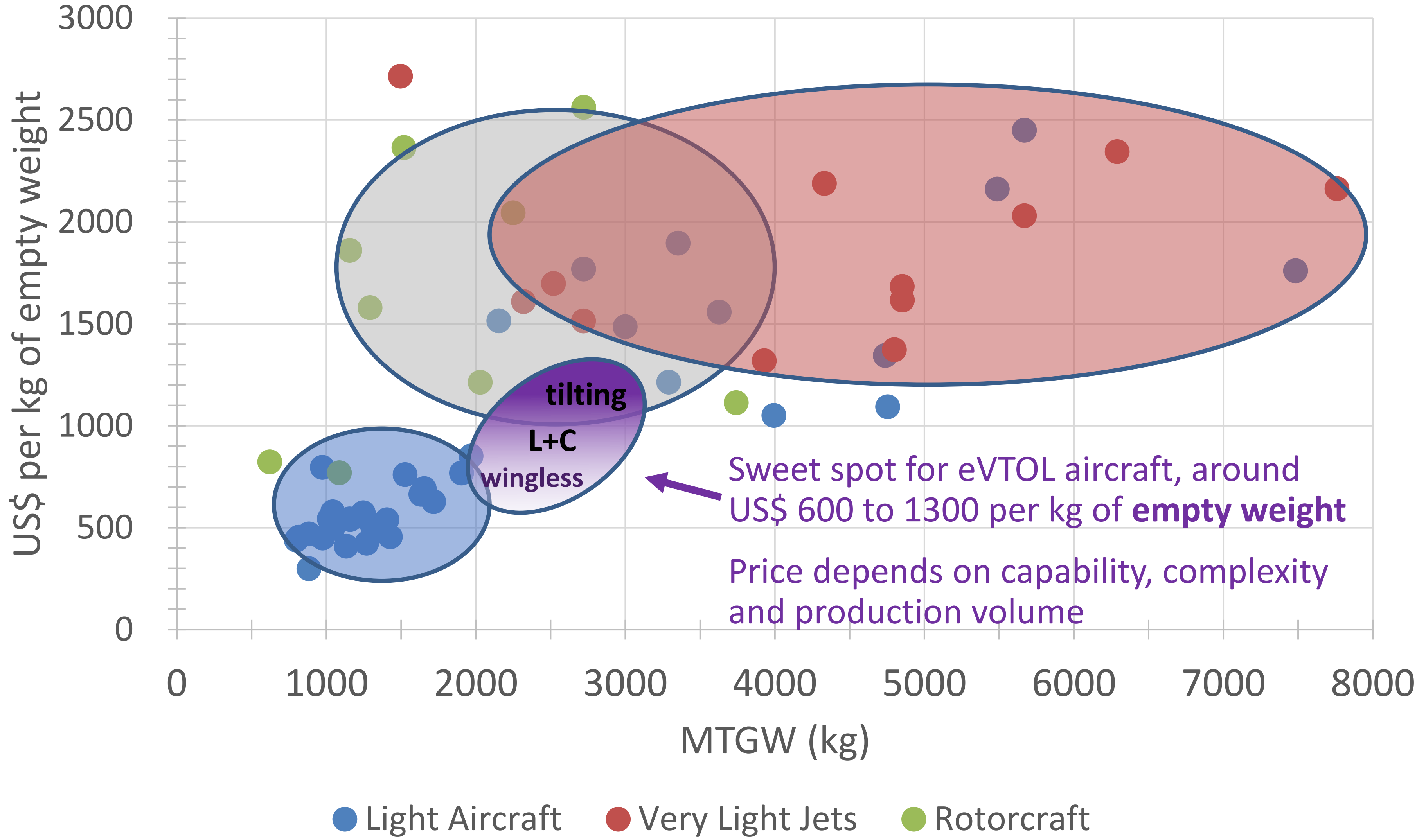
250 $/lb x 5900 lbs = US$ 1.48 million **for wingless, multicopter type**

