Observations from Exploration of VTOL Urban Air Mobility Designs

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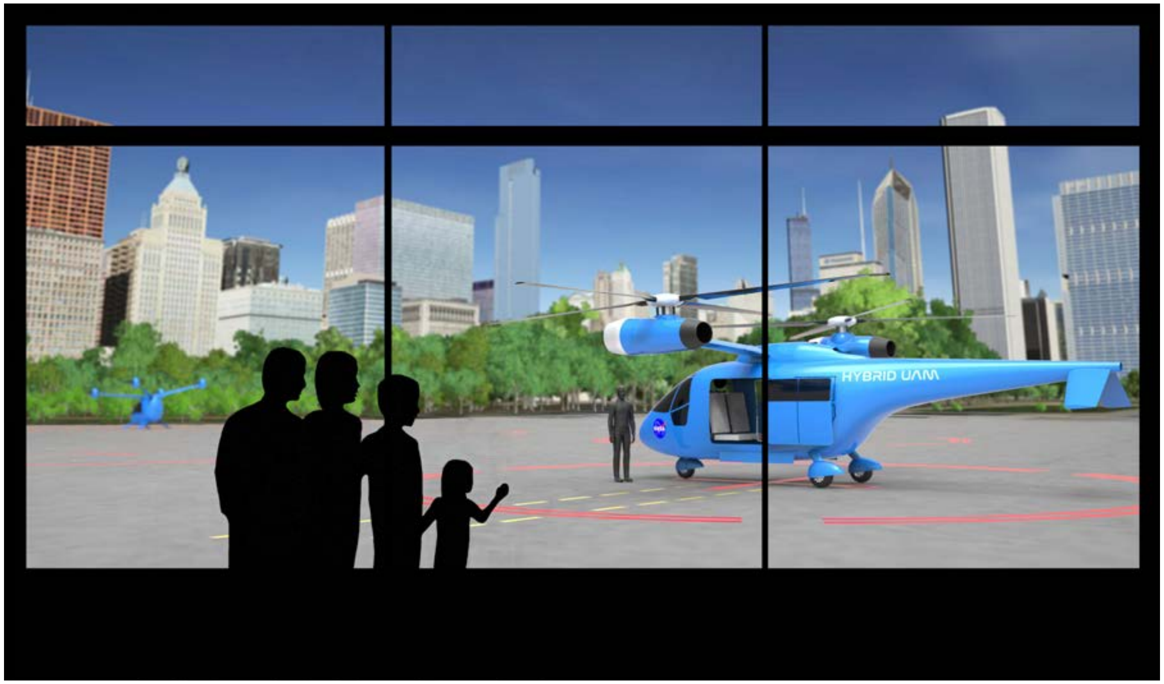
NASA Exploration of VTOL Urban Air Mobility

- **Time is right to explore new ways to move people and goods**
  - Technology advances in structures, automation and control, energy generation/storage/utilization, tools for design and analysis
  - Coupled with pressures of resource availability and population density
- **Urban operations enabled by VTOL capability**
  - Power and energy minimized by using low disk-loading rotors
  - Short range allows non-traditional propulsion concepts



Designs to Focus and Guide NASA Research

- **Vehicles with relevant features and technologies**
  – Battery, hybrid, diesel propulsion
  – Distributed electric propulsion
  – High efficiency rotors
  – Quieter rotors
  – Autonomy

- **Reference models for NASA, academia, industry**
  – Communicate NASA's Urban Air Mobility research
  – Design and analysis tool development
  – Identify goals for enabling technology
  – Simulation support

- **Help us understand the Urban Air Mobility Market**
  – Quantify the impact of regulations
  – Identify the economic drivers
  – Find technology solutions

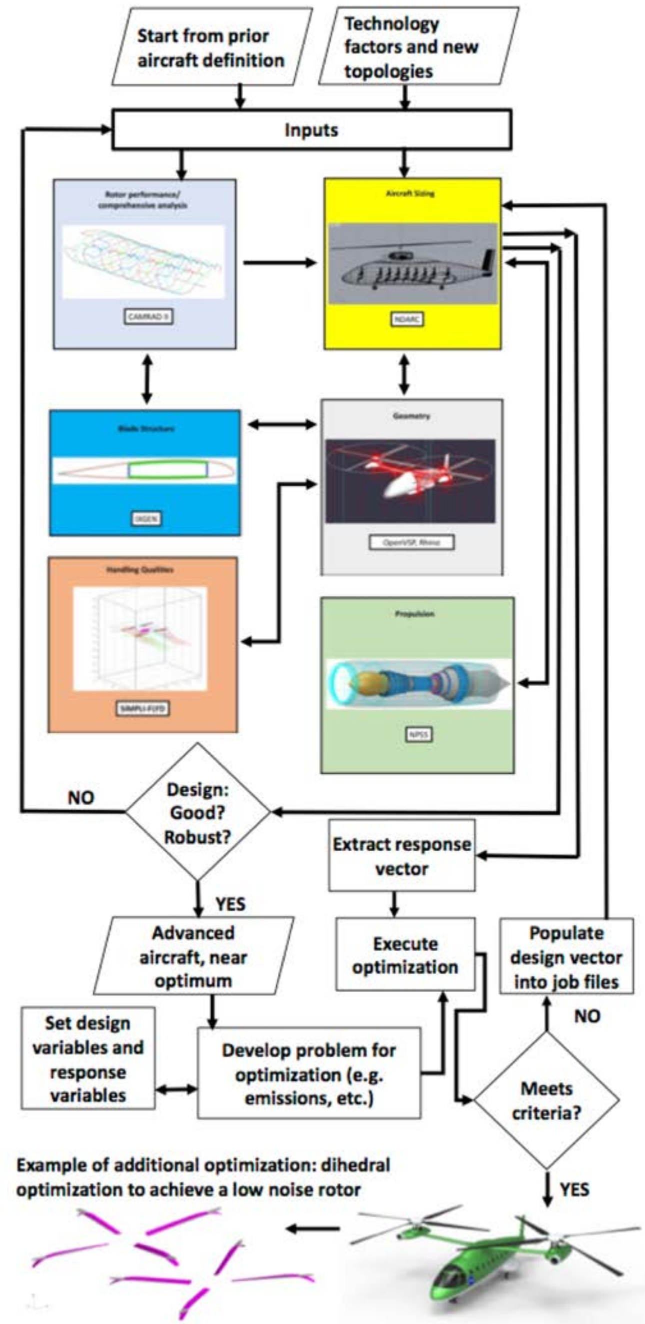
Outline

- Introduction
- NASA Exploration of Urban Air Mobility
- Reduced-Emission Rotorcraft Concepts
- Concept Vehicles for Air Taxi Operations
- Vehicles for UAM Mission and Market
- Observations
- Conclusion

NASA RVLT Conceptual Design Tool Suite

- **Tool suite geared to design space exploration and optimization**

- NASA software
  - NDARC: Design
  - RCOTools: OpenMDAO
  - ANOPP/ANOPP2/AARON: Noise
  - NPSS: Engines
- SIMPLI-FLYD: Handling qualities & control
- CAMRAD II: Aeromechanics
- IXGEN: Blade stiffness
- OpenMDAO: Execution and Optimization
- OpenVSP: Initial parametric geometry
  - Rhino (McNeel): Final geometry
- Needs: Structures, Transient Thermal, Cost and Economics



NASA Studies: What enables UAM?

- **NASA addressing Urban Air Mobility (UAM) needs in several areas**
- **Revolutionary Vertical Lift Technology Project (RVLT)**
  - Tools, operations, technologies, support within and outside NASA
  - Where should project invest efforts with so many unknowns?

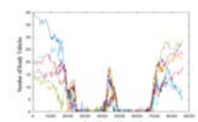
2017 → **2019+**

Previous NASA Projects and Research

Air Vehicles and Aeromechanics

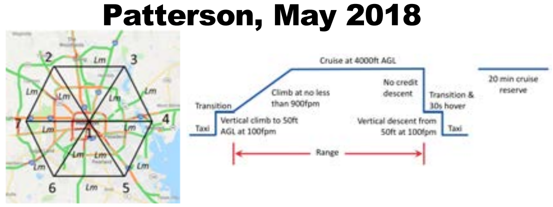
Johnson, January 2018

Energy Limits



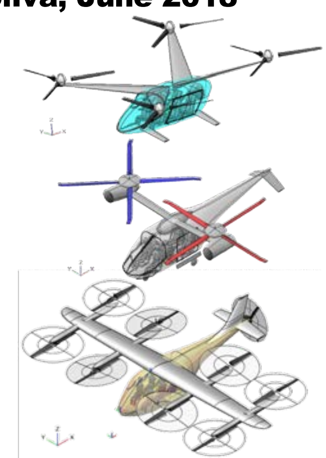
Kohlman, June 2018

Patterson, May 2018



Mission

Silva, June 2018



Sized to Mission

Research with these vehicles

Acoustics
- *Perception*
- *Source noise*

Air traffic integration

Handling & Control

Propulsion systems
- *Performance*
- *Safety and reliability*

Structures
- *Safety*
- *Weights*

Tools and methods
- *Acoustics*
- *CFD*
- *Design*
- *Propulsion*

Networks Operations

Technology

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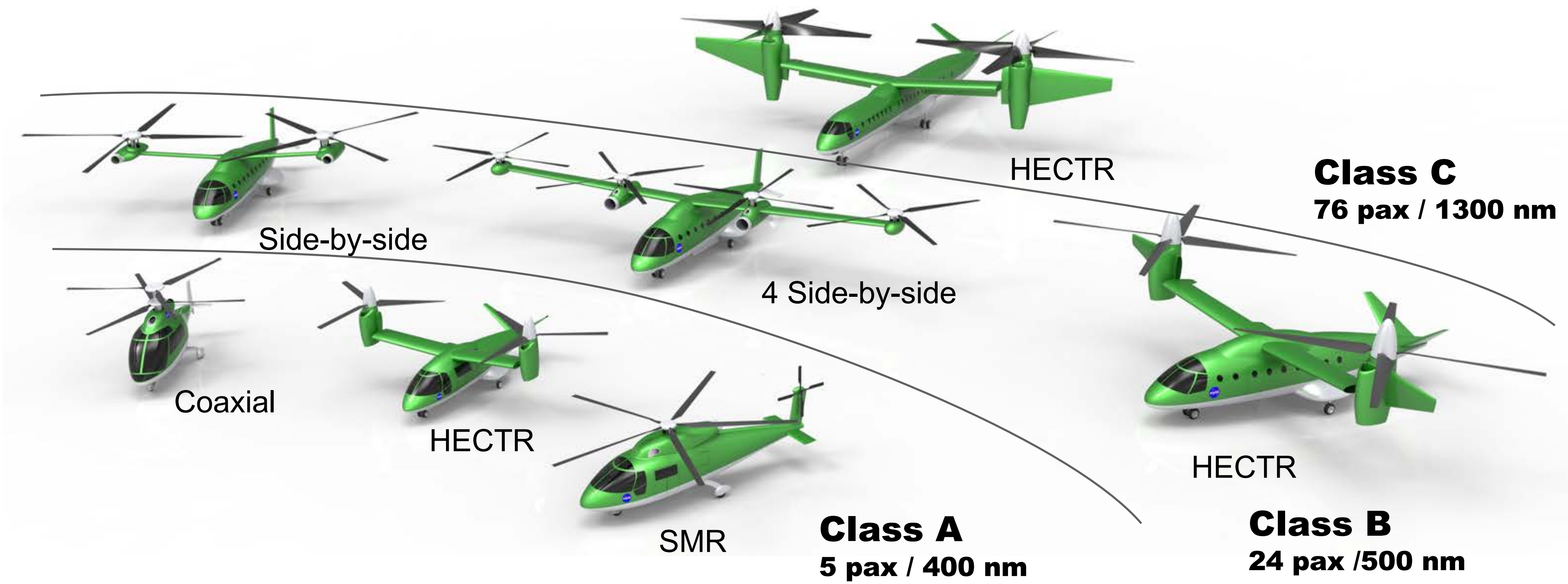
Reduced-Emission Rotorcraft Concepts

- **NASA Goal: Design aircraft which will produce less than 50% of the climate-impacting emissions of today's fielded technology**
  - And develop tools to enable such metric-oriented VTOL studies



Silva, Johnson, and Solis. "Multidisciplinary Conceptual Design for Reduced-Emission Rotorcraft." American Helicopter Society Technical Conference on Aeromechanics Design for Transformative Vertical Flight, San Francisco, CA, January 2018.

Cleanest VTOL is Not Just a Cleaner Helicopter

- **Applied the best available technologies**
  - Looked beyond the horizon for batteries and fuel cells
    - Need a lot of tech to be cleaner than new turboshafts
  - TRL 5+ technology alone could not make helicopters clean enough

- **Found ways to reduce emissions by more than 50%**
  - With today's technology, but different-looking aircraft
    - Side-by-side helicopter, coaxial helicopter, tiltrotor
    - But did not achieve emission goal for small class

NDARC Emission Models

- **Emissions Trading Scheme (ETS) of the European Union**
  - ETS is a CO2-only metric; kg CO2 per mission
    - Jet fuel: 3.16 kg/kg (0.07 kg/MJ)
    - U.S. grid electricity: 0.5 kg/kWh (0.14 kg/MJ)
    - Hydrogen from Methane: 4.8 kg/kg (0.03 kg/MJ)

- **Average Temperature Response (ATR)**
  - ATR captures long-time integrated effects of CO2, H2O, NOx, O3, CH4, SO4, soot, and Aviation Induced Cloudiness (AIC)
    - Turboshaft engine NOx emission model
  - Units of nano-degC of warming per mission
  - AIC dominates when active; model is simple with large uncertainty
    - Morning daylight AIC cools the Earth by reflecting sunlight into space
    - Afternoon and evening AIC prevents the Earth from radiating heat
    - AIC formation depends on many atmospheric factors

Today’s approach (TRL 9) is the baseline

Technologies and Features

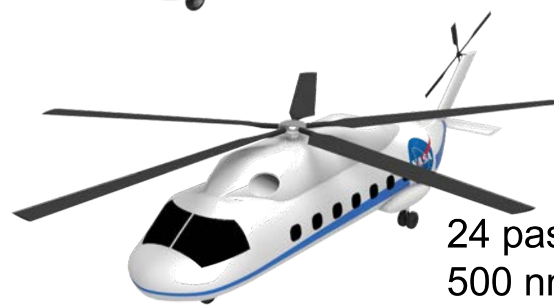
- Helicopters
  - Unfaired hubs
  - Aluminum structure
- Tiltrotors
  - Fly-by-wire
  - Fastened composites
- Today’s turboshaft technology
- Crashworthy structures
- Inclement weather operation
  - Anti-ice
  - Instruments
  - Communications
  - Furnishings
  - Environmental control systems

Size Classes and Baseline Vehicles

Class A

5 passenger + pilot
400 nm range

Class B



24 passenger + 3 crew
500 nm range

Class C

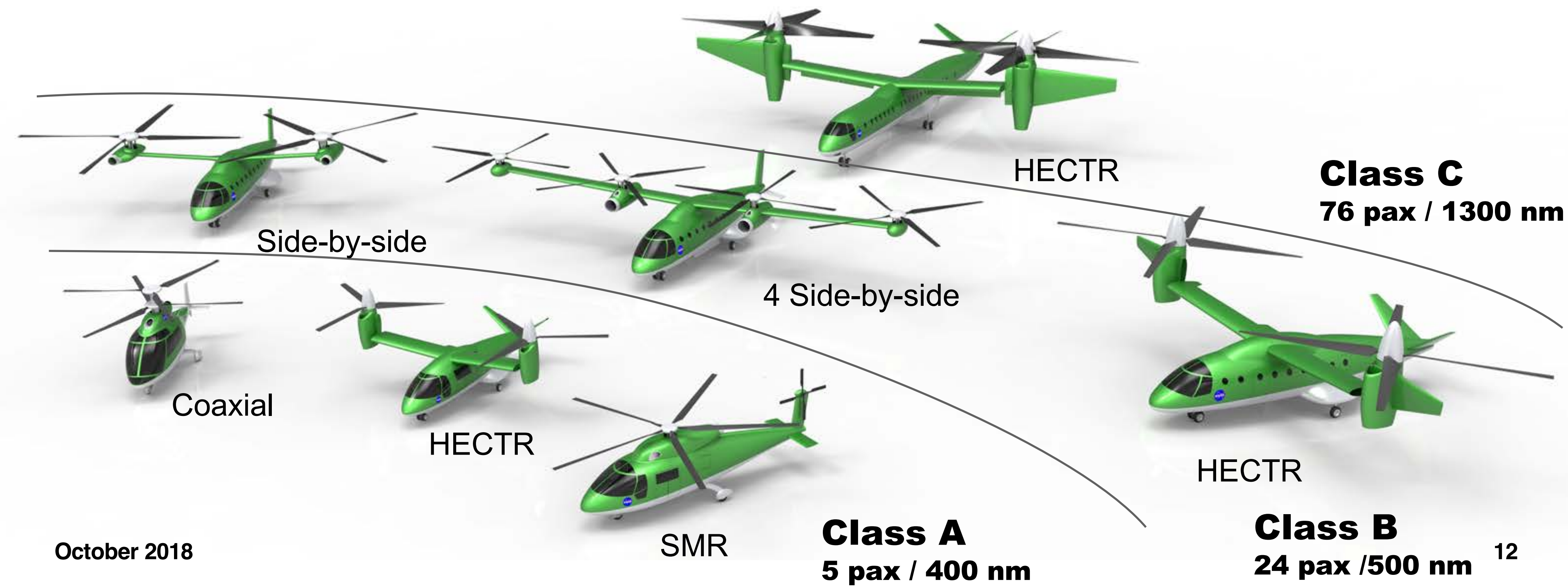
76 passenger + 3 crew
1300 nm range

Advanced aircraft types & technologies

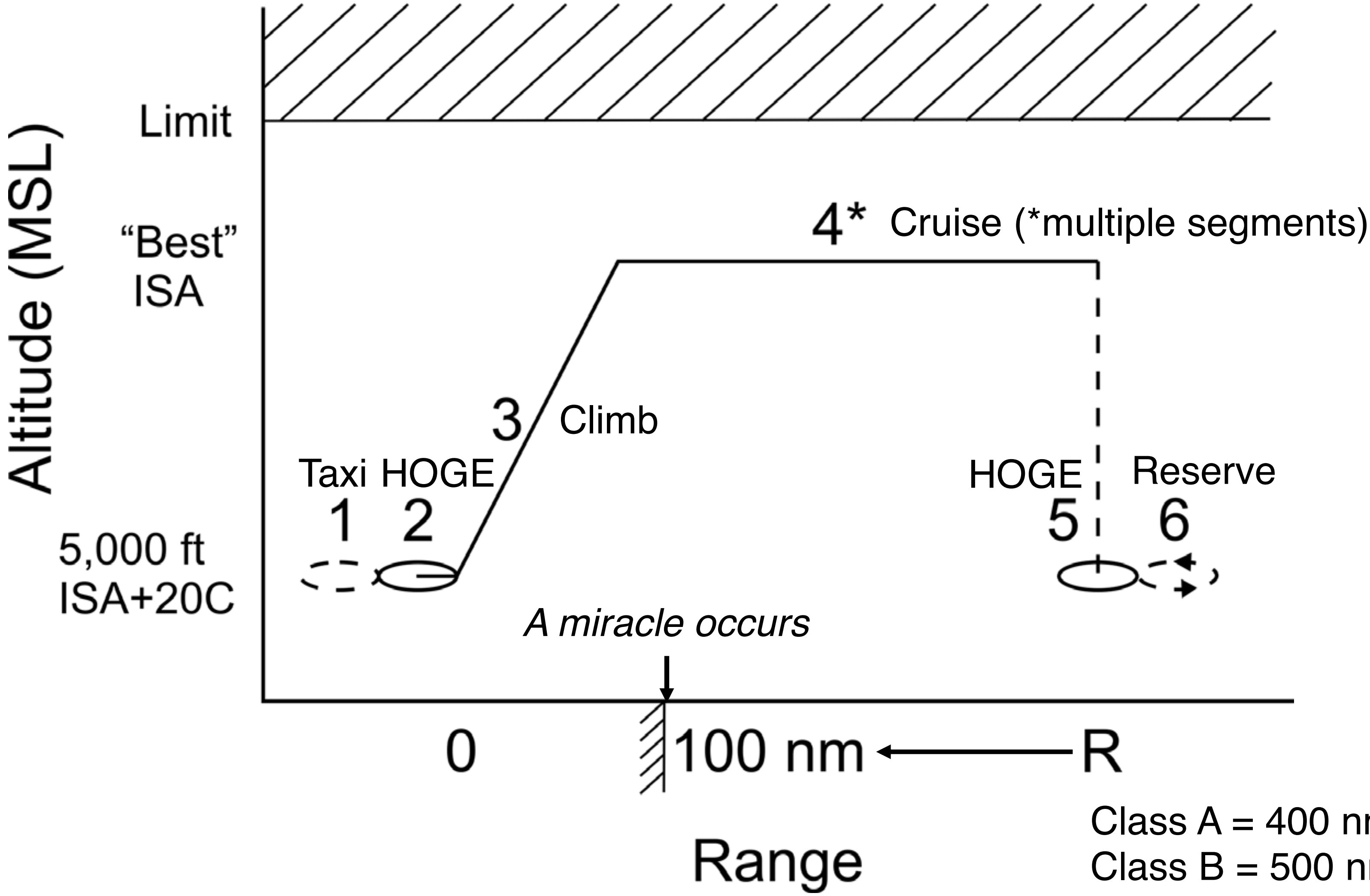
- More attention to drag: faired hubs, landing gear
- More composites, bonded instead of fastened
- Advanced drive systems materials and approaches
- Coaxial and side-by-side helicopters for efficiency
- LCTR2 heritage for high efficiency civil tiltrotors (HECTR)
- Advanced turboshafts for Classes B and C
- Li-ion and Fuel Cell for Class A, hybrids for B