350 $/lb x 5900 lbs = US$ 2.07 million **for lift + cruise type**

500 $/lb x 5900 lbs = US$ 2.95 million **for tiltrotor and tiltwing type**

The eVTOL $/kg are author's estimate based on bottom-up calculations

Price-per-kilo Selling Price Data for Many Aircraft



The eVTOL $/kg are author's estimate based on bottom-up calculations

Should Also Conduct a Bottoms Up Estimate

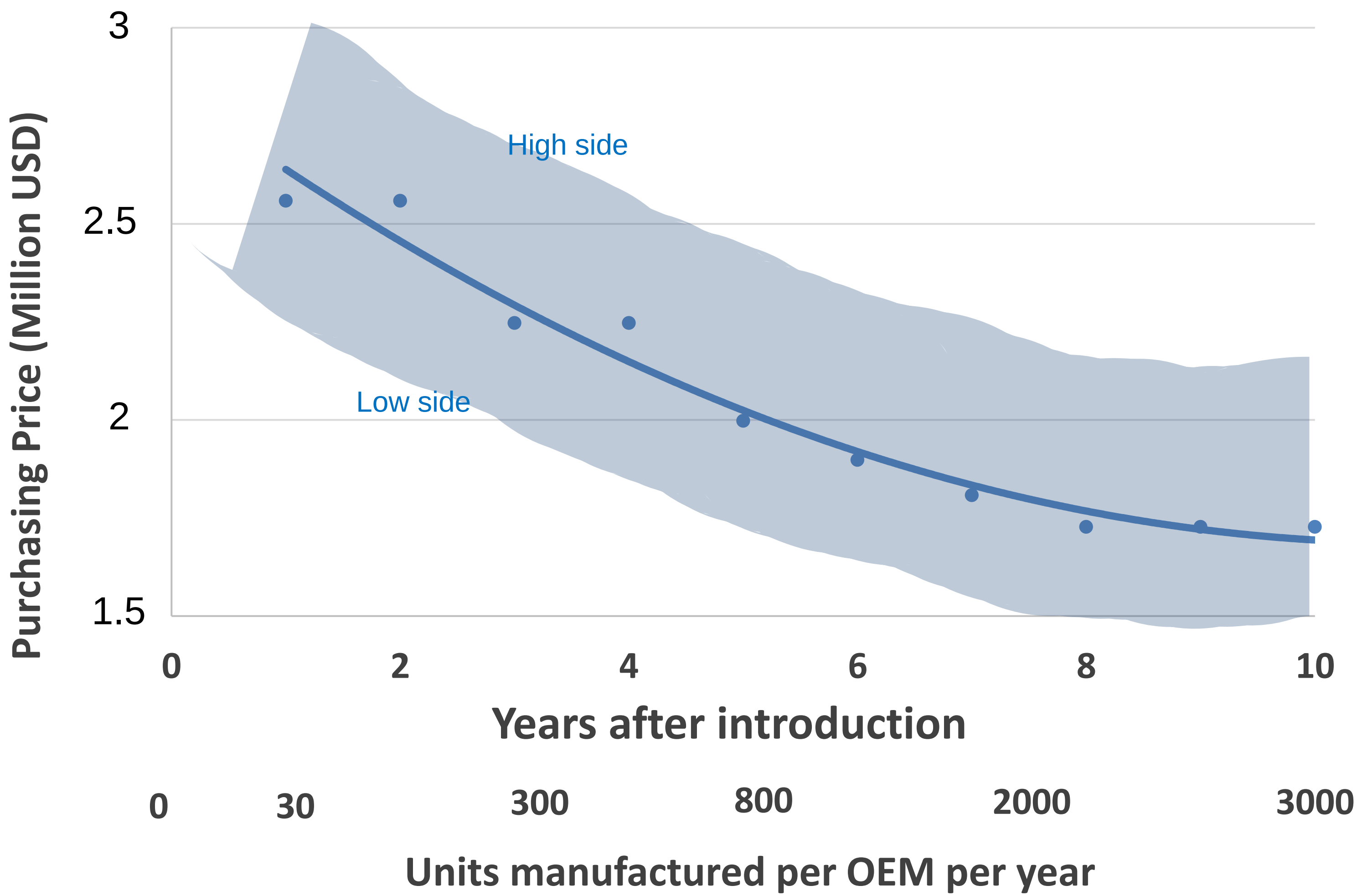
- **Avionics and flight control cost**
  - Flight computers, sensors, navigation instruments, communication equipment,…..
  - Control actuators
- **Battery cost**
  - Cells
  - Management system and cooling
  - Packaging
- **Structure cost**
  - Fuselage, wing, tail, windows, landing gear, motor pylon, tilting mechanism, …..
- **Propulsion cost**
  - Electric motor, inverter, electrical wiring, connectors, rotors, engine, generator, …..
- **Miscellaneous**
  - Furnishing: seats, cabin interior
  - Parachute?
  - Environmental control system?
  - Painting and final assembly
  - Contingency
- **Overhead, G&A, Marketing, Profit**

Optimistic Global eVTOL Market Forecast

	0 eVTOL	0 trip/year
2025		
	10,000 eVTOL	60 million trips/year
2030		
	200,000 eVTOL	1 billion trips/year
2040		
	8,000,000 eVTOL	45 billion trips/year

Source: Boston Consulting Group 2018, Morgan Stanley 2018, Porsche Consulting 2018, UBS 2019, Lufthansahub 2021

Aircraft Unit Price vs. Production Volume

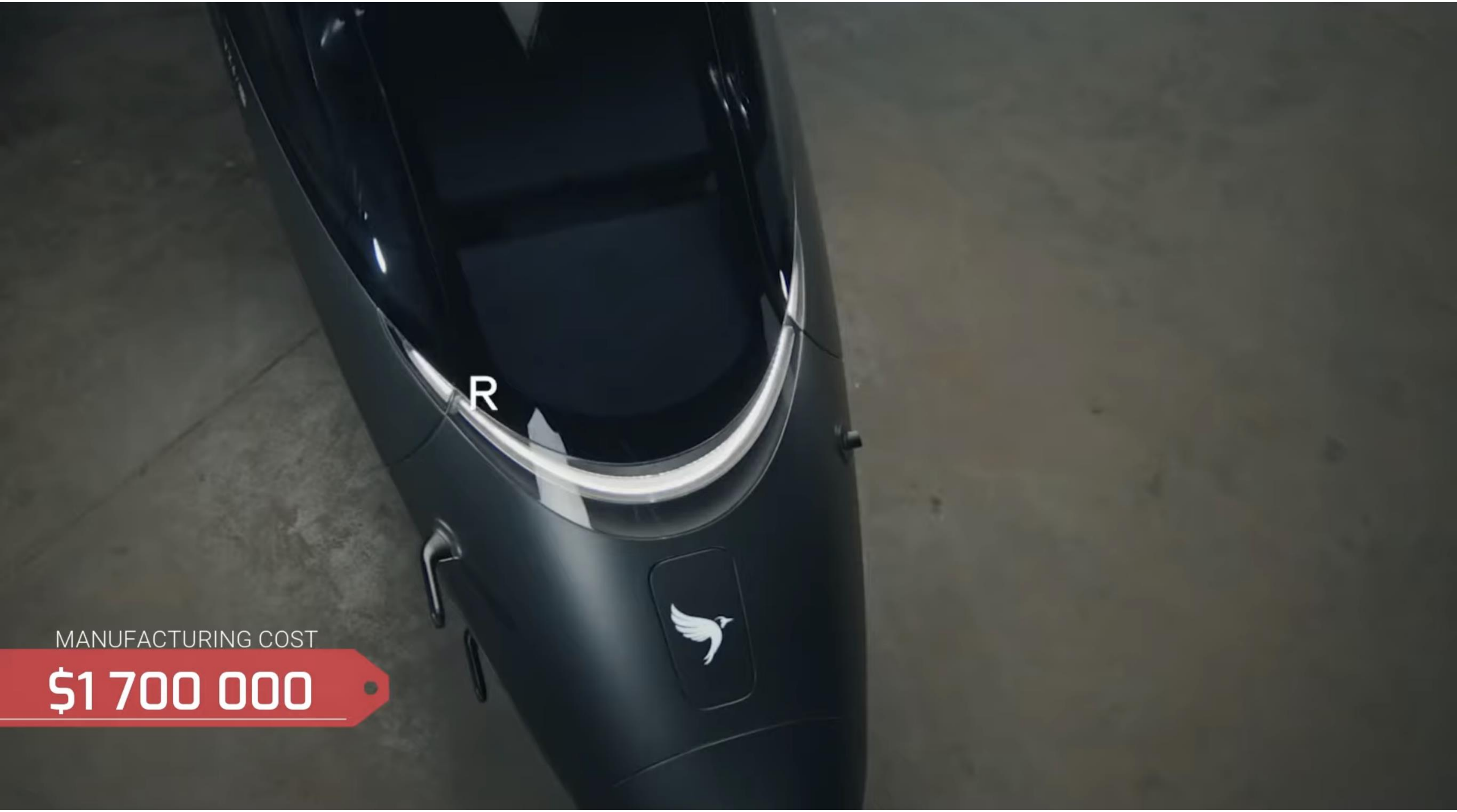


For generic eVTOL aircraft based on bottom-up calculations by James Wang

Archer 2-Pax Maker