TRL 5+ by 2020

Below TRL 2



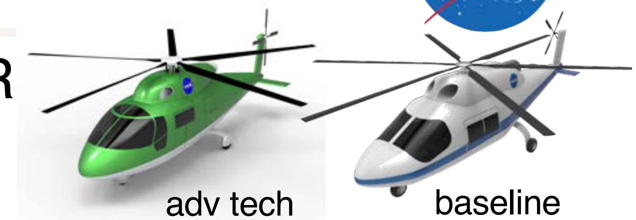
Design Mission



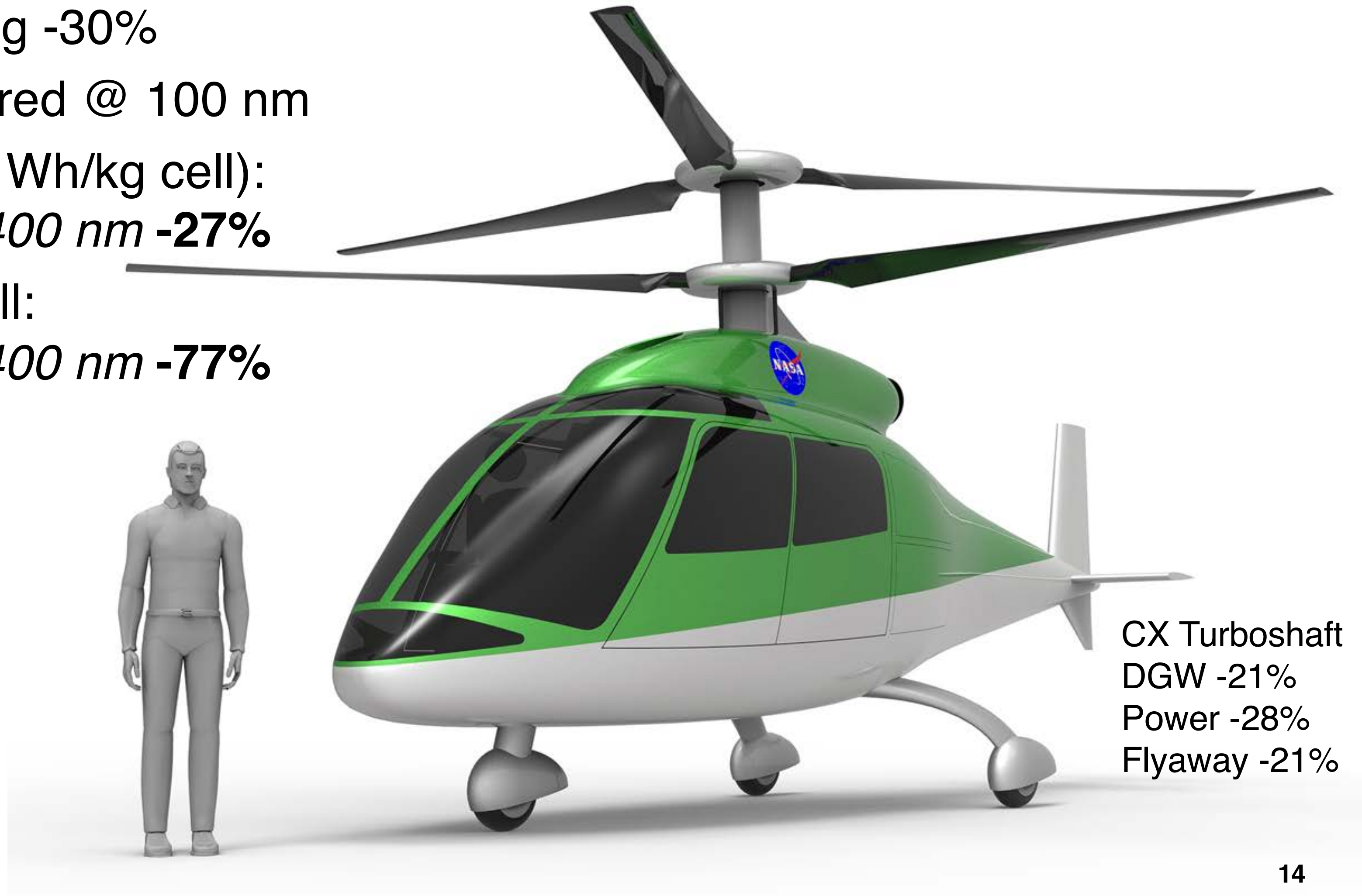
Class A = 400 nm
Class B = 500 nm
Class C = 1300 nm

100 nm was an arbitrary lower bound for Li-Ion and Fuel cell
Upon reaching 100 nm limit, technology improves to make aircraft feasible

Class A Coaxial Helicopter: -30% from baseline



- Advanced tech SMR achieves **-19%** in ETS and ATR
- Conventional coaxial (CX) turboshaft:
  - ETS CO_2 **-30%**
  - ATR heating -30%
- TRL < 2 Required @ 100 nm
- CX Li-ion (650 Wh/kg cell):
  ETS CO_2 *per 400 nm* **-27%**
- CX H_2 Fuel Cell:
  ETS CO_2 *per 400 nm* **-77%**

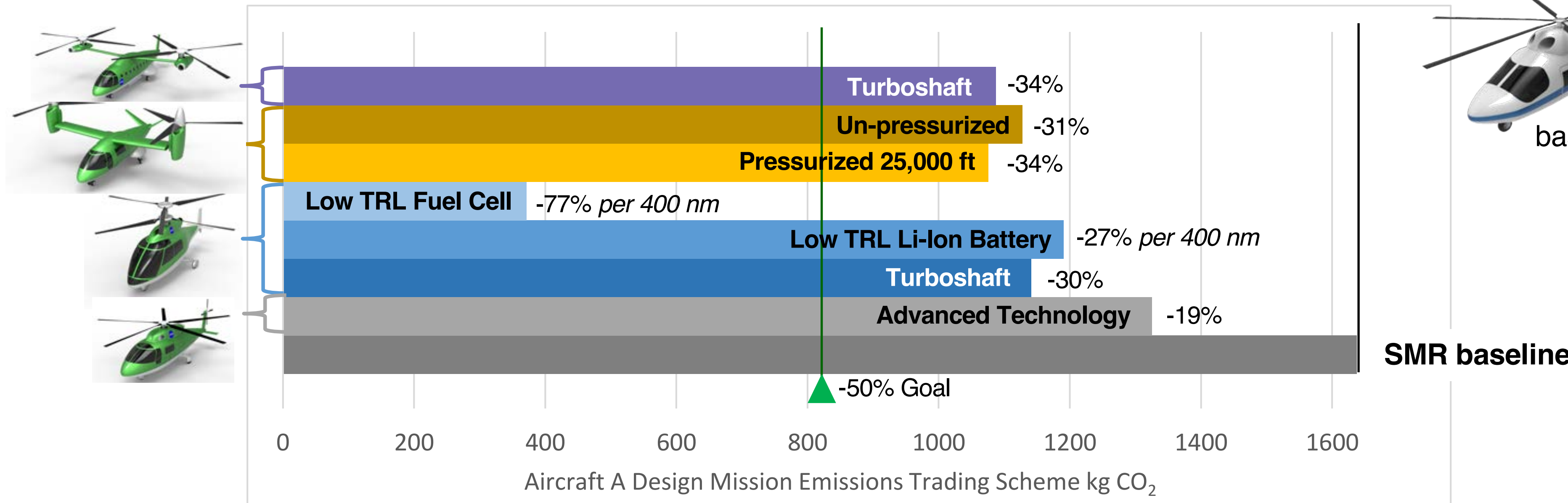


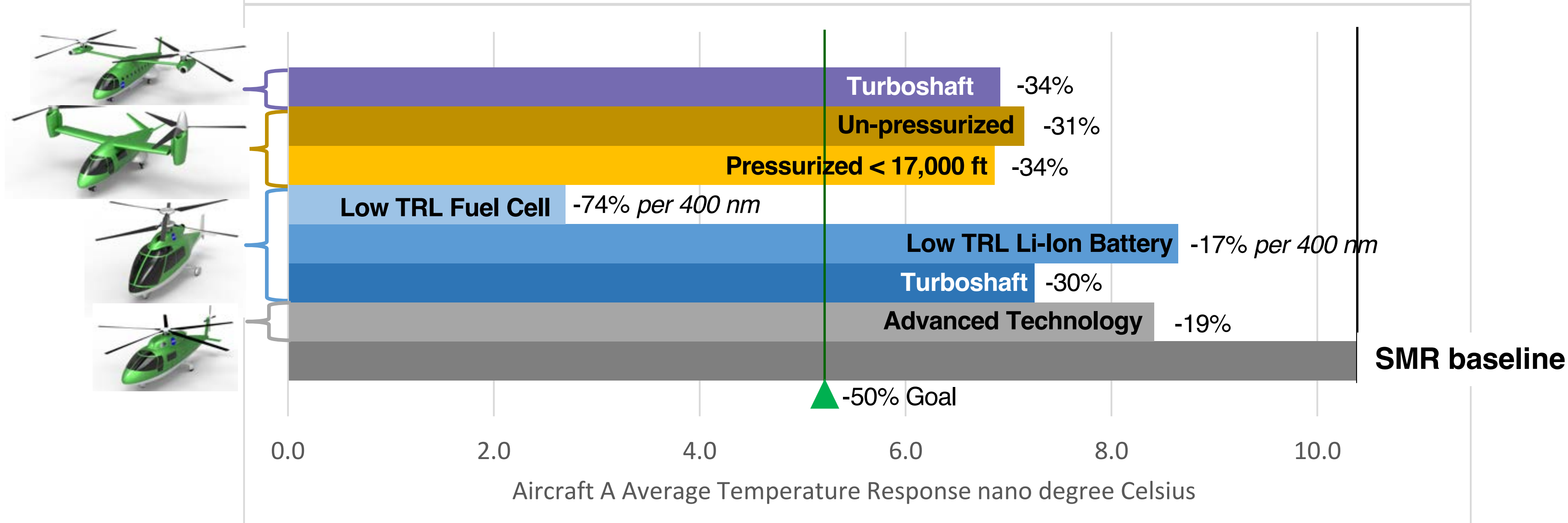
Class A HECTR: Fly high or low?

- Advanced tech SMR achieves **-19%**, CX **-30%** for ETS and ATR
- Pressurized HECTR at 25,000 ft:
  - ETS CO_2 **-34%**
  - ATR heating **+254%**
- Unpressurized HECTR at 12,000 ft:
  - ETS CO_2 **-31%**
  - ATR heating -31%

Pressurized HECTR
DGW +30%
Power +40%
Flyaway +93%

Class A (5 pax, 400 nm) Emission Reductions





Interesting results in Class A

- The lack of efficient small (<1,000 shp) turboshaft development is limiter for achieving goal of > 50% emissions reduction
- The coaxial helicopter is better than a SMR helicopter
- Do you fly high or do you fly low? What should emission objective be?
  - ETS says fly high if wing-borne to burn less fuel
  - ATR says fly not-too-high to avoid making contrails
- Tiltrotor doesn't get light enough to take advantage of cruise efficiency
  - Drop the wing extension (weight) because small payload and range
  - Dropping pressurization (weight) and flying low has same emissions
- Batteries fall short (specific energy); U.S. electric grid emissions high
- Fuel cells can't make it (specific power); emissions can be very low even if we are getting hydrogen from methane source

Class B turboshaft technology is a big improvement

- Advanced tech SMR achieves **-43%** ETS and -42% ATR
- SbS Turboshaft:
  - ETS CO_2 **-65%**
  - ATR heating -64%
- SbS Li-ion
  (650 Wh/kg cell):
  ETS CO_2 *per 500 nm* **-45%**

baseline

SbS Turboshaft
DGW -44%
Power -66%
Flyaway -49%

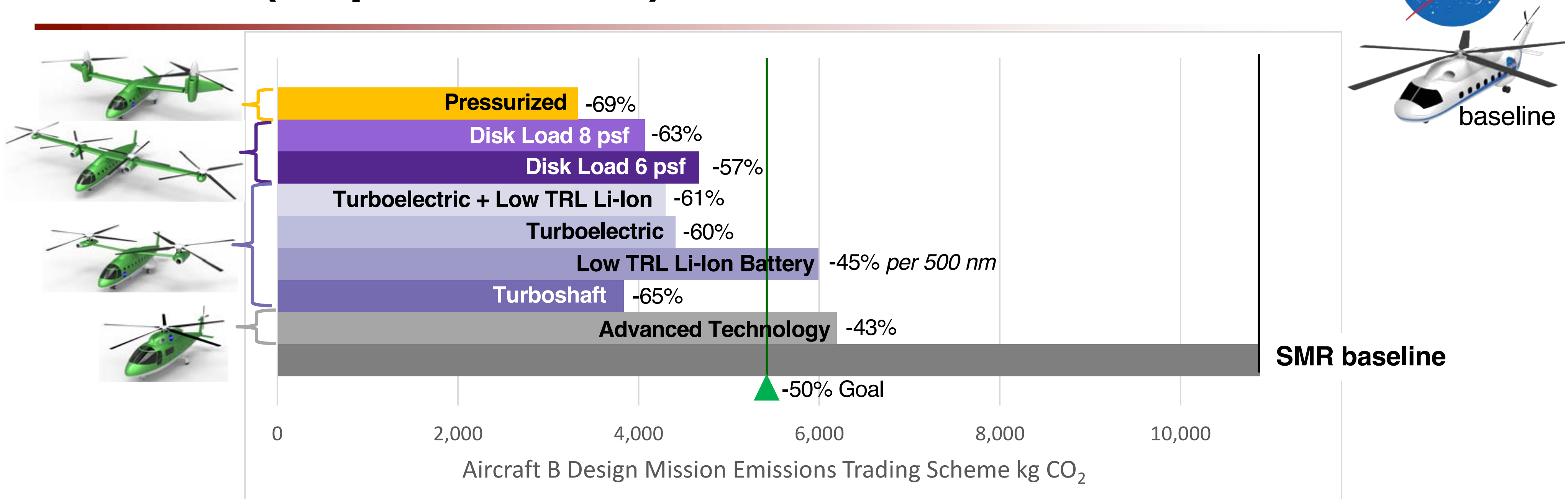
- SbS4 Turboshaft:
  - ETS CO_2 **-63%**

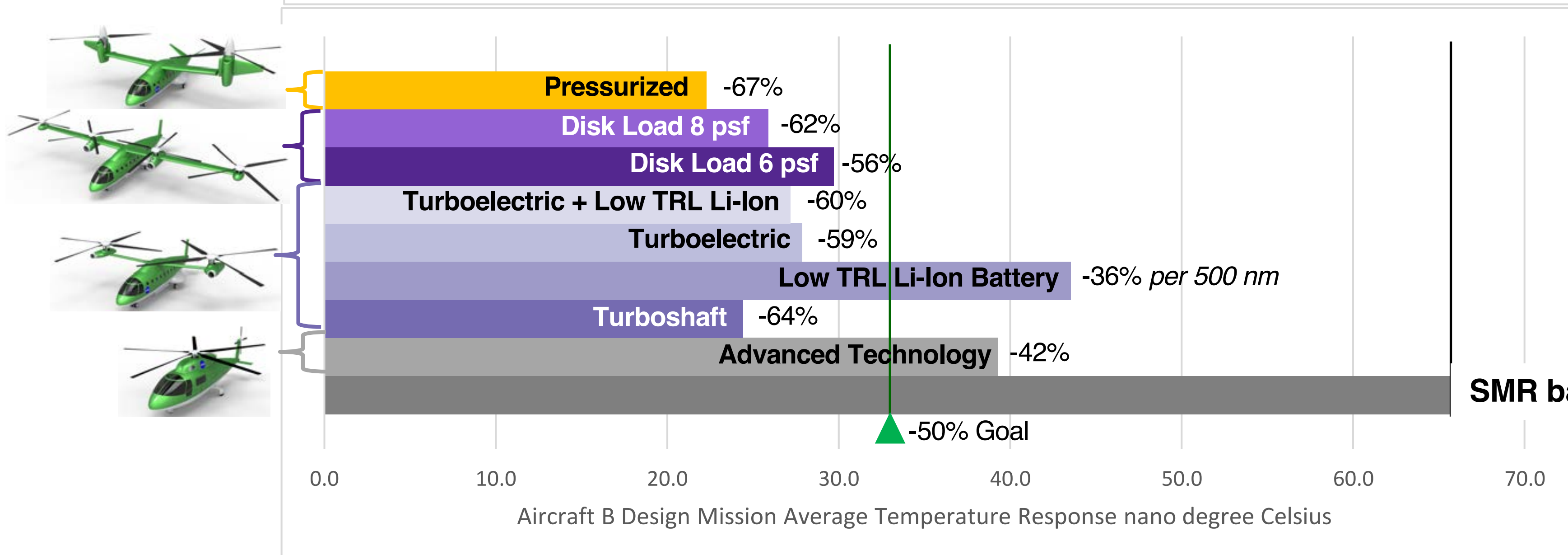
SbS4 Turboshaft
DGW -43%
Power -61%
Flyaway -41%