Source: https://www.youtube.com/watch?v=Ryy-7tcZqC8

Vertical VX-4A

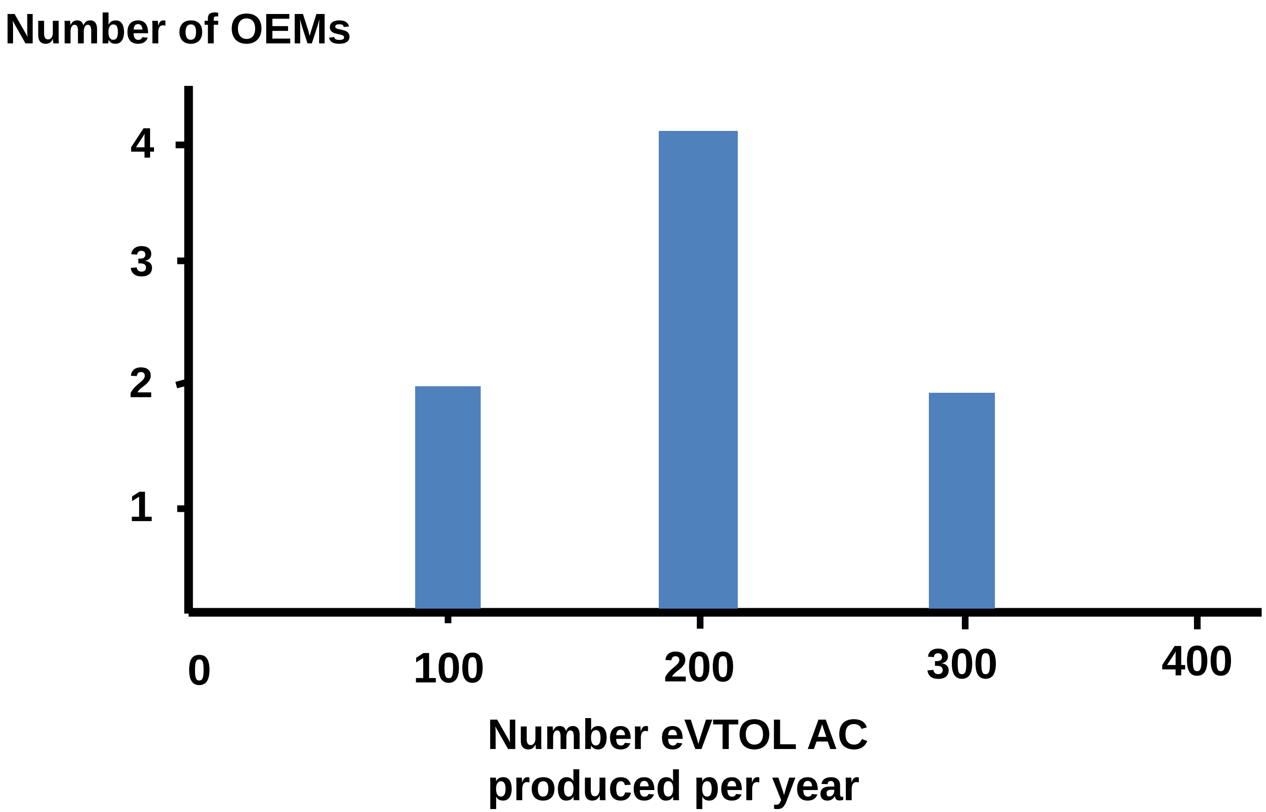


Source: https://www.youtube.com/watch?v=Ryy-7tcZqC8

Joby S4

Source: https://www.youtube.com/watch?v=Ryy-7tcZqC8

Estimate eVTOL Aircraft Produced in 2030



Assume 8 OEMs received type certificates. 2 OEMs produce 100 eVTOLs / year, 4 OEMs produce 200 eVTOLs / year, and 2 OEMs produce 300 eVTOLs per year. Total = 1,600 eVTOL aircraft produced per year

Estimates by James Wang

Annual eVTOL Sales in 2030

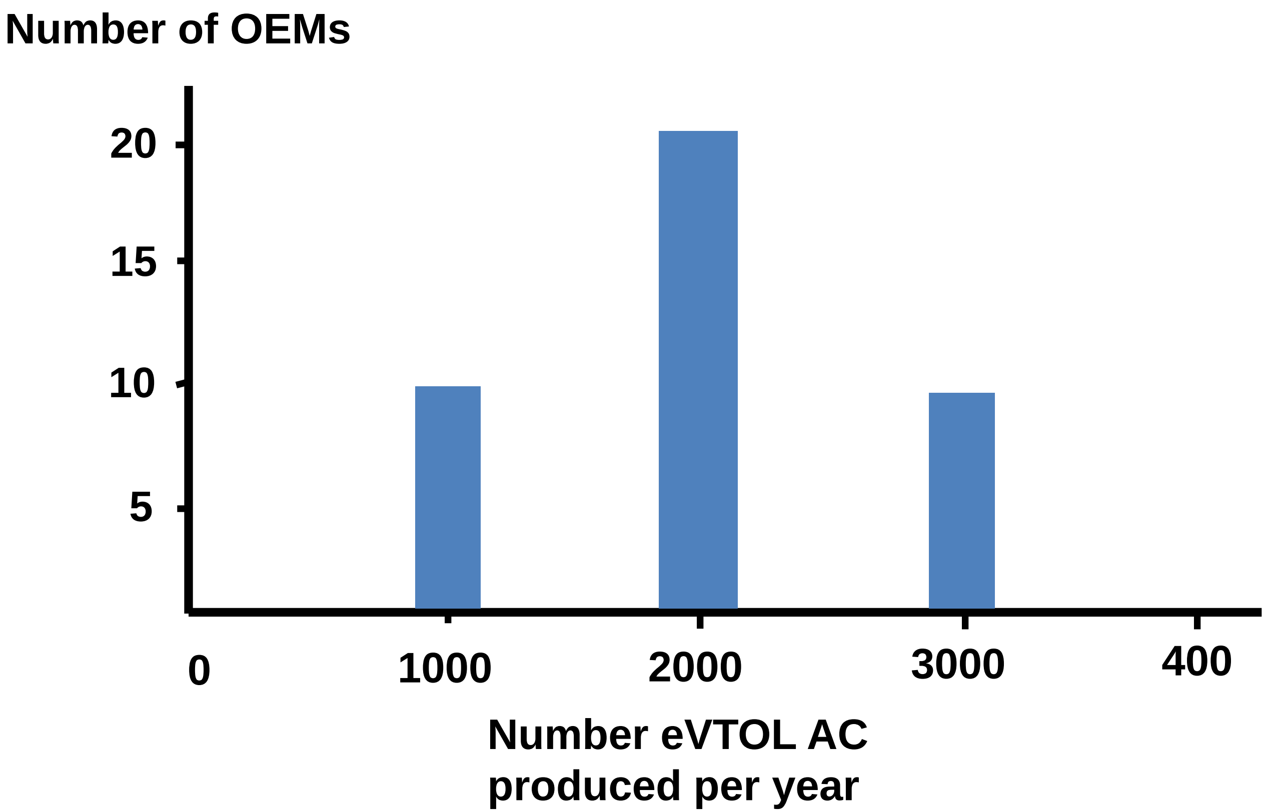
Assumptions:

- **1600 eVTOL Aircraft produced per year**
- **US $2.2 million per aircraft (today's dollar)**

Annual aircraft sales = 1600x $2.2M = $3.52 billion

Compare this to the forecasted global new civil helicopter sale for 2030 which could be around US$6-$8 billions annually (not including spares, support and training).