- HECTR Turboshaft:
  - ETS CO_2 **-69%**
  - ATR heating -67%

HECTR Turboshaft
DGW -26%
Power -21%
Flyaway +5%

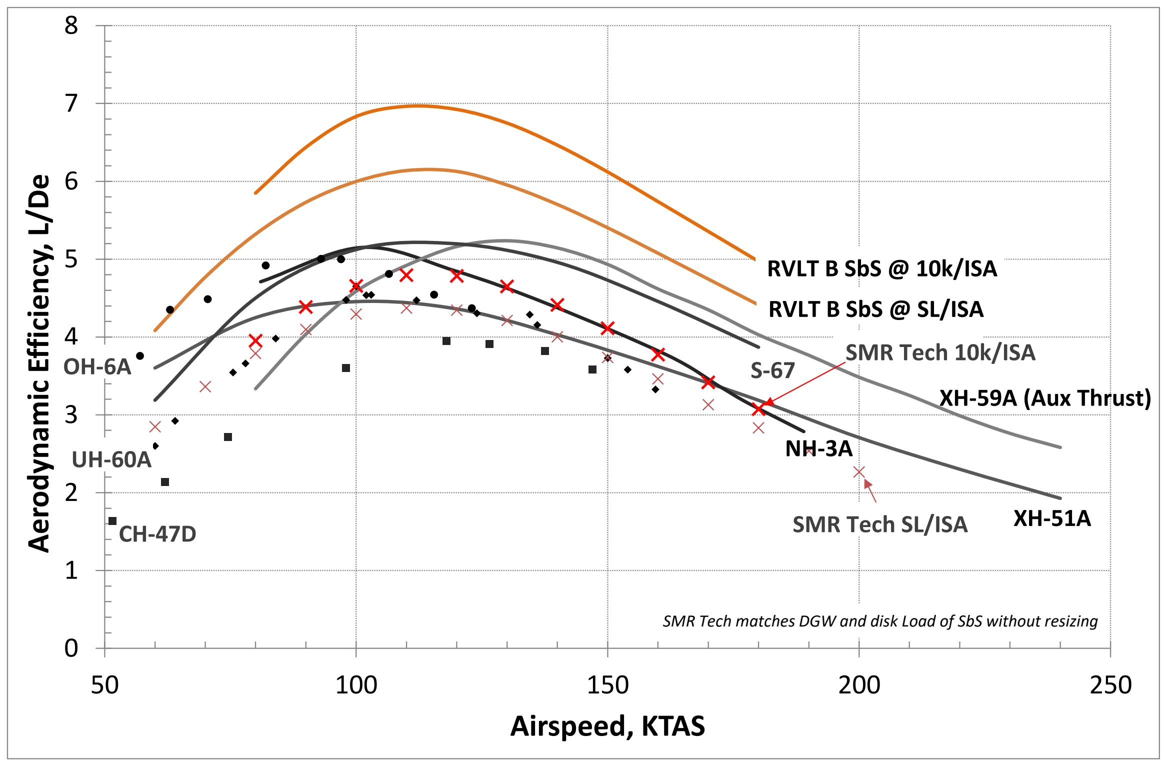
Class B (24 pax, 500 nm) Emission Reductions





Interesting results in Class B

- The recent focus on engine technologies at this size pays off
  - Even the advanced tech SMR gets 43% reduction in emissions
- Tiltrotor might as well fly high (but below AIC)
  - The wing extension is worth it for payload and range
  - Cruise fuel burn with payload and range favors pressurization
- Side-by-side looks promising
  - Low installed power from low disk loading
  - Light weight despite the cross-bars due to small engines and fuel
  - Cruise efficiency 50% better than helicopters
  - Low flyaway and operating costs, in addition to low emissions



Class C HECTR: Very efficient VTOL

- Advanced tech TR achieves **-35%** ETS, -36% ATR
- Seed HECTR at 18,000 ft:
  - ETS CO_2 **-65%**
  - ATR heating -65%
- Gradient-optimized HECTR at 20,638 ft:
  - ETS CO_2 **-71%**
  - ATR heating -72%

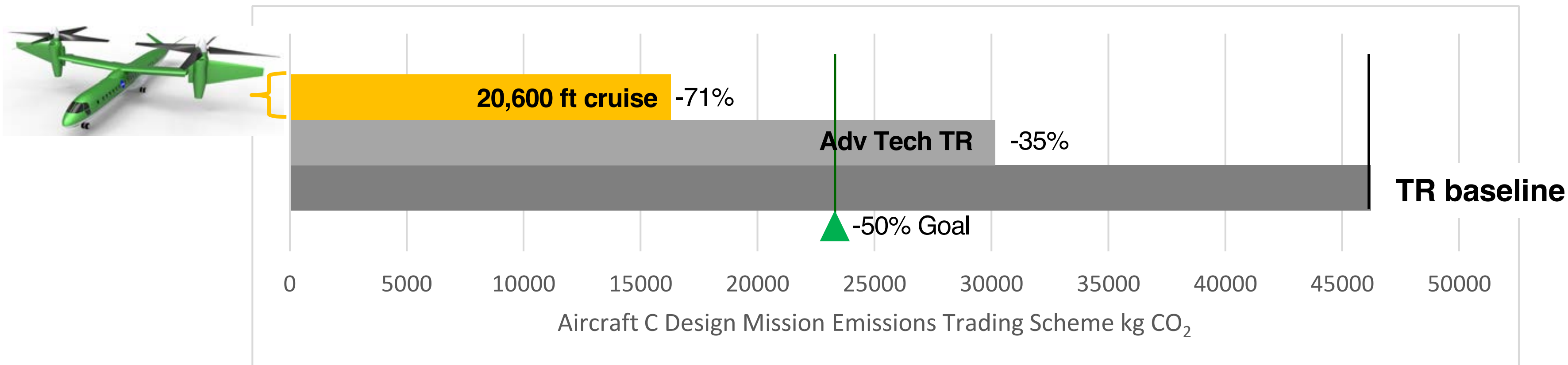
LCTR2/HECTR approach still looks good for large rotorcraft

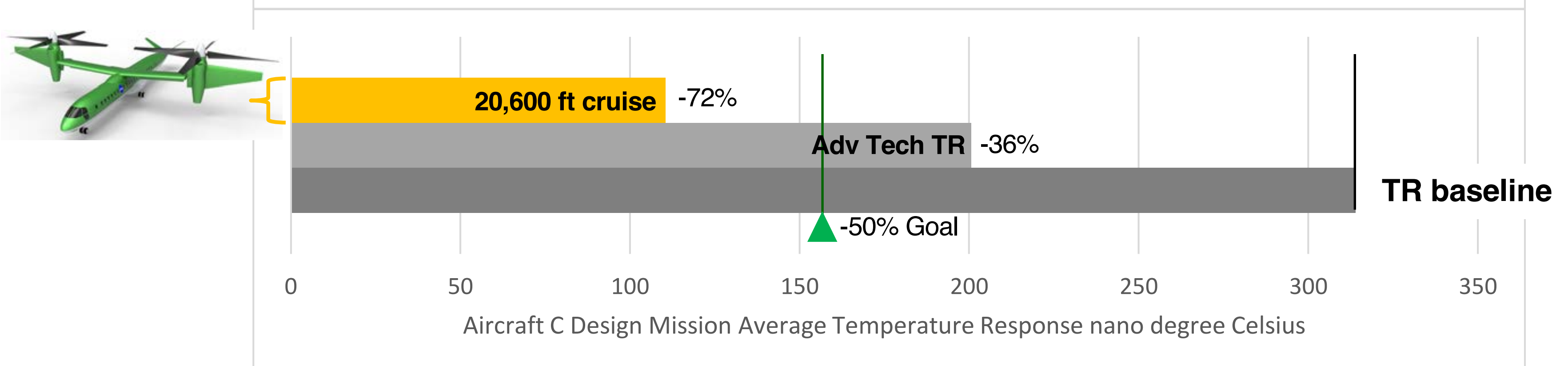
Climate considerations are yet another good reason to consider a large civil tiltrotor

Class C (76 pax, 1300 nm) Emission Reductions

baseline

Pressurized 25,000 ft





Product of Low-Emission Rotorcraft Investigation

- **Foundation for exploring UAM designs**
  - Development of integrated tool suide for multidisciplinary design and optimization of VTOL aircraft
- **Demonstration of alternative propulsion architectures in NDARC**
  - Including electric power
- **Quantification of cruise efficiency of side-by-side helicopter type**

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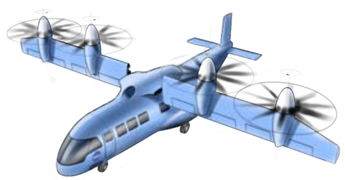
NASA Concept Vehicles for Air Taxi Operations

- **Exploration of UAM design-space: payload, range, aircraft type, propulsion system**

» Single-passenger (250-lb payload), 50-nm range electric quadrotor

» Six-passenger (1200-lb payload), 4x50 = 200-nm range hybrid side-by-side helicopter



» Fifteen-passenger (3000-lb payload), 8x50 = 400-nm range turbo-electric tiltwing

- **Research areas identified to support aircraft development for emerging aviation markets, in particular VTOL air taxi operations**

Johnson, Silva, and Solis. "Concept Vehicles for VTOL Air Taxi Operations." American Helicopter Society Technical Conference on Aeromechanics Design for Transformative Vertical Flight, San Francisco, CA, January 2018.

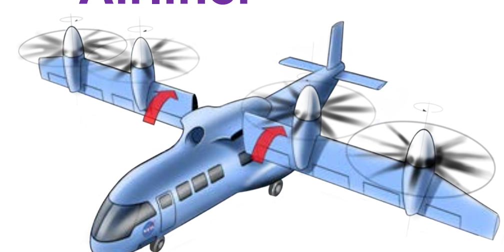
Considered large aircraft design space

Passengers	Range	Market	Type	Propulsion
1	50 nm	Air Taxi	Helicopter	Electric
			Multicopter	
2	100 nm	Commuter Scheduled		Fuel Cell
			Compound	
4	200 nm			Hybrid
		Mass Transit	Side-by-Side	
6	400 nm		Lift+Cruise	Turboshaft
		Air Line		
			Tiltwing	
15	800 nm			Turboelectric
			Tiltrotor	
30				Diesel

Quadrotor "Air Taxi"

Side by Side "Vanpool"

Tilt wing "Airliner"



Desirable that NASA concept vehicles be different in appearance and design detail from prominent industry concepts

NASA Concept Vehicles for UAM

Objective: Identify NASA vehicles to serve as references to openly discuss technology challenges common to multiple concepts in the UAM community and provide focus for trade studies and system analysis

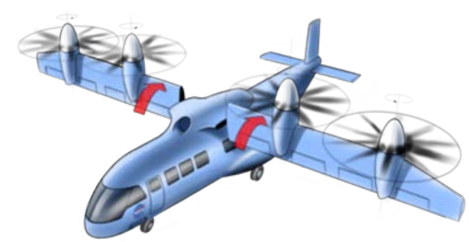
Passengers	Range	Market	Type	Propulsion
1	1 x 50 nm	Air Taxi	Multicopter	Battery
	2 x 37.5 nm		Compound	Diesel
2	2 x 50 nm	Commuter Scheduled	Side by Side	Parallel hybrid
4	4 x 50 nm	Mass Transit	Tilt Wing	Turboelectric
6	8 x 50 nm	Air Line	Tilt Rotor	Turboshaft
15			Lift + cruise	Hydrogen fuel cell

Quadrotor “Air Taxi”

Side by Side “Vanpool”

Lift+Cruise “Air Taxi”

Tilt Wing “Airliner”



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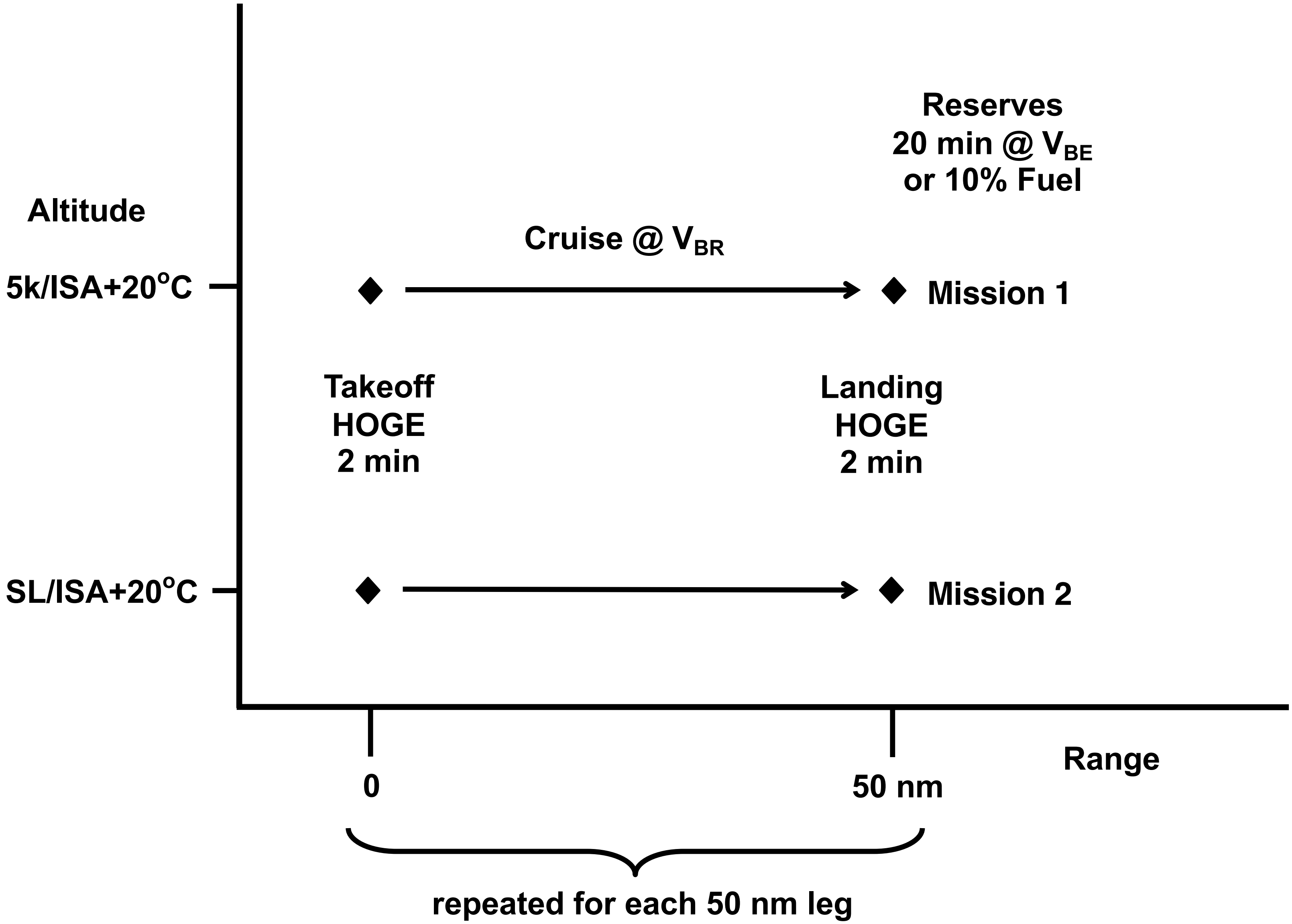
Air Taxi Requirements — Mission



(50, 4x50=200, 8x50=400)

Design Requirements

All weather operations

Low aircraft noise

Fallout maximum speed

Quadrotor with Electric Propulsion

- **Single-passenger (250 lb payload), 50 nm range**

disk loading = 2.5 lb/ft^2

rotor radius = 6.5 ft

tip speed = 450 ft/sec

power = 4x23 hp

battery = 186 MJ = 42 kWh

battery specific energy = 400 Wh/kg

design gross weight = 1325 lb

$W_{battery}$/GW = 0.22

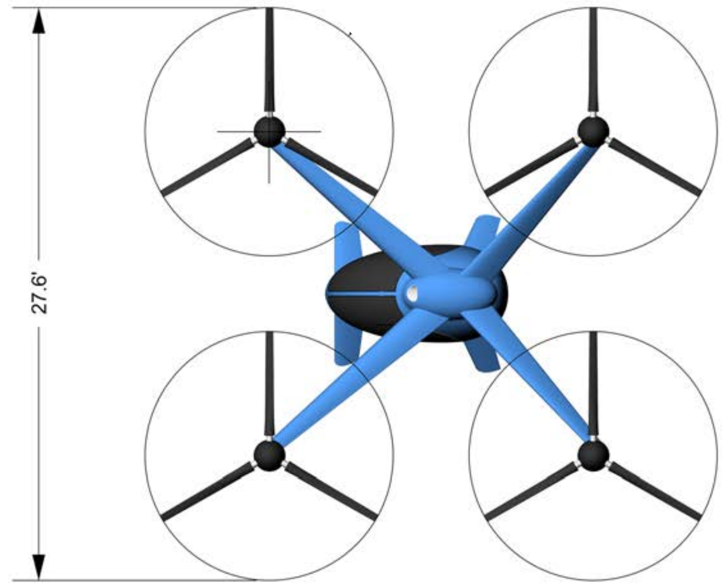
$W_{payload}$/GW = 0.19

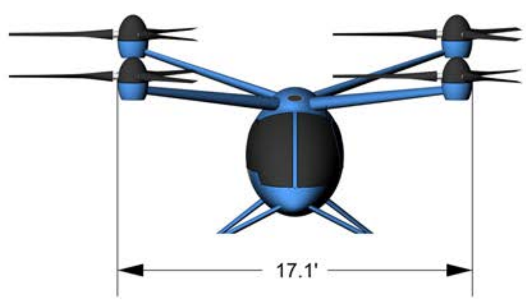
cruise L/D_e = WV/P = 5.3

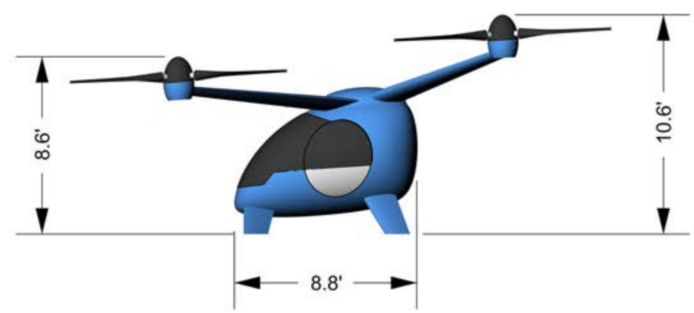
rotor L/D_e = 7.6

V_{br} = 86 knots

V_{max} = 71 knots







Excursions: electric and conventional propulsion, flapping and hingeless rotors, collective and rotor speed control