Estimate eVTOL Aircraft Produced in 2040



Assume 40 OEMs received type certificates. 10 OEMs produce 1000 eVTOLs / year, 20 OEMs produce 2000 eVTOLs / year, and 10 OEMs produce 3000 eVTOLs per year. Total = 80,000 eVTOL aircraft produced per year

Estimates by James Wang

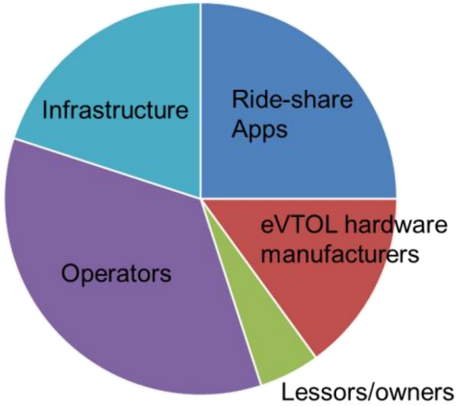
Annual Market Size in 2040

Assumptions:

- **80,000 eVTOL Aircraft produced per year**
- **US $1.6 million per aircraft (today's dollar)**

Annual aircraft sales = 80,000x $1.6M = $128 billions
Adding spares and support could total $200 billions

If eVTOL hardware = 15% of total manned air mobility ecosystem



Steady state revenue
2035 and beyond

Then the total annual market value is $200b/.15 = US $1.3 trillion

Battery Amortization is the Key Component in Direct Operating Cost (DOC) for eVTOL

- Assume the battery can last 400 charge cycles. Assume each cycle delivers half hour flight time or 100 km range with reserve. That means a total of 200 hours of usage. Then, the total kilometers travelled = 40,000 km

- Assume for a 3175 kg eVTOL aircraft, the battery we use is 1,000 kg and 250 wh/kg at pack level, then that gives 250 kwh capacity.

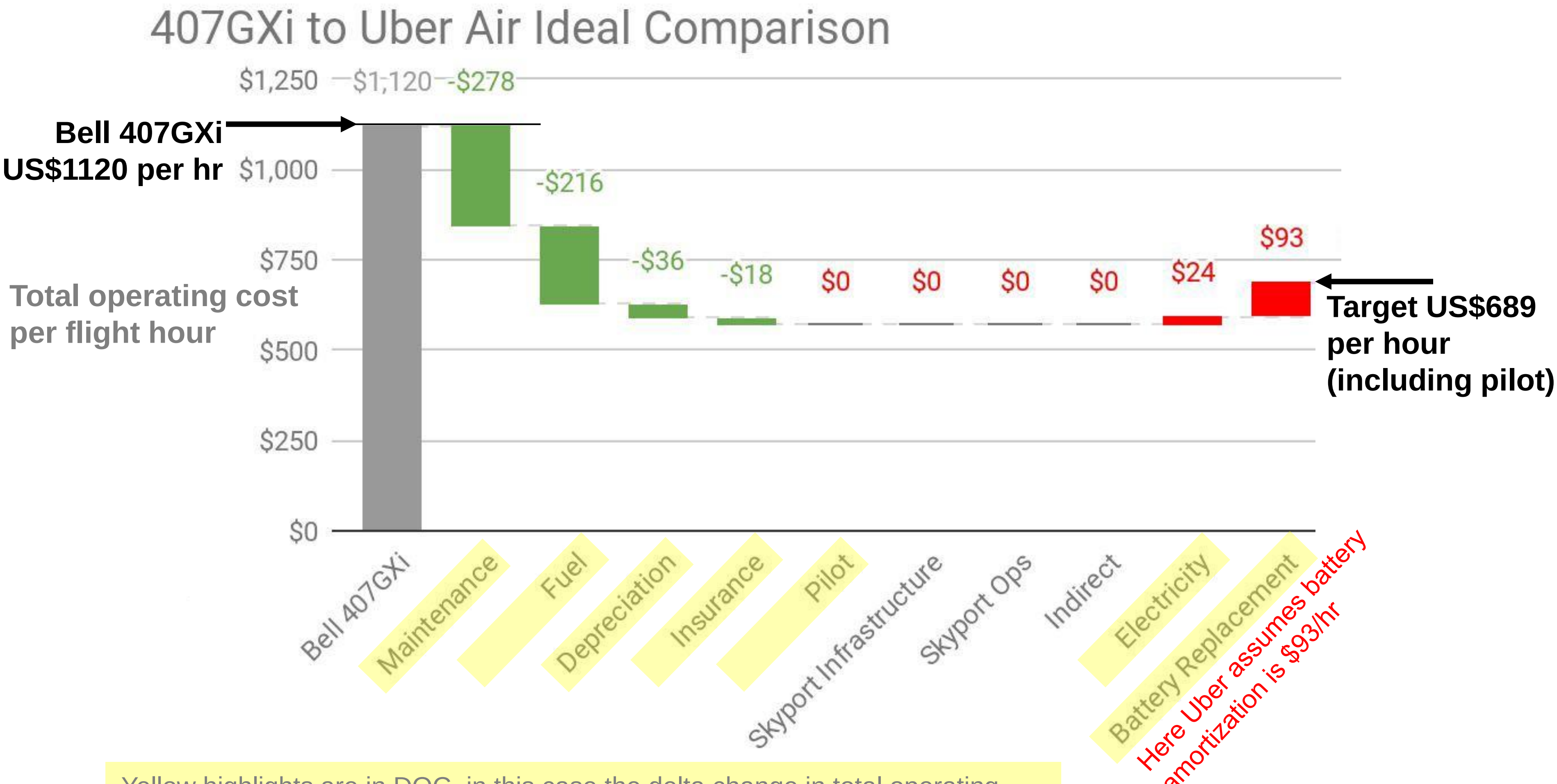
- If the battery *pack* cost is US $100 per kwh, then $100/kwh x 250 kwh = $25,000 ⬅ *Note, aviation may pay 2x or 3x more than auto battery !*