Side-by-Side with Turboshaft Hybrid Propulsion

- **Six-passenger (1200 lb payload), 4x50=200 nm range**

disk loading = 4.5 lb/ft^2

span = 0.85D (overlapped & intermeshed)

rotor radius = 11.8 ft

tip speed = 550 ft/sec

power = 2x187(TS)+100(M) hp

fuel = 350 lb

battery = 66 MJ = 18 kWh

design gross weight = 3950 lb

W_{fuel}/GW = 0.08

$W_{battery}$/GW = 0.03

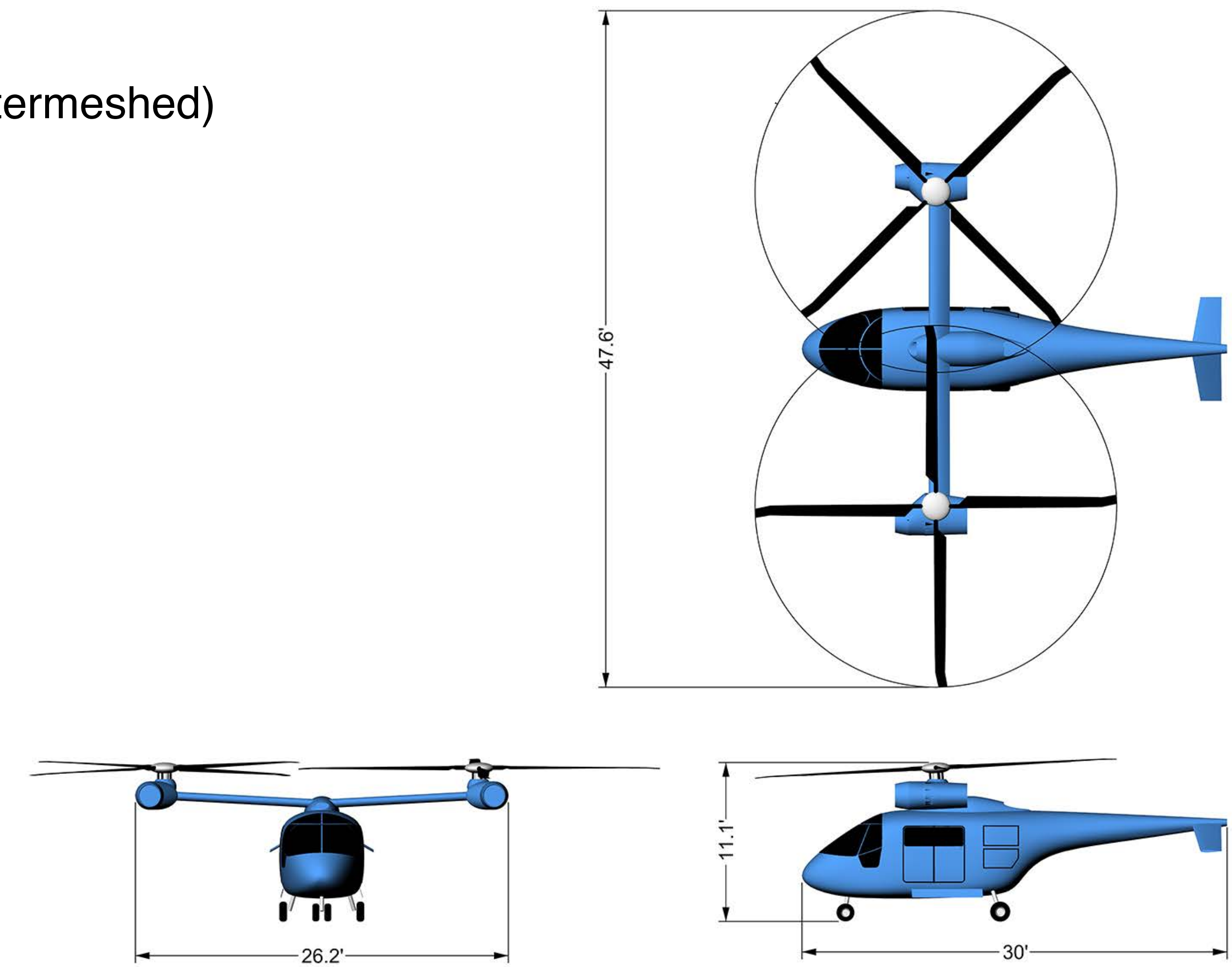
$W_{payload}$/GW = 0.31

cruise L/D_e = WV/P = 6.0

rotor L/D_e = 11.4

V_{br} = 114 knots

V_{max} = 127 knots



Tiltwing with TurboElectric Propulsion

- **Fifteen passenger (3000 lb payload), 8x50=400 nm range**

disk loading = 30 lb/ft^2

wing loading = 60 lb/ft^2

rotor radius = 6.1 ft

tip speed = 550/275 ft/sec

power = 4730 hp

motor = 4x731 hp

fuel = 2101 lb

battery = 288 MJ = 80 kWh

design gross weight = 14039 lb

W_{fuel}/GW = 0.14

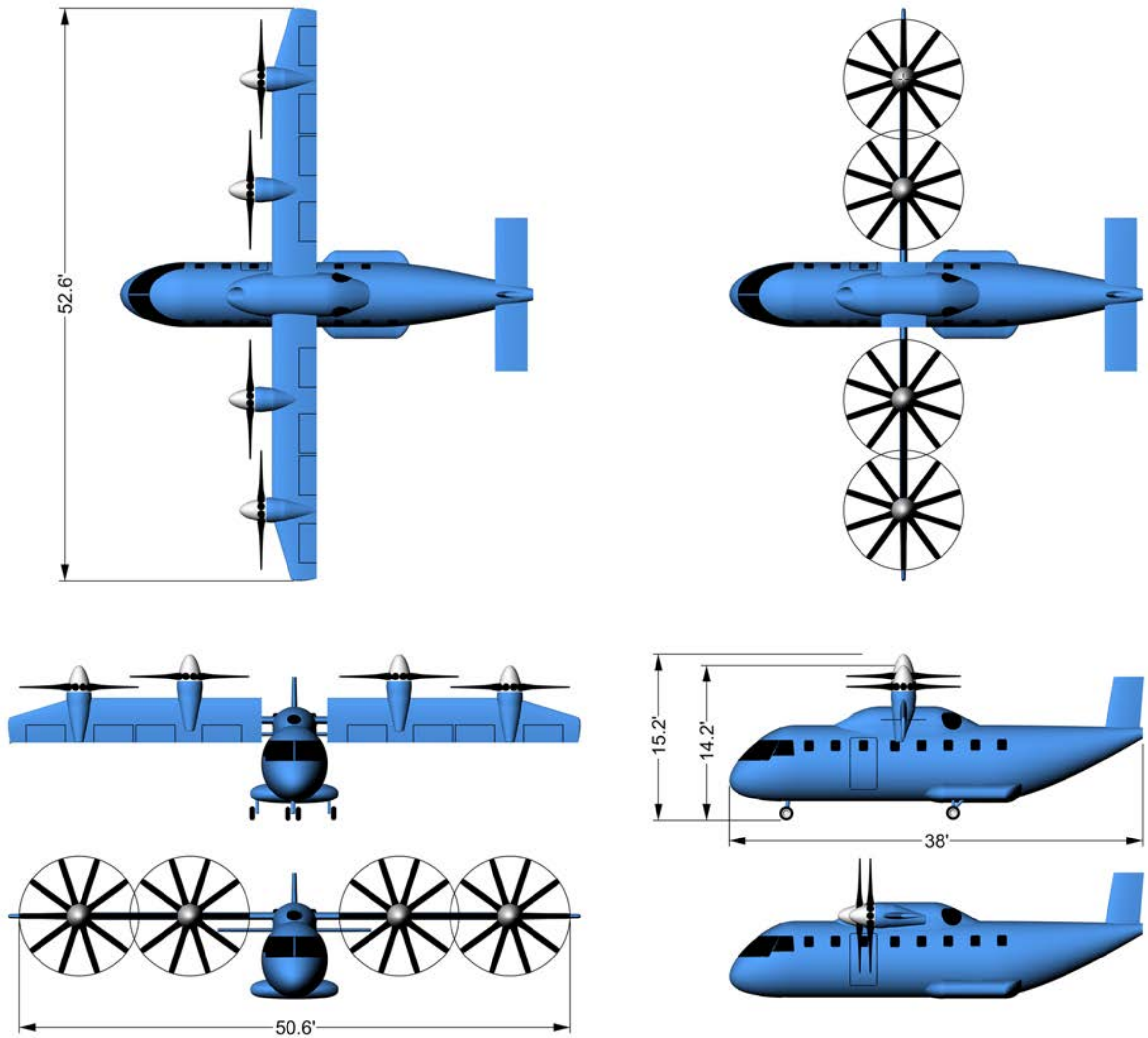
$W_{battery}$/GW = 0.03

$W_{payload}$/GW = 0.22

cruise L/D_e = 7.2

V_{br} = 200 knots

V_{max} = 230 knots



Excursions: turboelectric and turboshaft, cyclic pitch and tail prop control

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Vehicles for the UAM Mission

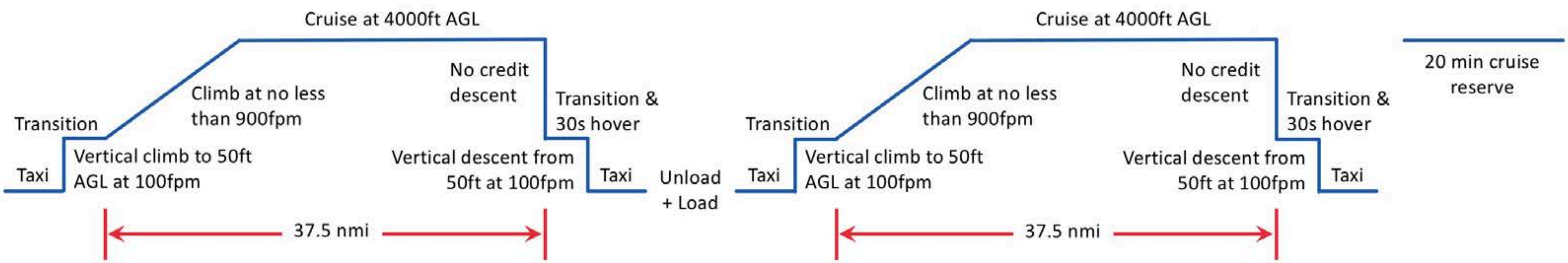
- **Initial air taxi vehicle investigation explored technology themes**
  - Using aircraft of various sizes
  - Designed for several candidate missions

- **Performed focused study to better understand urban air mobility market**
  - Defined mission that accounts for existing geography, population patterns, infrastructure, and weather in 28 market across US

- **Defined sizing requirement for aircraft design**
  - Actual operational missions will be different
  - Driven by economics, air traffic, etc.

Vehicles for the UAM Mission and Market

- **Projected size of markets based on U.S. population patterns**
  - Large metro areas with suburban commuters
  - Historic weather considered for takeoff and cruise
  - Triangular / Hexagonal network topology fits many metros
- **Design mission parameters that determine vehicle size**
  - Vehicle sized for ***6 occupants***
  - Payload of ***1200 lb***
  - ***2 x 37.5 nm*** unrefueled range, cruise V_{br} with 10 kt headwind
  - ***900+ fpm*** to climb over obstacles



Patterson, M.D.; Antcliff, K.R.; and Kohlman, L.W. "A Proposed Approach to Studying Urban Air Mobility Missions Including an Initial Exploration of Mission Requirements." American Helicopter Society 74th Annual Forum, Phoenix, AZ, May 2018.

Silva, C.; Johnson, W.; Antcliff, K.R.; and Patterson, M.D. "VTOL Urban Air Mobility Concept Vehicles for Technology Development." AIAA Paper No. 2018-3847, June 2018.

Three Types of Vehicles Sized to Same Mission

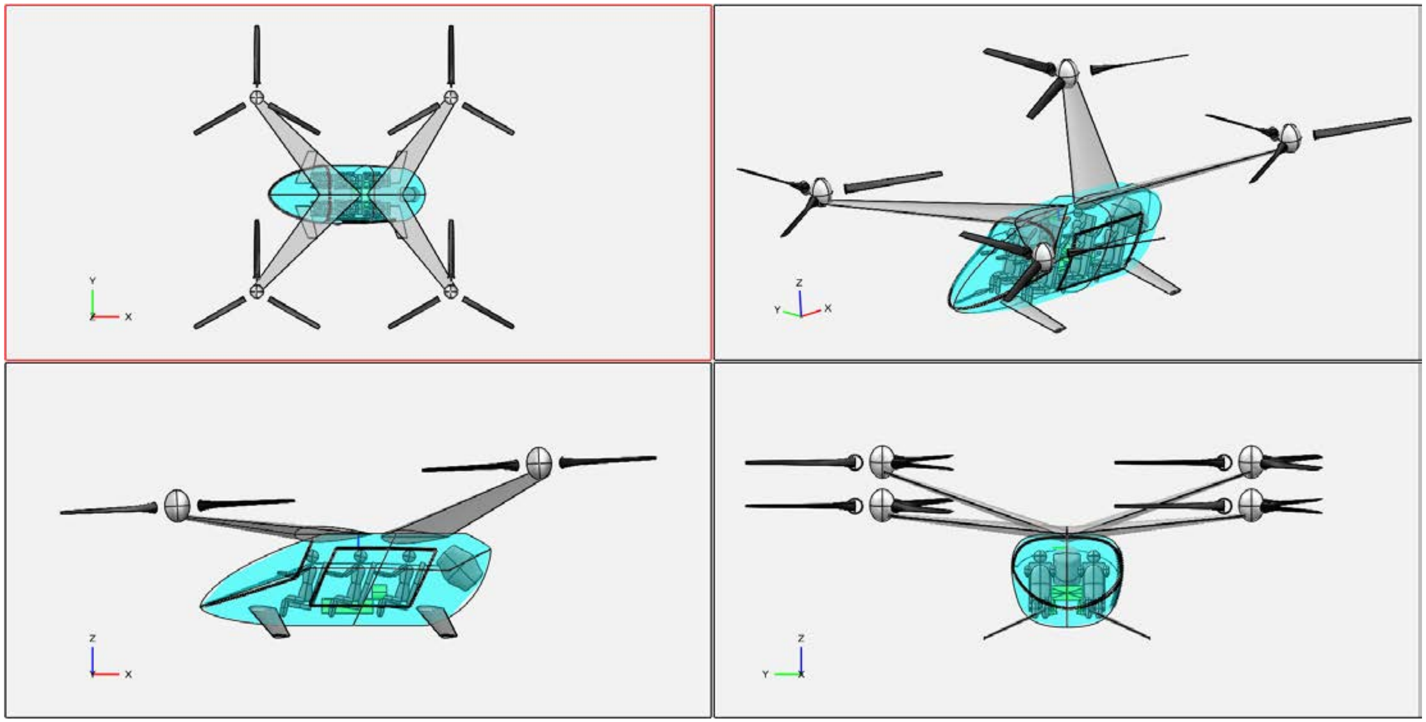
Fuel Burning		***All Electric***
Turboshaft	 *Quadrotor*	Battery
Turboshaft	 *Side-by-side helicopter*	Battery
Turbo-electric	 *Lift+Cruise VTOL*	Battery

Consistent Technology Assumptions for Sizing

- **Battery pack modeled as Li-Ion (TRL 1)**
  - Usable specific energy ***400 Wh/kg*** (well beyond state-of-the-art)
  - Max. mission current ***4C***, emergency ***14C*** (high end state-of-the-art)
- **Wiring and accessory electric systems as fractions (TRL 3)**
- **Structures (TRL 3+)**
  - Composite VTOL structures, *very lightweight booms*
- **Aerodynamics (TRL 5+)**
  - Passive rotor and airframe lift/drag
- **Propulsion (TRL 5+)**
  - High Torque/weight electric motors
  - High torque/weight transmissions
- **Systems (TRL 5+)**
  - Equipment for IFR operations (autonomy without additional weight)
  - Environmental control systems, insulation, seating

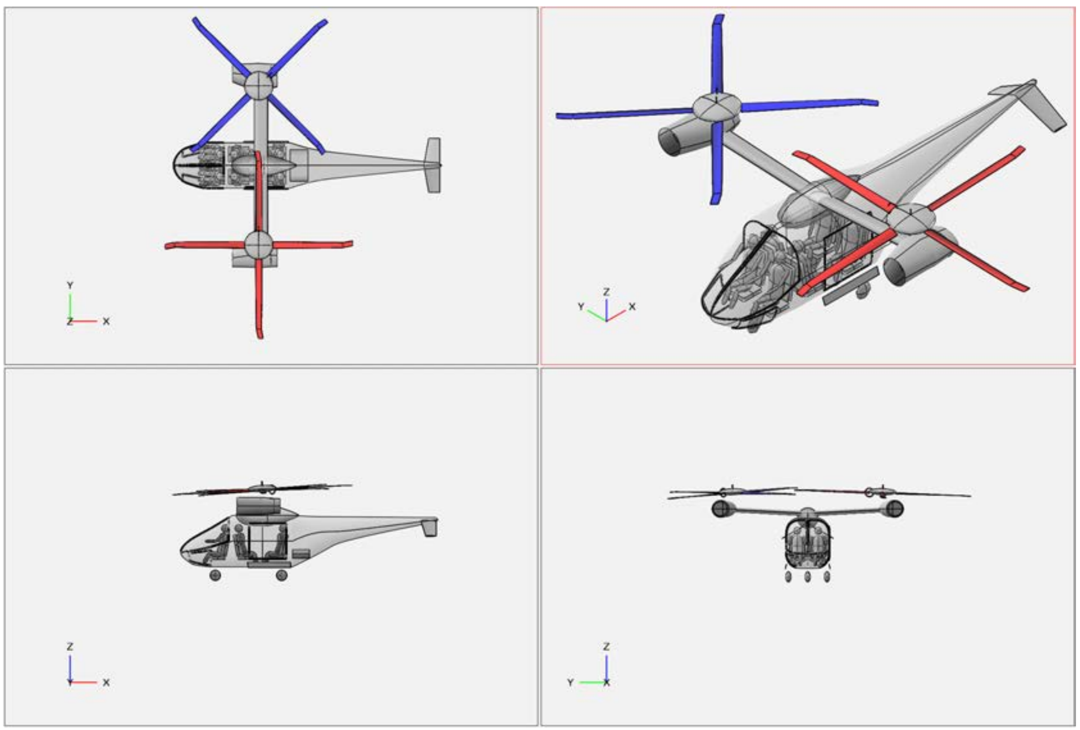
Aircraft: Quadrotor

- Battery- or turboshaft-powered variants
  - Low disk load = 3 - 3.5 lb/ft^2
  - Efficient cruise L/D_e = 5 - 6
  - Edgewise cruise rotors
  - No cyclic control
  - Simple fuselage, booms
  - Rear rotors elevated to avoid wake interactions
  - Cross-shafting for safety
  - Capable of autorotation (collective)



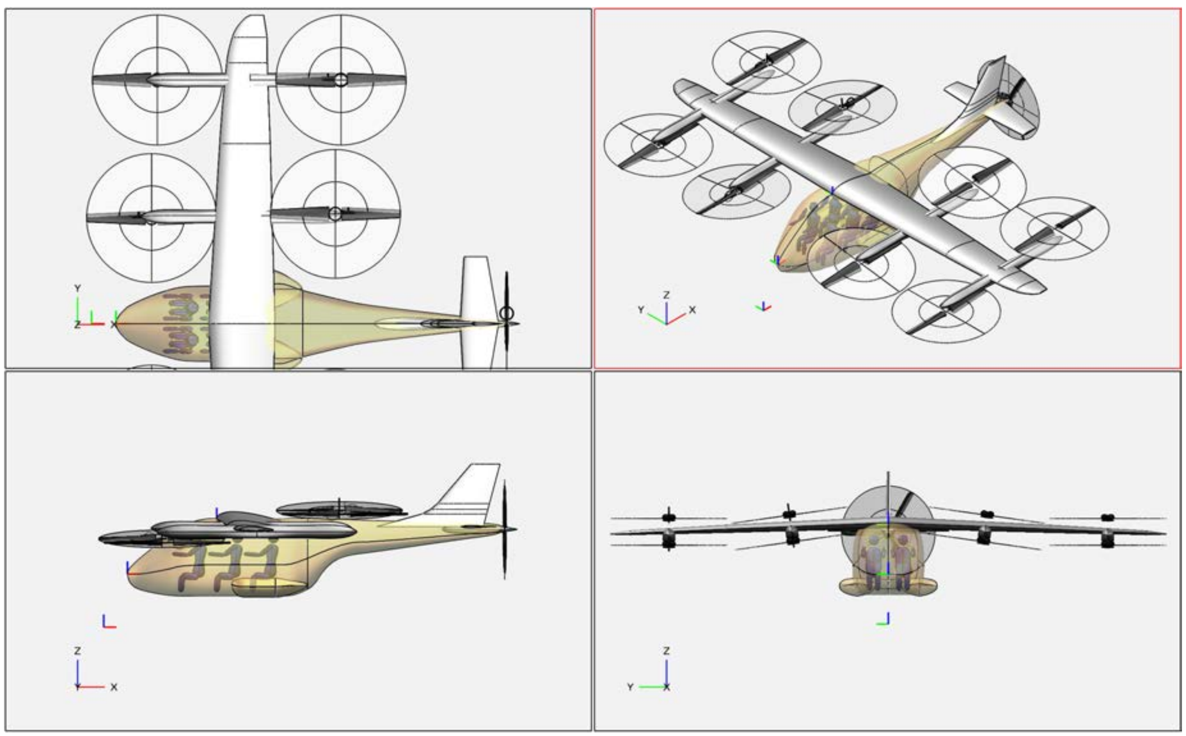
Aircraft: Side-by-Side Helicopter

- Battery- or turboshaft-powered variants
  - Mid disk load = 3.5 - 5 lb/ft^2
  - Efficient cruise = L/D_e 6 - 7
  - Helicopter rotors, controls
  - Fixed wing fuselage
  - Simple boom for rotors
  - Efficient wake interactions
  - Cross-shafting for safety
  - Capable of autorotation

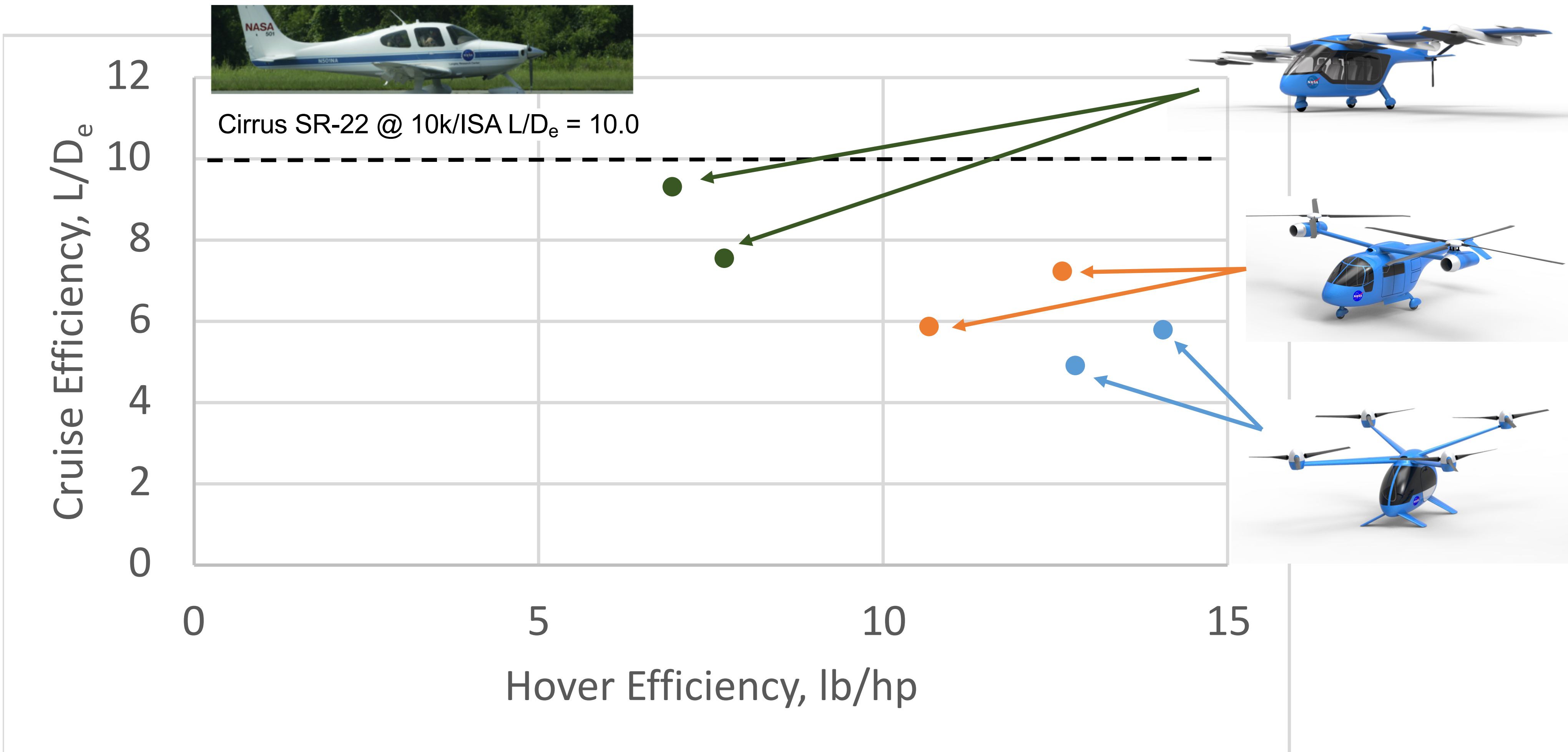


Aircraft: Lift+Cruise

- Battery- or turboelectric-powered variants
  - Higher disk load = 9 - 11 lb/ft^2
  - Efficient cruise L/D_e = 7 - 9
  - Fixed pitch lifters, RPM only
  - Pusher plane fuselage
  - Simple booms for rotors
  - Complex wake interactions
  - Redundant lifters for safety
  - Capable of gliding
  - Lifters stop, align in cruise

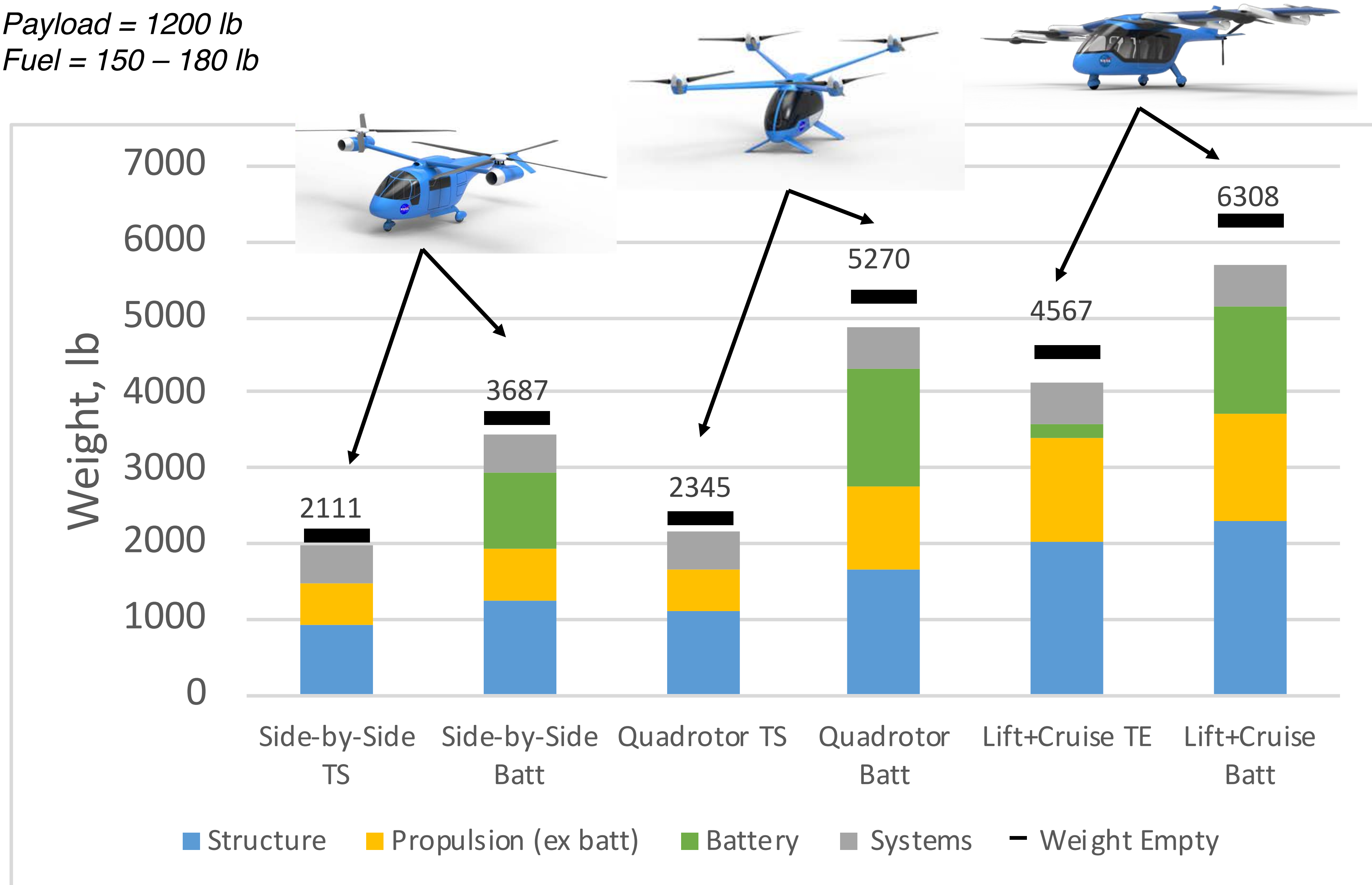


Concepts Have a Range of Aerodynamic Efficiencies



Structure, Propulsion, Battery Dominate Empty Weight

Payload = 1200 lb
Fuel = 150 – 180 lb



Sizing Results for the Three Types



		Quad TS	Quad Batt	SbS TS	SbS Batt	L+C TurboE	L+C Batt
Disk load	lb/ft^2	3.5	3.0	5.0	3.5	8.6	10.9
L/D_e	--	4.9	5.8	5.9	7.2	7.6	9.4
DGW	lb	3,700	6,500	3,500	4,900	5,900	7,500
Structure	lb	1,100	1,600	900	1,200	2,000	2,300
Propulsion	lb	600	1,100	500	700	1,400	1,400
Battery	lb	--	1,600	--	1,000	200	1,400
Block speed	KTAS	105	87	97	83	101	94
Hover C-rate	1/hr	--	0.9	--	1.1	0.0	2.2

A Range of Hover, Cruise, and Structural Efficiencies



		Quad TS	Quad Batt	SbS TS	SbS Batt	L+C TurboE	L+C Batt
Disk load	lb/ft^2	3.5	3.0	5.0	3.5	8.6	10.9
L/D_e	--	4.9	5.8	5.9	7.2	7.6	9.4
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Block speed	KTAS	105	87	97	83	101	94
Hover C-rate	1/hr	--	0.9	--	1.1	0.0	2.2

Even High Specific Energy Batteries are Heavy



		Quad TS	Quad Batt	SbS TS	SbS Batt	L+C TurboE	L+C Batt
Disk load	lb/ft^2	3.5	3.0	5.0	3.5	8.6	10.9
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Block speed	KTAS	105	87	97	83	101	94
Hover C-rate	1/hr	--	0.9	--	1.1	0.0	2.2

Battery-Powered Slower: Flat Part-Power Efficiency



		Quad TS	Quad Batt	SbS TS	SbS Batt	L+C TurboE	L+C Batt
Disk load	lb/ft^2	3.5	3.0	5.0	3.5	8.6	10.9
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Battery	lb	--	1,600	--	1,000	200	1,400
Block speed	KTAS	105	87	97	83	101	94
Hover C-rate	1/hr	--	0.9	--	1.1	0.0	2.2

Mission Range Enough to Keep Current Reasonable

		Quad TS	Quad Batt	SbS TS	SbS Batt	L+C TurboE	L+C Batt
Disk load	lb/ft^2	3.5	3.0	5.0	3.5	8.6	10.9
L/D_e	--	4.9	5.8	5.9	7.2	7.6	9.4
DGW	lb	3,700	6,500	3,500	4,900	5,900	7,500
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Block speed	KTAS	105	87	97	83	101	94
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Outline

- Introduction
- NASA Exploration of Urban Air Mobility
- Reduced-Emission Rotorcraft Concepts
- Concept Vehicles for Air Taxi Operations
- Vehicles for UAM Mission and Market
- Observations
- Conclusion

Design Metrics

- **Feasibility of concept**
  - Sensitivity to requirements and technology
- **Weight, power, energy**
  - Principal drivers of cost
  - Feasibility may require meeting threshold values
    - Hover lb/hp, cruise L/D_e, battery C-rate
- **Cost**
  - Development, purchase, maintenance, operating costs
- **Emissions**
  - Accounting for grid emissions may be necessary
- **Noise and annoyance**
  - FAA Depart, Flyover, Descent (dB)
  - Annoyance is subject of active research with human subjects
- **Passenger acceptance**
  - Vibration, handling qualities

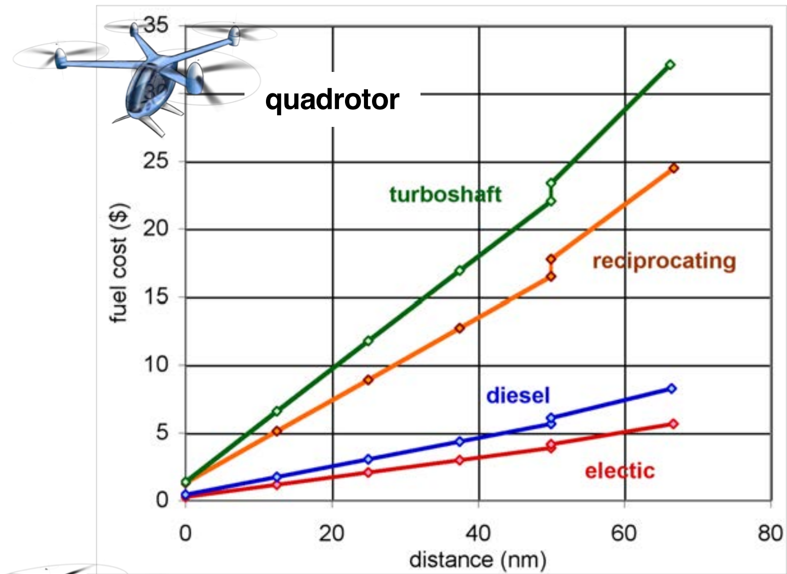
Operational Effectiveness — Cost

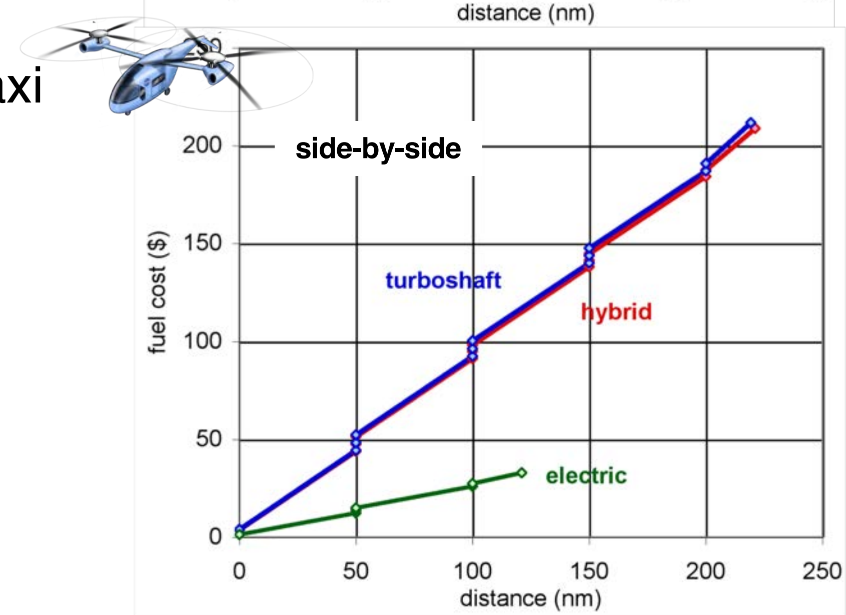
- **Purchase price**
  - Approximately (± 20% accuracy) driven by empty weight, installed power, complexity
  - Plus cost of electronic systems (MEP)
  - Plus cost of batteries

- **Maintenance cost**
  - Data available for helicopter flying traditional missions
  - But not for unconventional aircraft, in air taxi operations, with to-be-established maintenance concept

- **Operating costs**
  - Fuel or energy is significant component
  - Battery replacement costs important

fuel/energy cost flying design mission





Noise and Annoyance

- **Anticipate requirement for significant noise reduction in order to operate in urban environment**

- **Regulations establish noise metrics and requirements for rotorcraft**
  - Suitability and applicability to air taxi operations not yet established
  - Possibly new metrics will be needed

- **Air taxi vehicles designed with low hover tip speed**
- **Low tip speed probably not sufficient**

- **Aircraft configuration impacts noise**
  - Rotor-rotor interactions will increase blade-vortex interaction noise
- **Blade shape and spacing can be optimized for low BVI and HSI noise**

- **Active control of rotor noise: 6-12 dB reduction demonstrated through analysis, wind tunnel test, and flight test**

Safety and Airworthiness

- **Airworthiness approval means a document, issued by the FAA for an aircraft, which certifies that the aircraft conforms to its approved design and is in a condition for safe operation (14 CFR 21.1(b)(2))**

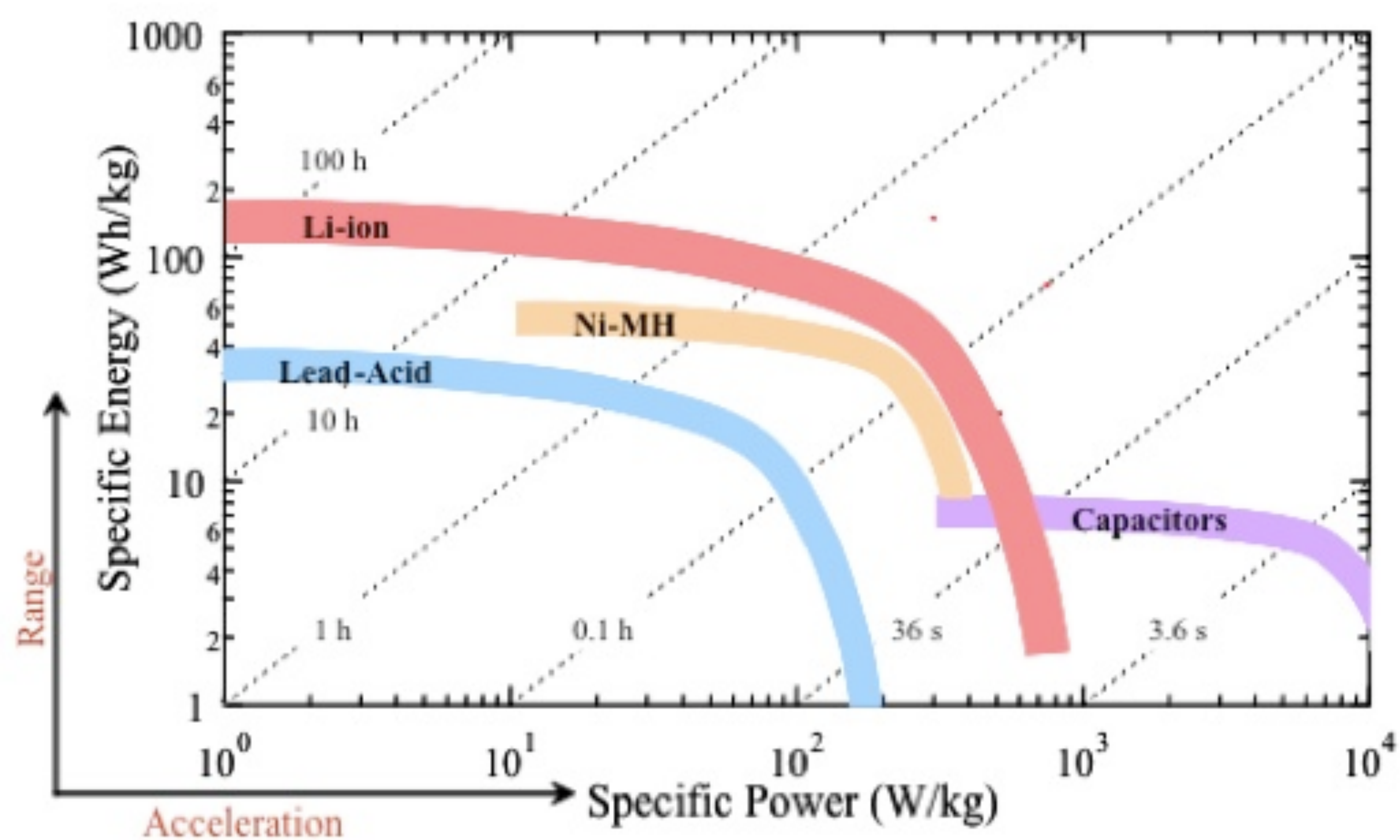
- **Every innovative aircraft type and non-traditional propulsion system requires an extensive failure mode, effects, and criticality analysis (FMECA)**