- $25,000 /40,000 km = $0.625 per flight kilometre = US$1 per mile

- $25,000 / 200 h = $125 per hour is battery amortization cost, also need to add electricity charging cost ($0.12/kwh in US, $0.21 per kwh in Europe)

The operating cost of eVTOL aircraft is higher than electric cars because aircraft consumes more kWh of energy per hour of operation.

UberAir Targets a Total Operating Cost for eVTOL to be 35% lower than operating helicopters

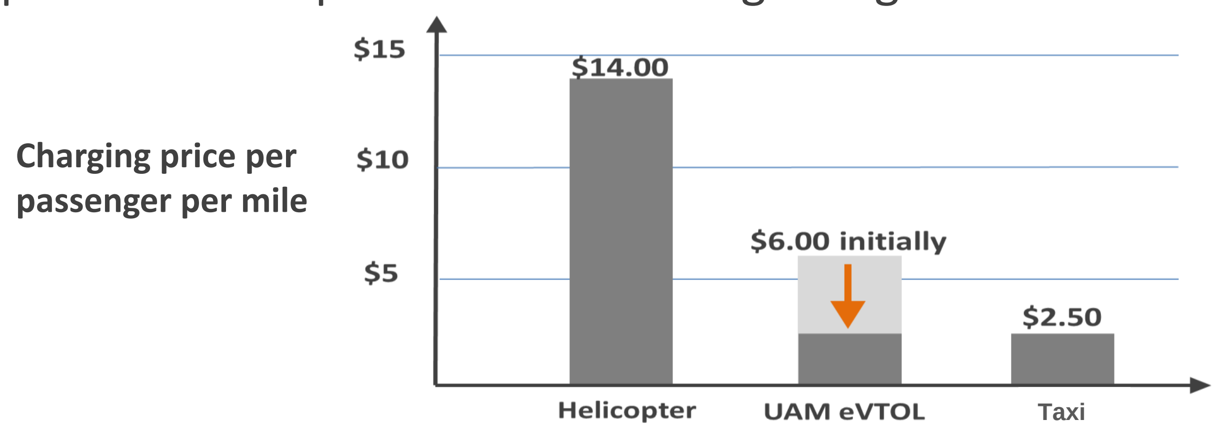


Yellow highlights are in DOC, in this case the delta change in total operating cost or DOC = -$278-$216-$36-$18+$24+93= - $431