- **Crashworthiness**
  - **Affects design of airframe structure, landing gear, passenger accommodation and restraint**
  - **Conceptual design: need impact on weights**

- **Propulsion system failures**
  - **Consider to single and multiple motor/engine failure, all power failure**
  - **Need requirements for control, and approaches for safe landing**
  - **Conceptual design: aircraft type (number and orientation of rotors, control methods) and design flight conditions for sizing**

Battery Technology

- **Li-Ion battery state-of-the-art: tradeoff of power and energy**
- Discharge current (fraction capacity, 1/hr) = specific power / specific energy

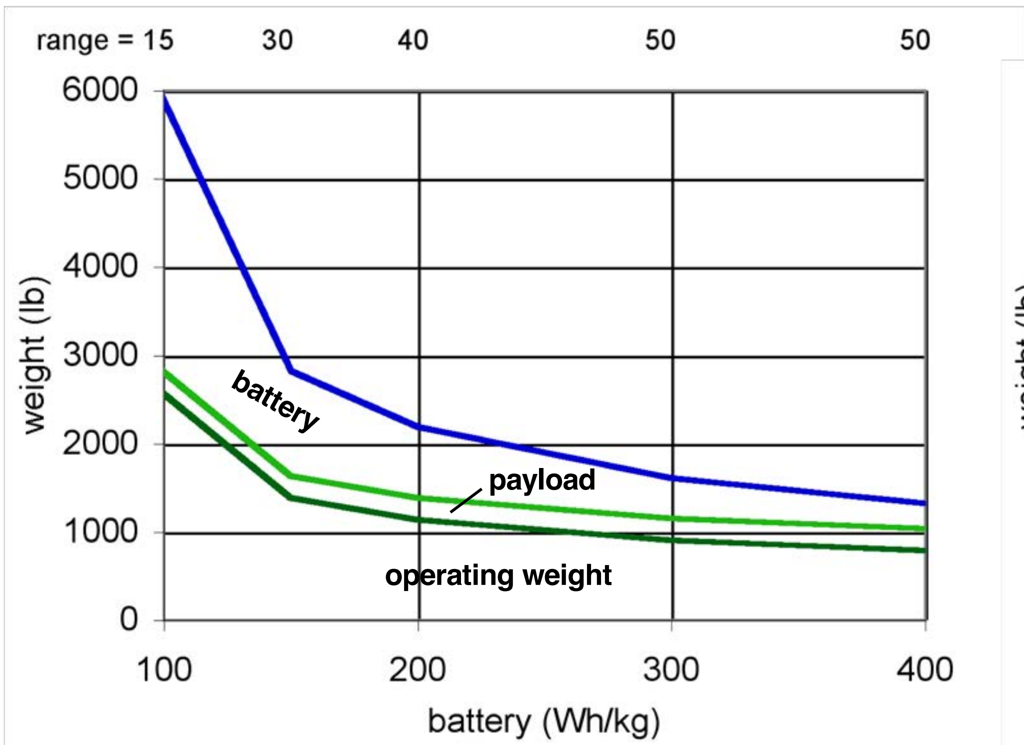


Impact of Battery Technology

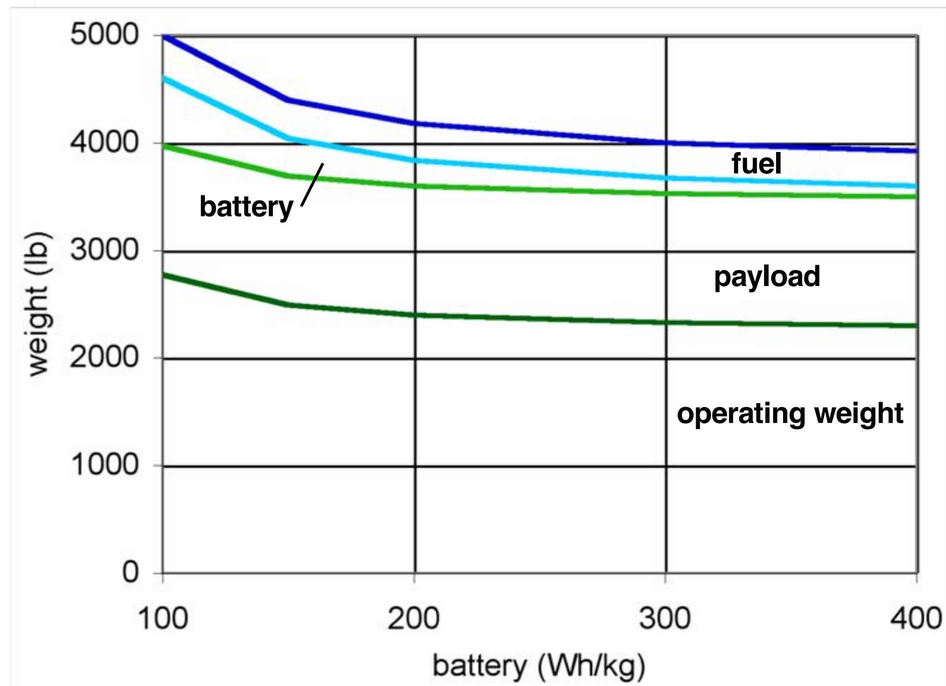
- **Need light-weight, high-power batteries**
- **Baseline designs: battery installed & useable specific energy = 400 Wh/kg**
  - State-of-the-art = 100-150 Wh/kg installed & useable

electric quadrotor

hybrid side-by-side



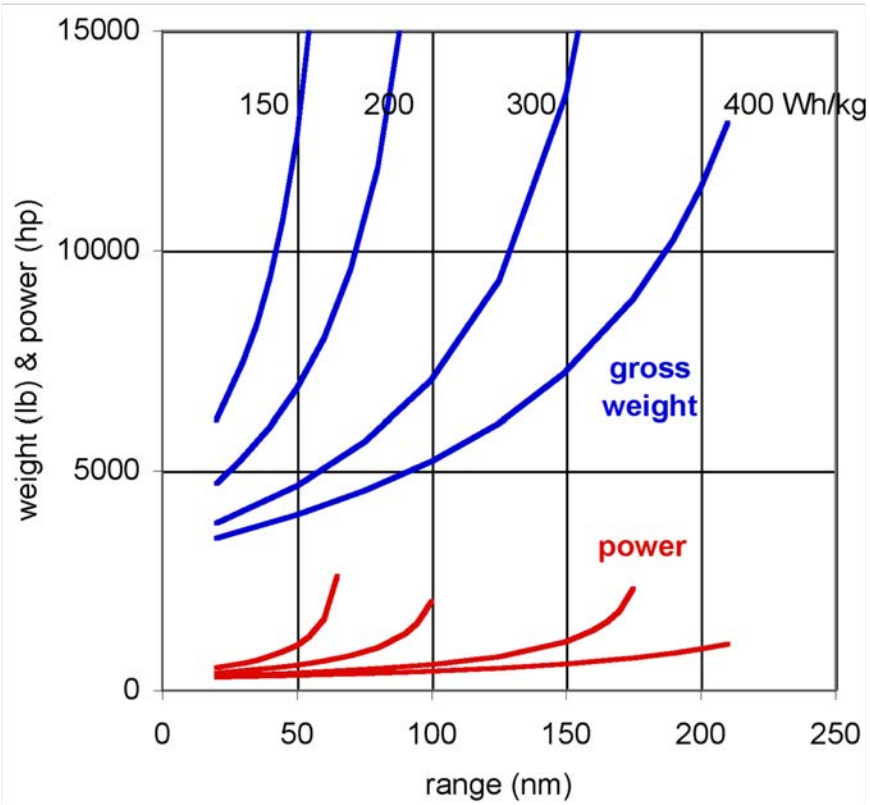
installed specific energy

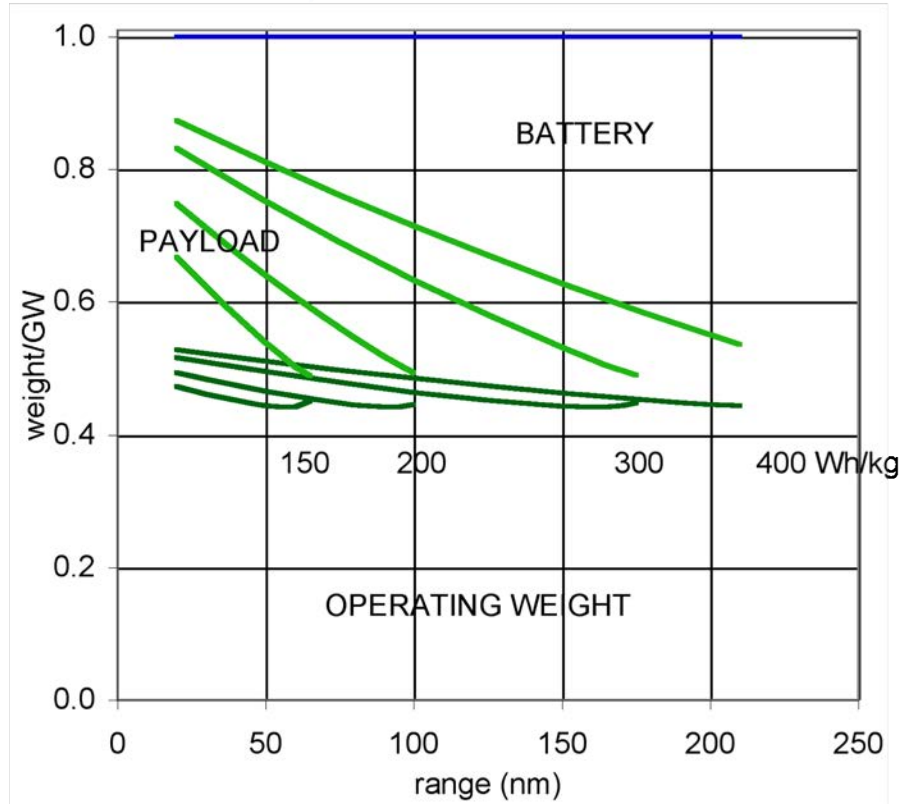


installed specific energy

Impact of Battery Technology — Concept Feasibility

Electric, side-by-side, 6 passengers





Battery Technology — Hover Discharge Current

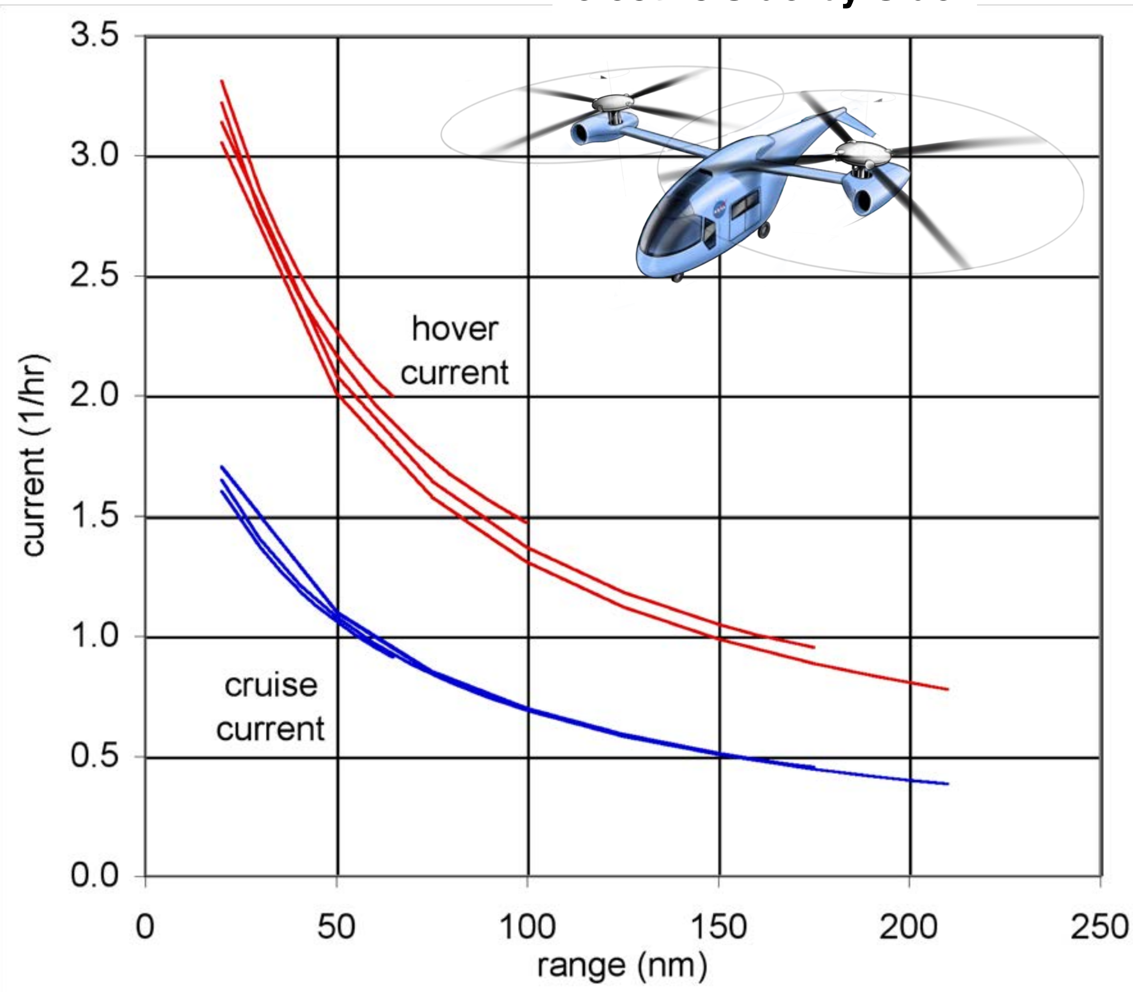
need high discharge current capability

current: $I = xC$

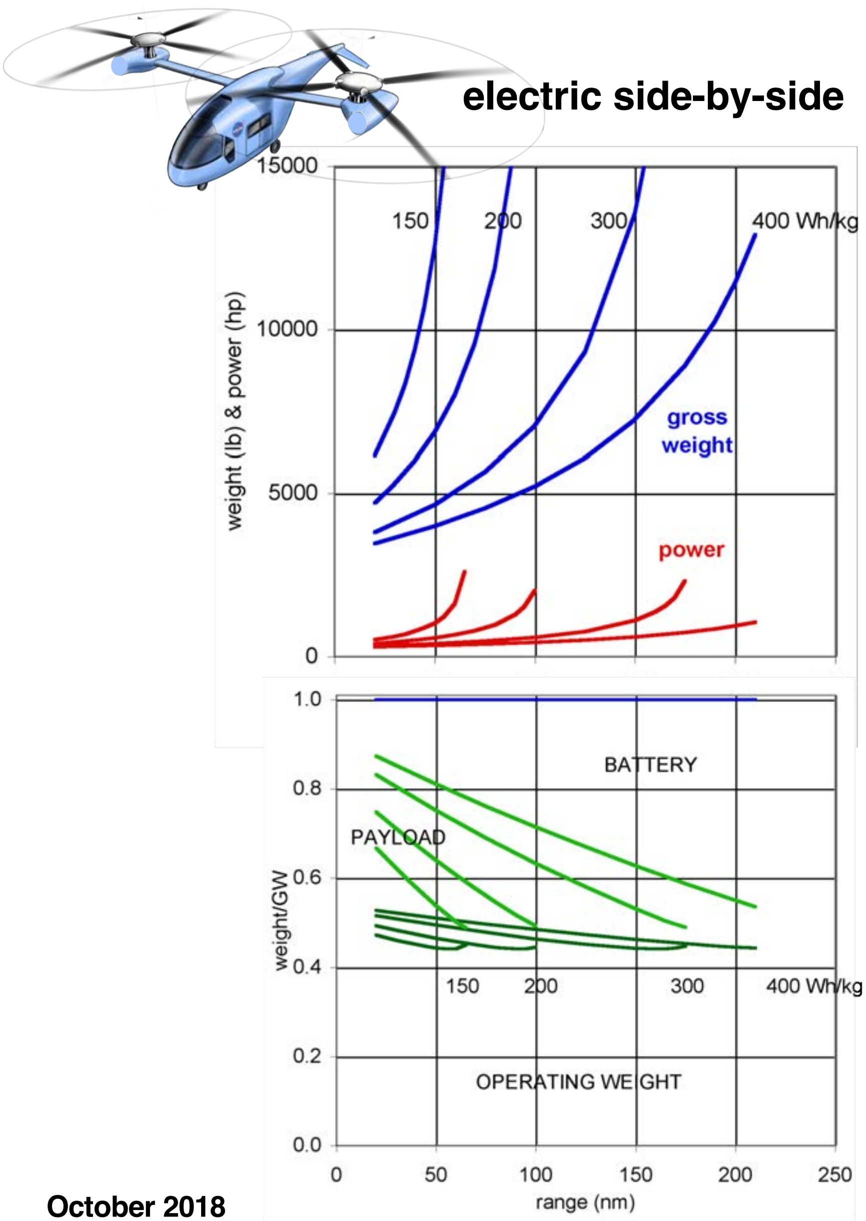
$$x_{\text{hover}} = \sqrt{W/2\rho A}\,\frac{\eta_c (L/D_e)}{\eta_h FM}\,\frac{1}{\text{Range}}$$

Cruise efficiency: battery energy
Hover efficiency: battery power

electric side-by-side

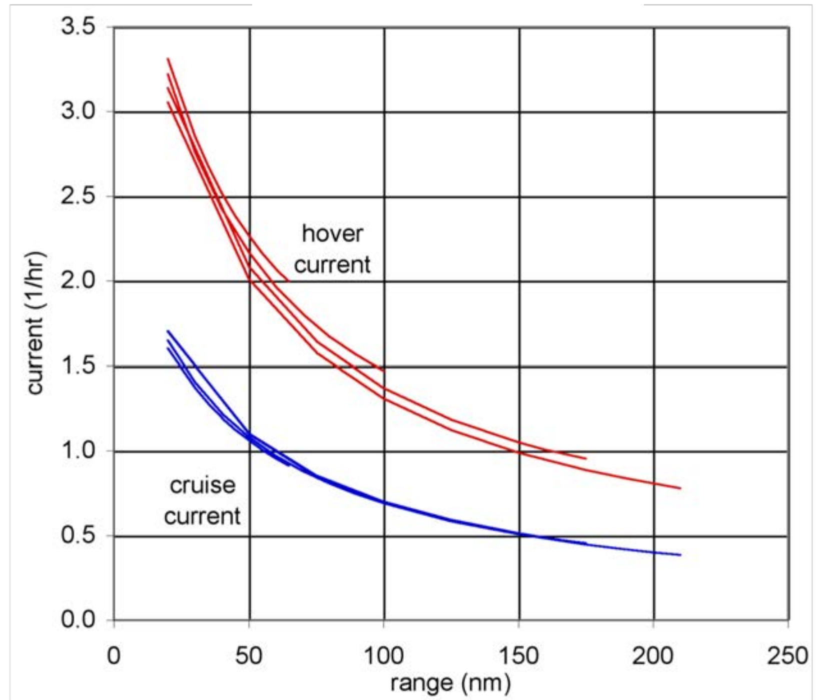


Battery Technology — Hover Discharge Current



need high discharge current capability

current: $I = xC$



$$x_{\text{hover}} = \sqrt{W/2\rho A}\,\frac{\eta_c (L/D_e)}{\eta_h FM}\,\frac{1}{\text{Range}}$$

Cruise efficiency: battery energy
Hover efficiency: battery power

Efficiency Enables Electric Propulsion

- **Electric propulsion enabled by aerodynamic efficiency of the aircraft, in both hover and cruise**

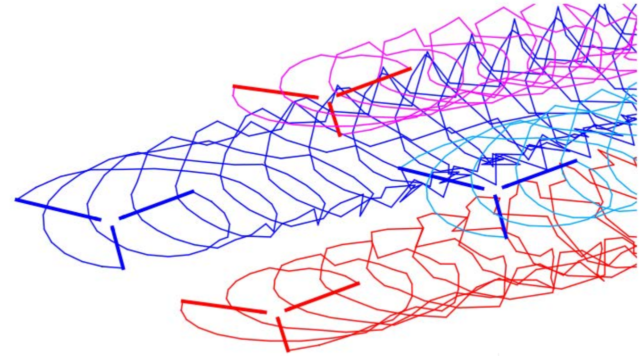
- **Aircraft optimization**
  - **Disk loading: minimize aircraft weight, power, energy**
    - Small aircraft with edgewise rotors optimize with low disk loading
  - **Rotor-rotor interference: optimum cruise performance**
  - **Interactional aerodynamics impact performance and operation**
    - Tiltwing: wing separation or buffet during conversion
    - Tiltrotor: hover download, rotor-tail interactions
    - Active flow control may be required

- **Rotor shape optimization**
  - Blade twist and taper, tip sweep and droop
  - System metrics, balancing hover and cruise performance

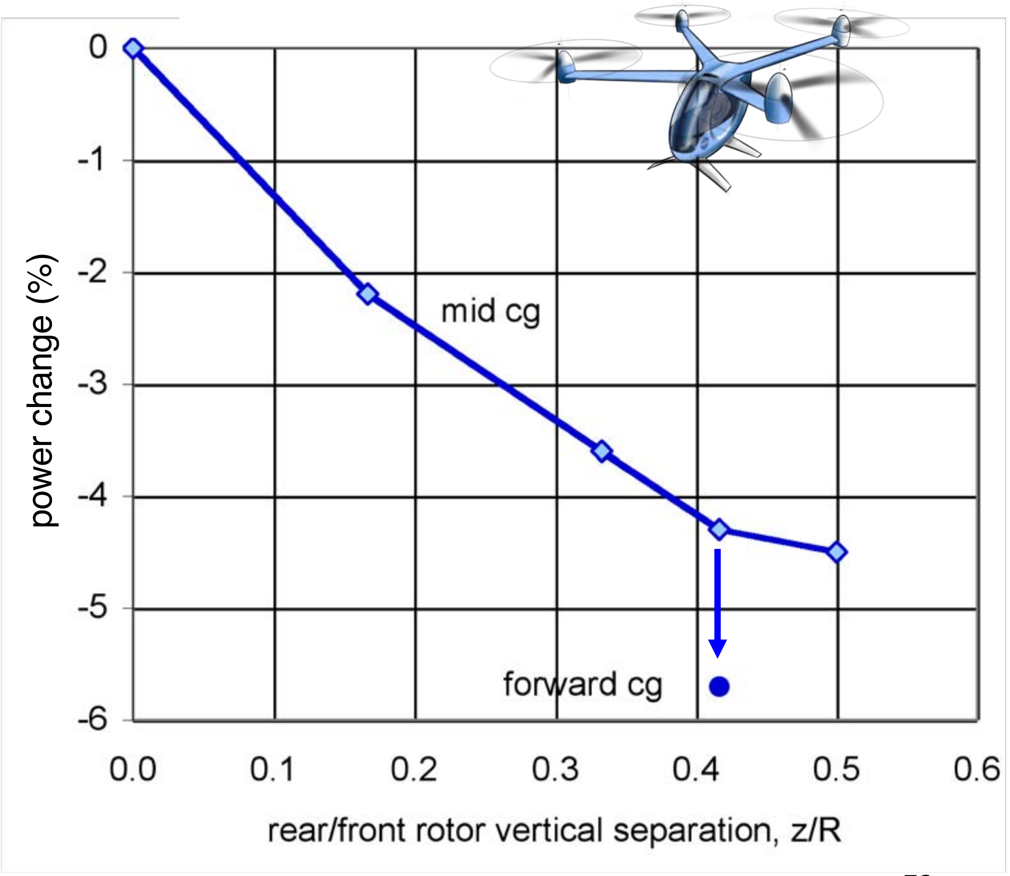
- **Drag minimization: hub, rotor support, airframe**

Rotor-Rotor Interaction Impact on Efficiency

- **Rotor-rotor interactions impact performance, vibration, noise, handling qualities**

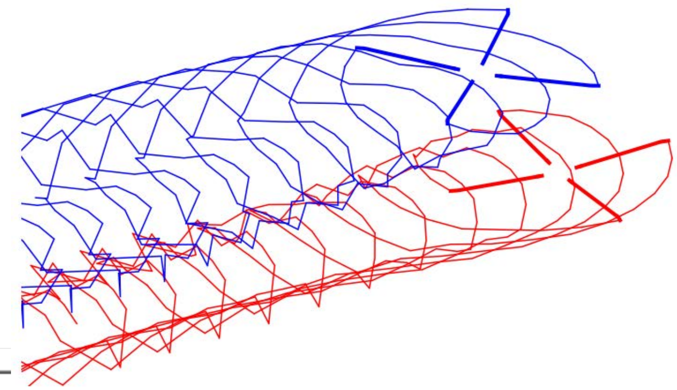


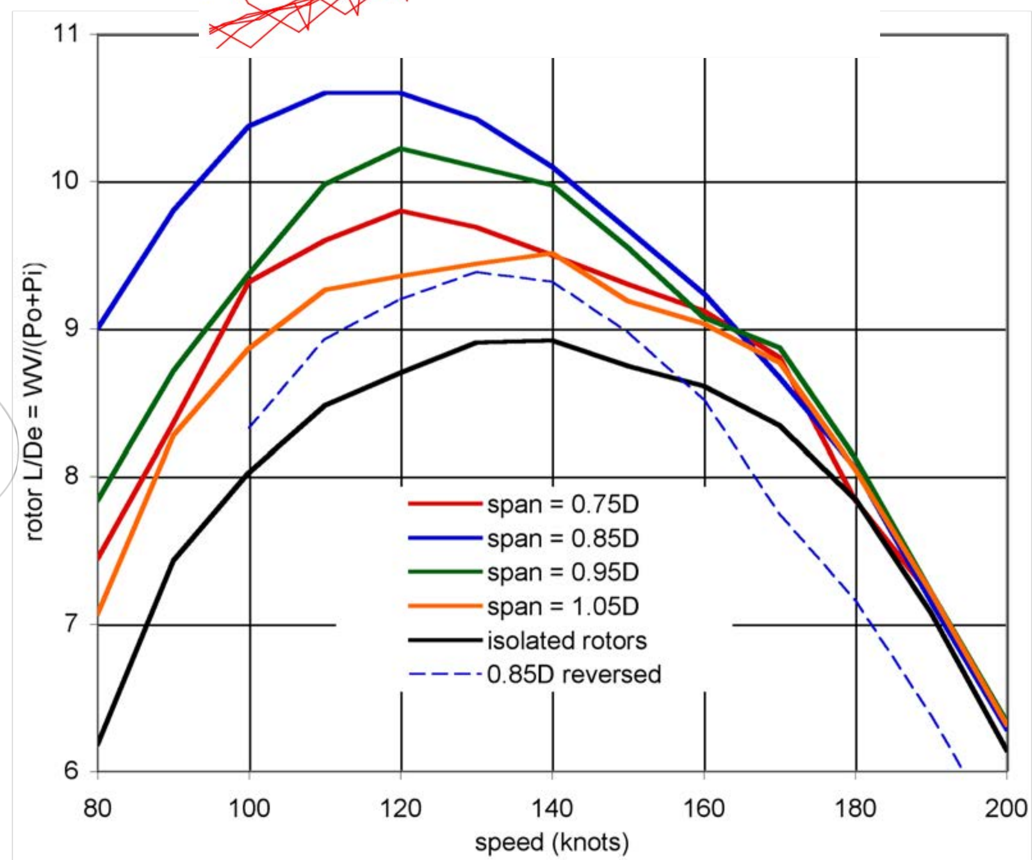
- **Quadrotor — reduce cruise power by**
  - Elevating rear rotors above front rotors
    - Also reduces noise and vibration
  - Forward center-of-gravity, so front and rear rotors trim closer to same thrust



Rotor-Rotor Interaction Impact on Efficiency

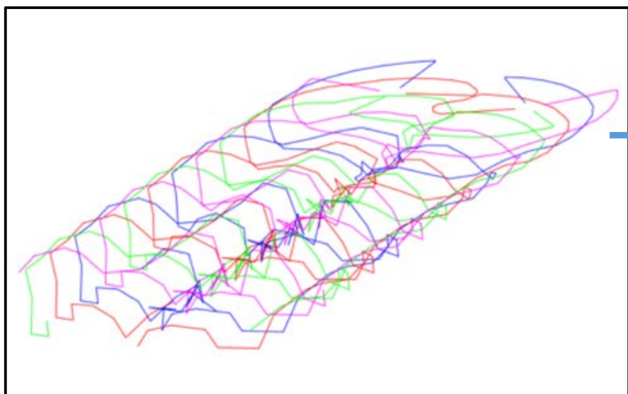
- **Overlap of side-by-side rotors improves cruise performance**
- **Twin rotors act as single, large-span wing system**



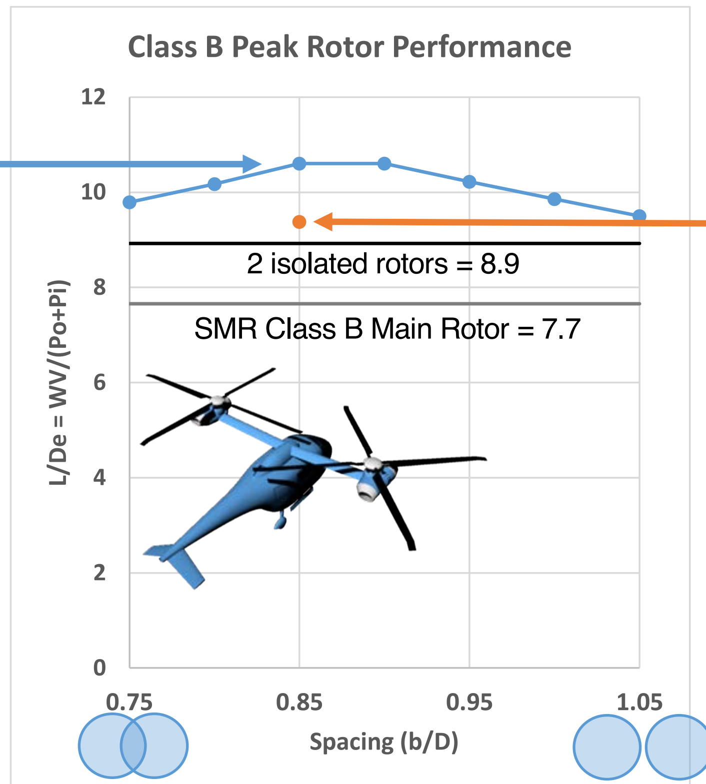


How does the Side-by-Side work?

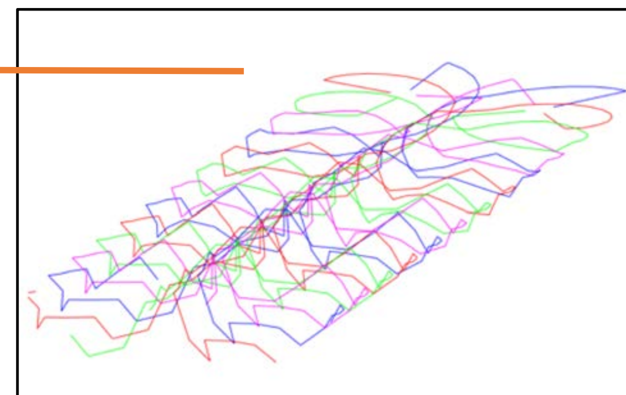
- The rotors act like a single wing, and induced drag varies as $(W/b_{tot})^2$
- You need analysis which captures wake interactions and aircraft system effects to make the right design choices
  - Outboard advancing is quite a bit better than outboard retreating
  - Twist trades between hover and forward flight need system effects
  - The supports/wings are sources of drag and weight, and maybe lift



Outboard advancing
Peak L/De ~ 10.5
Peak b/D ~ 0.85-0.9

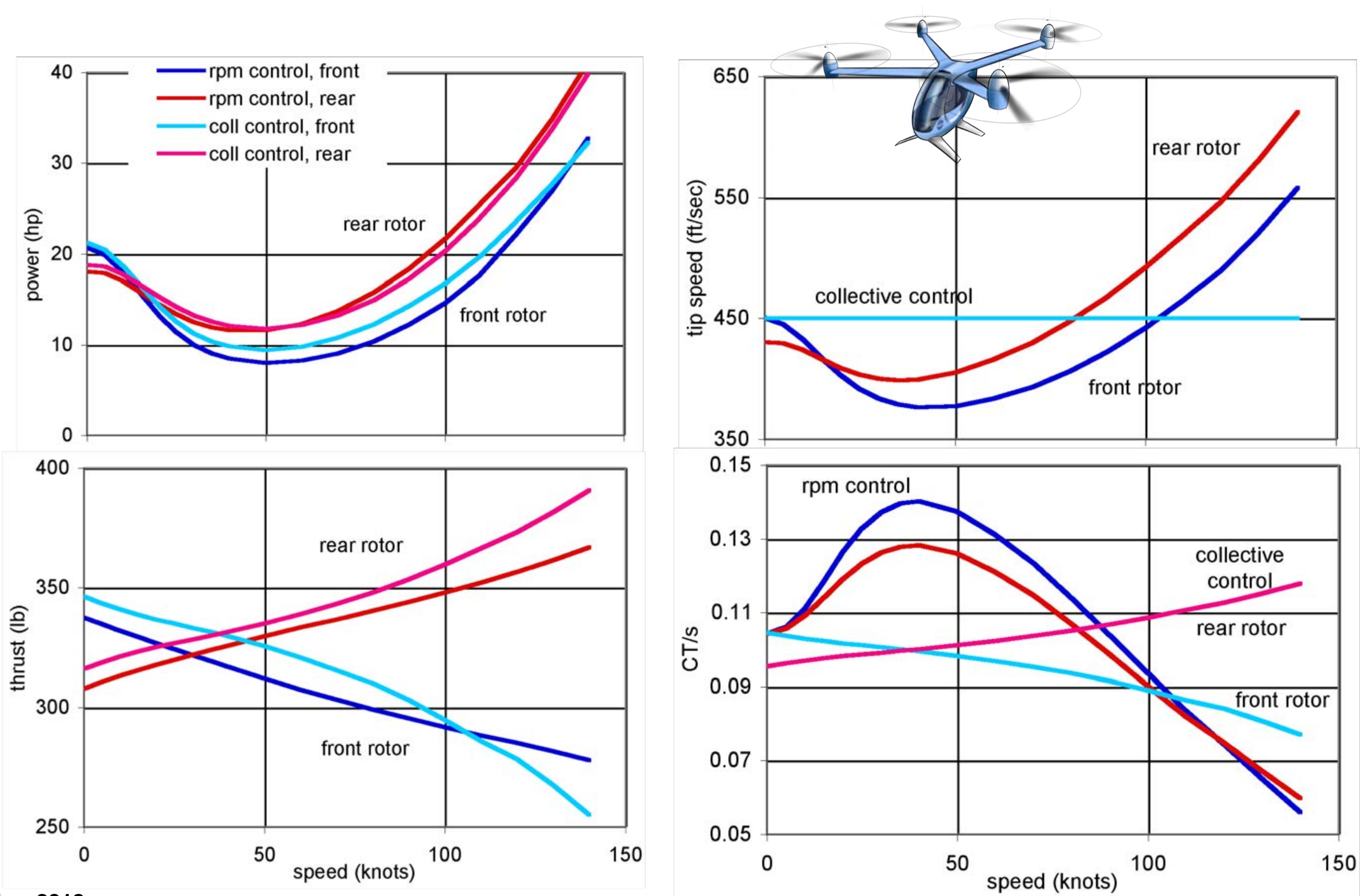


Outboard retreating
Peak L/De ~ 9.4



Trim of Multi-Rotor Aircraft

Interesting trim characteristics: collective control or rotor speed control



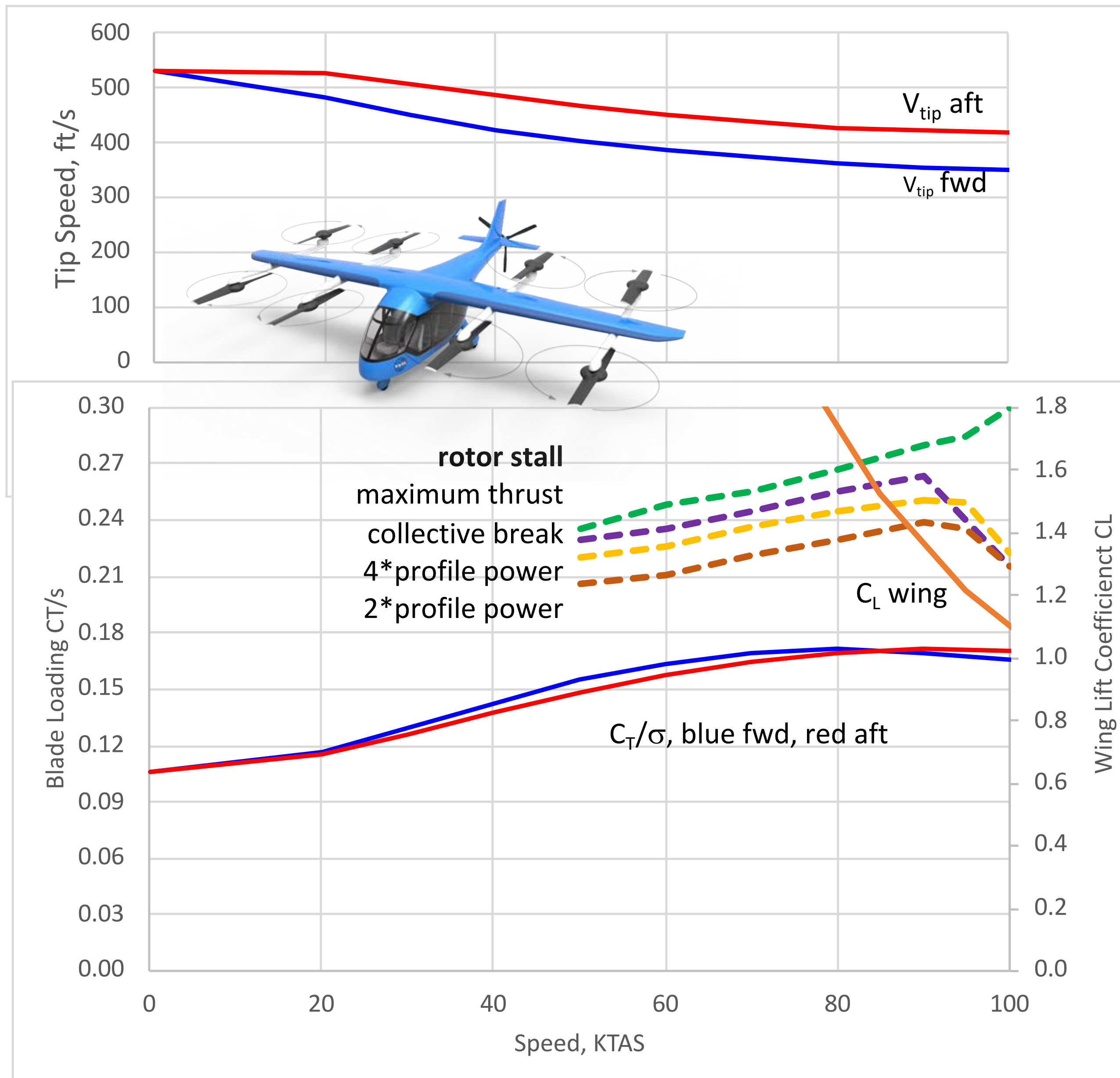
Fixed-Pitch Control and Conversion Aerodynamics