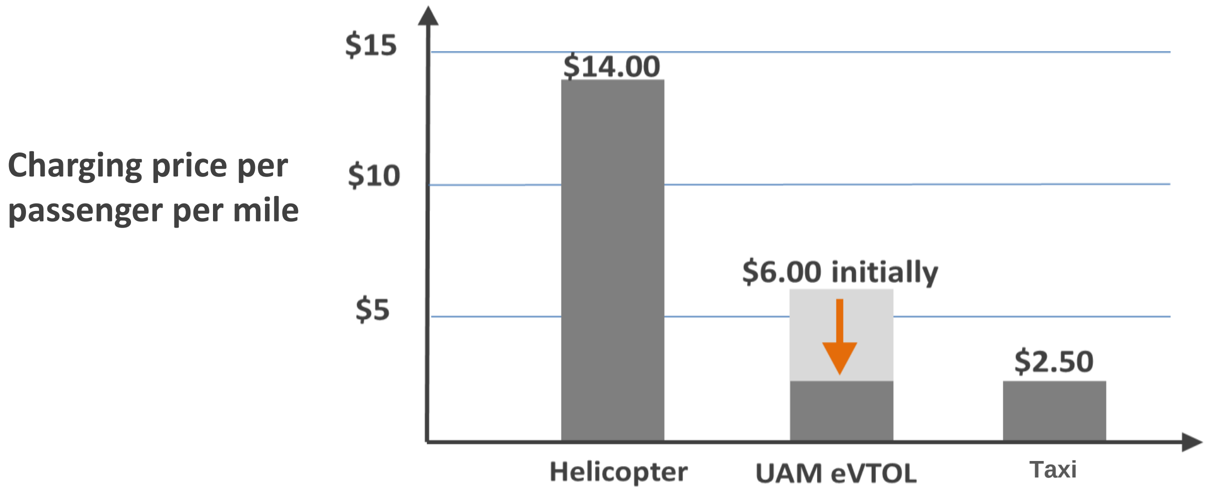
Source of graph: Uber presentation at 2019 VFS Forum, Philadelphia

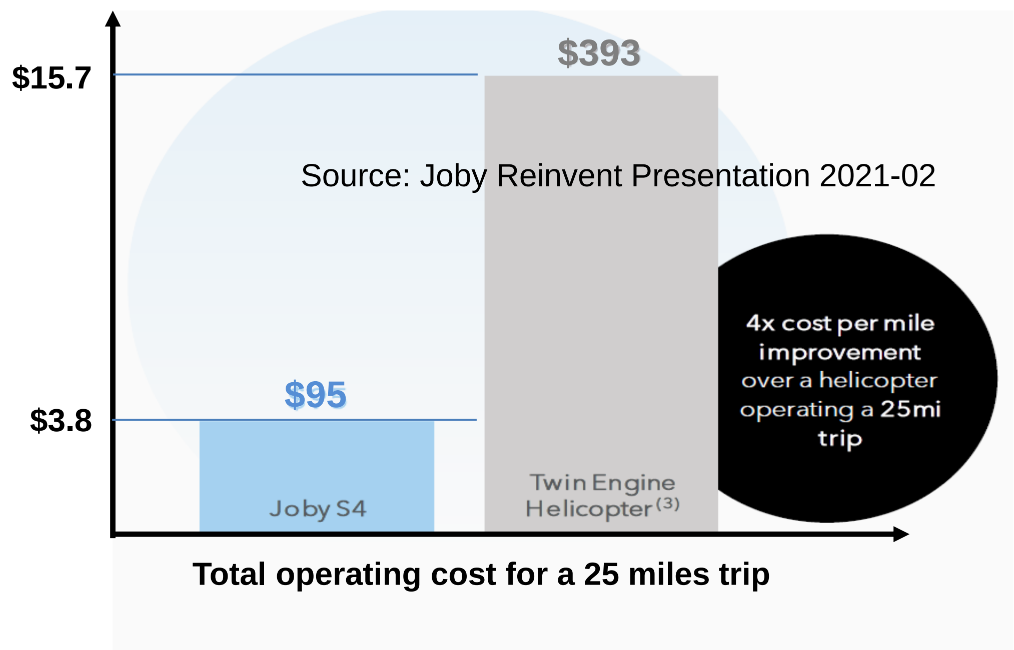
The “Cost” to the Operator per Pax per Mile

- Let’s say the eVTOL total operating cost = US$ 700 /hr includes pilot, depreciation, insurance, vertiport charge...
- Average passenger load factor = 67%, then 0.67 × 4 pax = 2.68 pax per flight
- Average mission = roughly 20 minutes (include ground run up)
- Average mission distance = 25 mile
- **The “Cost” to the operator per pax per mile = $700 / 2.68 / 3 / 25 mile = $3.48**
- The operator can initially charge US$5 to $6 per pax per mile for UAM. This sums up to what was presented at the beginning of the Short Course.



Compare Our Calculation to What Joby Has Presented





7. Benchmarking and Cost Estimation

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