Wing stall speed must be less than rotor stall speed

Edgewise rotor flight has reduced induced power for the same lift due to increased inflow

Helicopters reduce collective pitch

Fixed pitch propeller reduces rotational speed, increasing blade loading



Impact of Rotor/Propeller Design

- **Rotor or propeller design impacts weight, vibration, handling qualities**

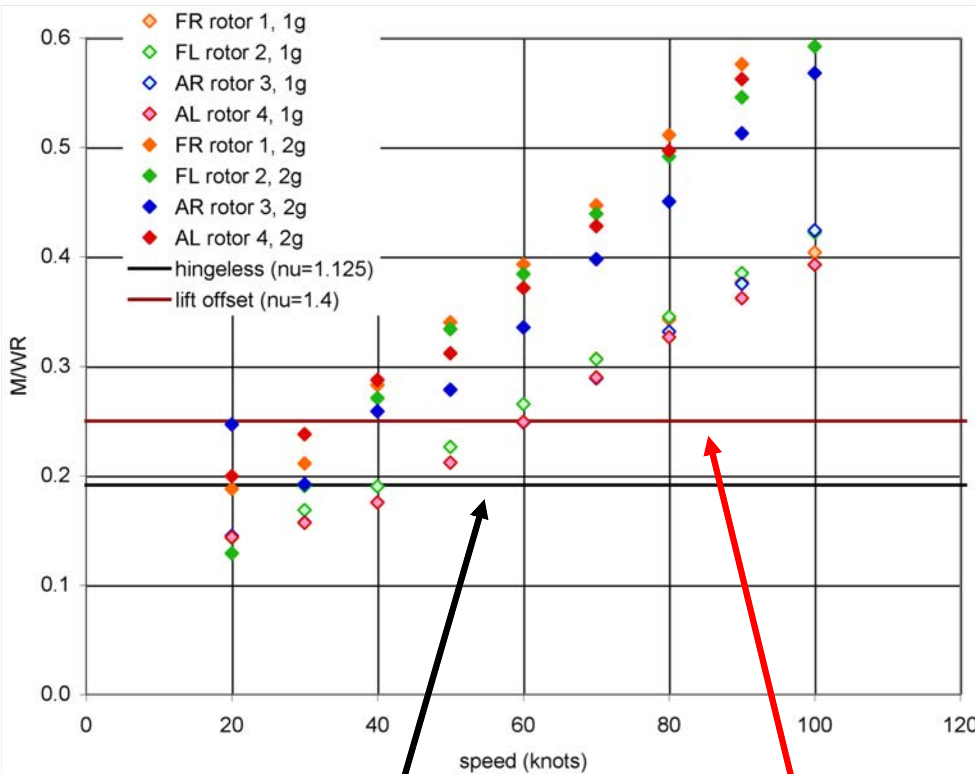
- **Quadrotor**
  - Flapping rotor
    - 4% hinge offset, with 45 deg pitch-flap coupling to minimize flapping relative shaft
  - Hingeless rotor
    - Higher blade and hub loads => higher rotor weight, larger weight for vibration control
    - Resulting aircraft has 25% larger design gross weight

- **Active control of rotorcraft vibration**
  - Up to 90% reduction of loads and vibration using HHC or IBC demonstrated through analysis, wind tunnel test, and flight test

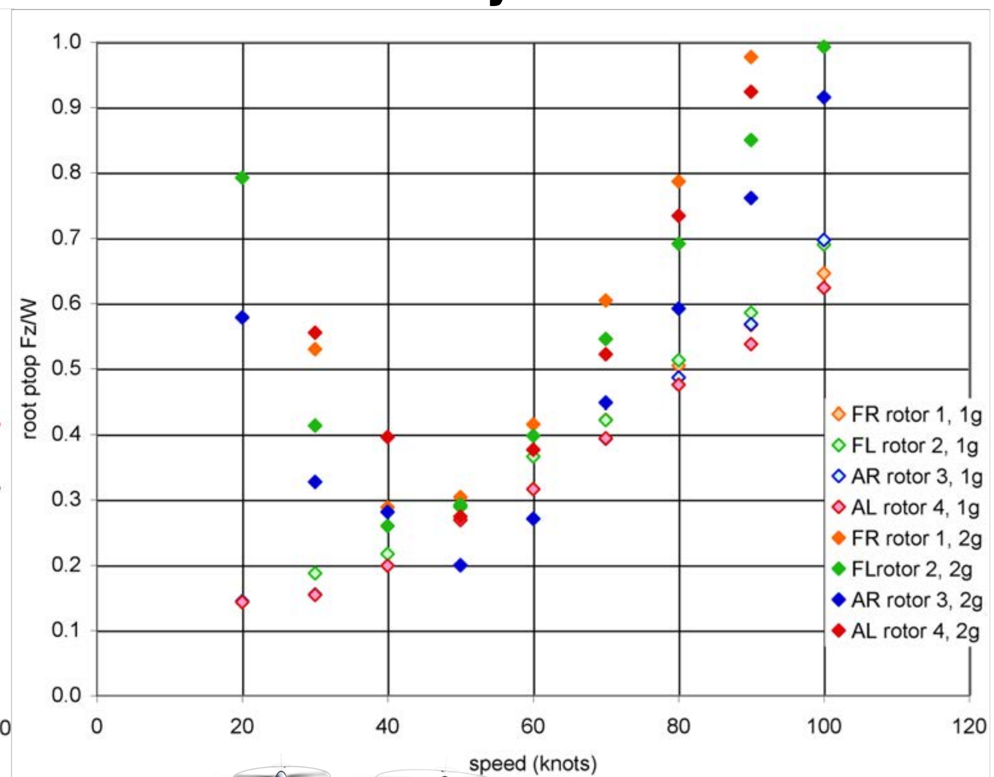
Rotor Design Loads

Quadrotor — fixed pitch, hingeless; level flight and 2g turn

mean hub moment



blade oscillatory vertical shear

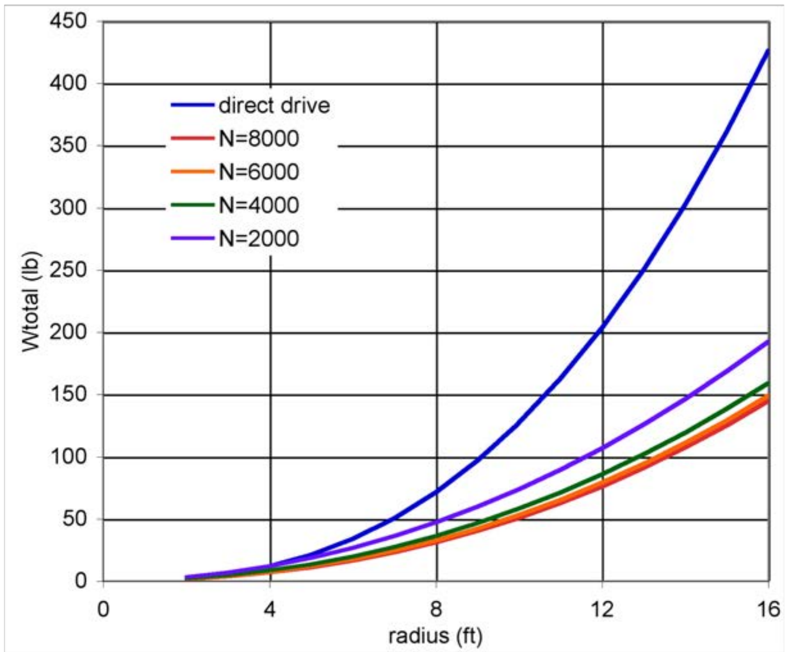


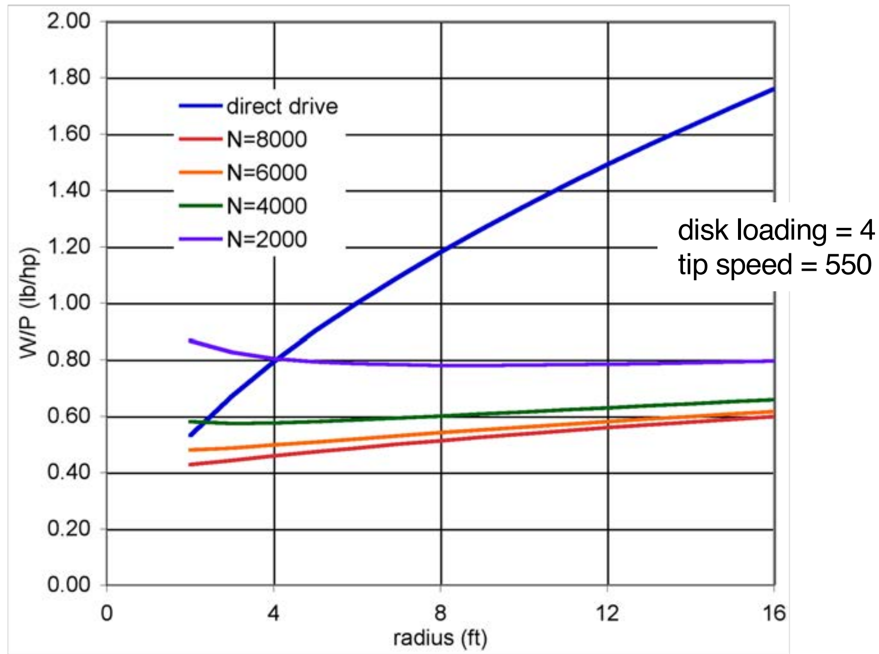
design load for hingeless helicopter rotor

design load for lift-offset rotor

Direct Drive or Transmission

- High speed motor + transmission almost always lighter than direct drive
- With weights of motor+trans based on parametric equations:



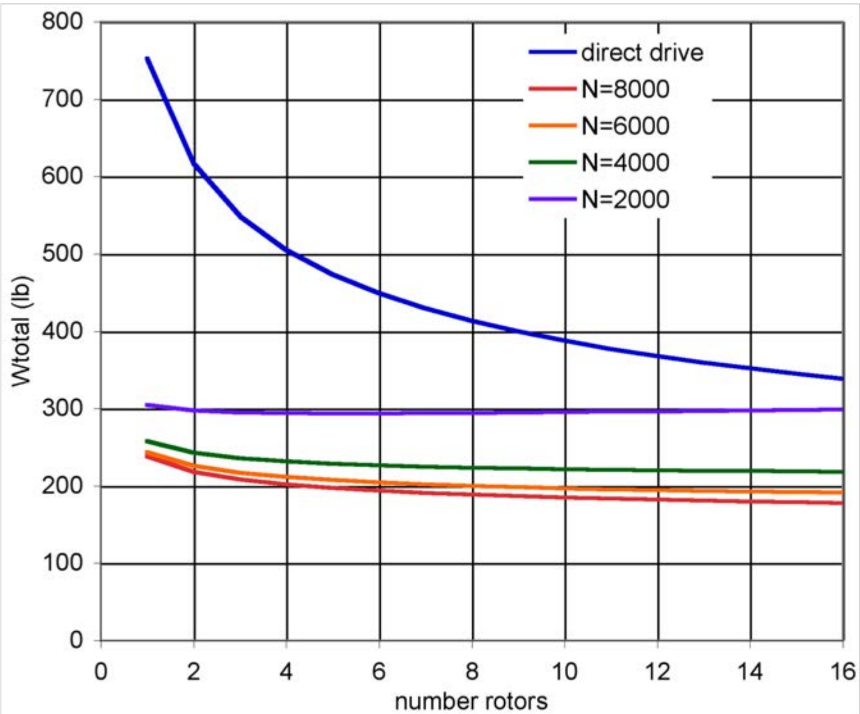


- Direct drive: requires light weight, low speed, high torque motor
  - Operating with large mean and oscillatory loads from rotor

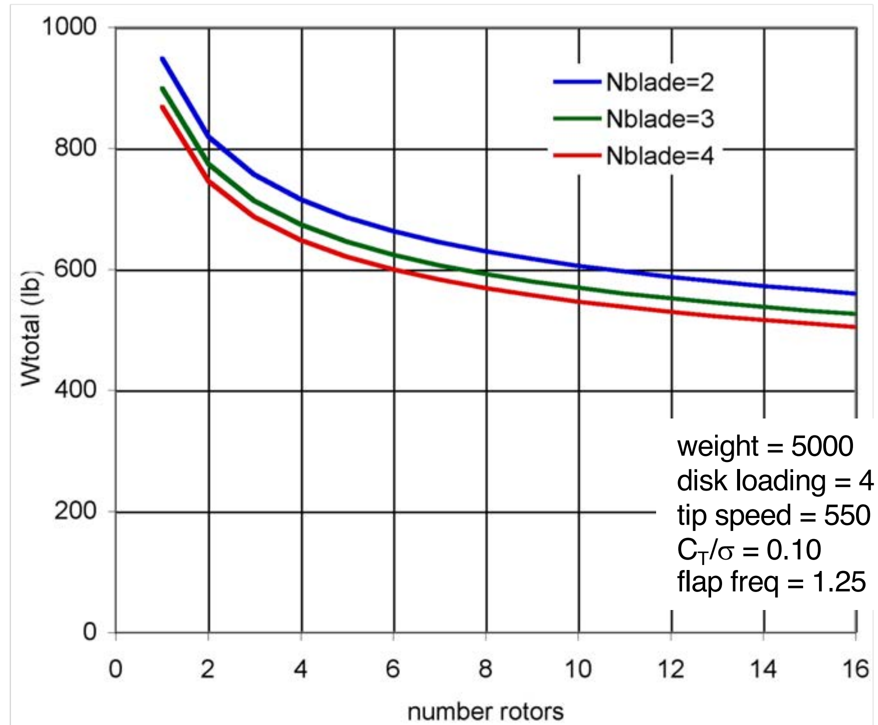
Number of Rotors

- **With weights of propulsion system based on parametric equations:**

motor+transmission



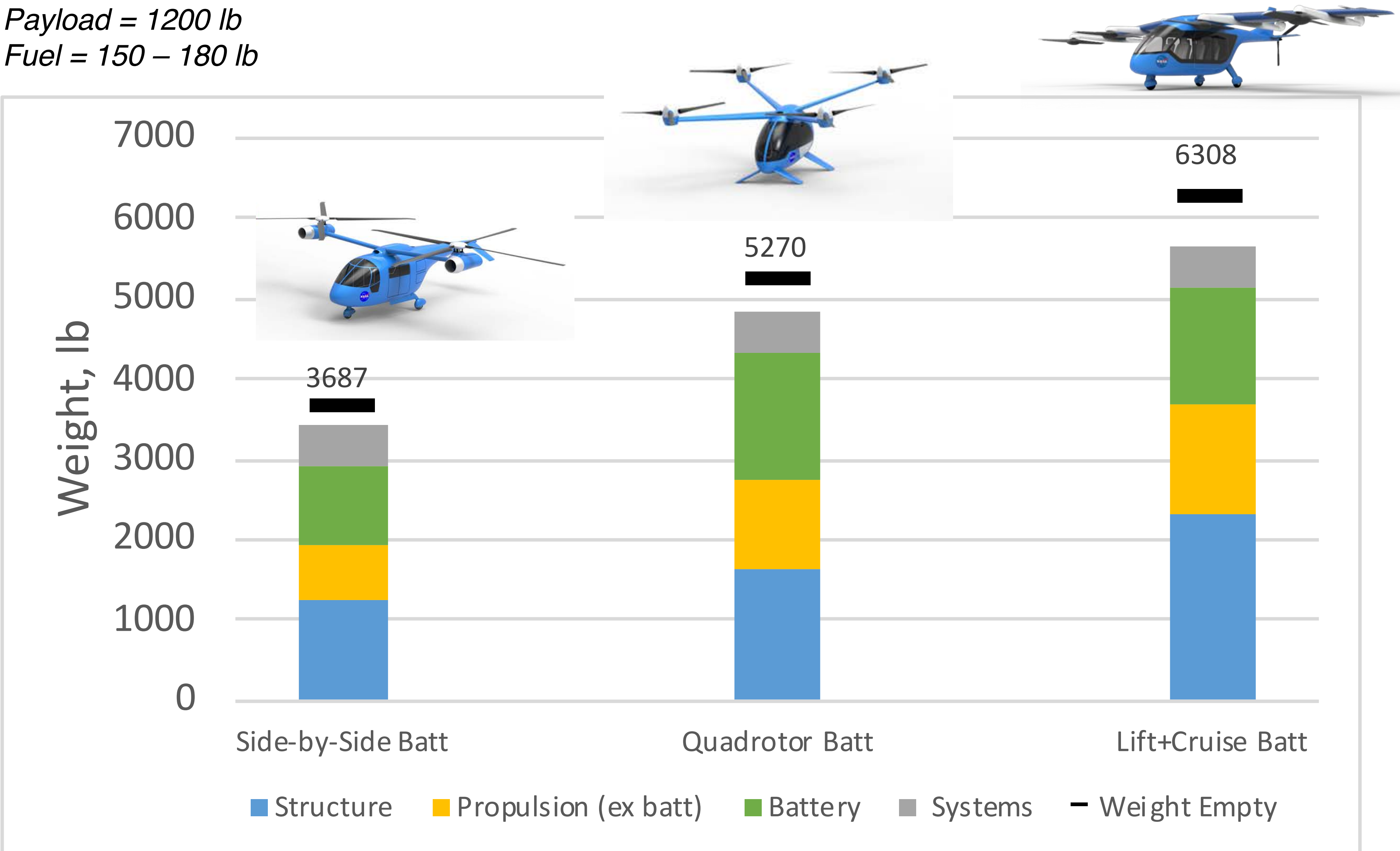
motor+trans+rotors



- **Adding weight (and drag) of structure that support the rotors changes the optimum**
  - **Usually single main rotor configuration (even with tail rotor) better than tandem**

Number of Rotors

Payload = 1200 lb
Fuel = 150 – 180 lb



Assessment of Tools and Data

- **Tools available for rotorcraft aeromechanics analysis and design are applicable to VTOL air taxi aircraft**
  - Comprehensive analyses, computational fluid dynamics codes, rotor and airframe structural analyses, acoustic codes
- **To support design results, need component design methods and data bases for unconventional aircraft propulsion systems**
  - Particularly electrical subsystems

- **Reliability of tools in design process rests on correlation of results with measured data for relevant aircraft types, systems, and components**
  - Need data from ground, wind tunnel, and flight tests to substantiate aeromechanics analysis capability for air taxi aircraft
- **Correlation with test data likely show need for improved or new analysis methods**

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NASA RVLT Project Research Areas for Urban Air Mobility

PERFORMANCE
aircraft optimization
rotor shape optimization
hub and support drag minimization
airframe drag minimization

ROTOR-ROTOR INTERACTIONS
performance, vibration, handling qualities
aircraft arrangement
vibration and load alleviation

PROPULSION EFFICIENCY
high power, lightweight battery
light, efficient, high-speed electric motors
power electronics and thermal management
light, efficient diesel engine
light, efficient small turboshaft engine
efficient powertrains

Quadrotor + Electric

Tiltwing + Turboelectric

ROTOR-WING INTERACTIONS
conversion/transition
interactional aerodynamics
flow control

SAFETY and AIRWORTHINESS
FMECA (failure mode, effects, and criticality analysis)
component reliability and life cycle
crashworthiness
propulsion system failures
high voltage operational safety

Side-by-side + Hybrid

Lift+Cruise + Turboelectric

STRUCTURE AND AEROELASTICITY
structurally efficient wing and rotor support
rotor/airframe stability
crashworthiness
durability and damage tolerance
High-cycle fatigue

OPERATIONAL EFFECTIVENESS
disturbance rejection (control bandwidth, control design)
all-weather capability
passenger acceptance
cost (purchase, maintenance, DOC)

NOISE AND ANNOYANCE
low tip speed
rotor shape optimization
flight operations for low noise
aircraft arrangement/ interactions
cumulative noise impacts from fleet ops
active noise control
cabin noise
metrics and requirements

AIRCRAFT DESIGN
weight, vibration
handling qualities
active control