Range and Endurance Tradeoffs on Personal Rotorcraft Design

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Motivation

There is increasing interest in vertical-lift vehicles, improving mobility and overall utility / flexibility. Baseline a nominal, one hour mission, assess performance for alternative missions.

Portions of or entire vertical-lift missions tend to be closer to the populace (and more flights expected), so environmental considerations (noise, emissions, etc.) are especially important.

Electric systems and new designs enabled by these systems offer the potential for reduced noise and point of use emissions, enhanced vehicle and mission capability, etc.

Compare and contrast previous and new vehicles; traditional versus all-electric architectures. Improve understanding for their strengths / weaknesses; identify future analysis and R&D areas.

Outline

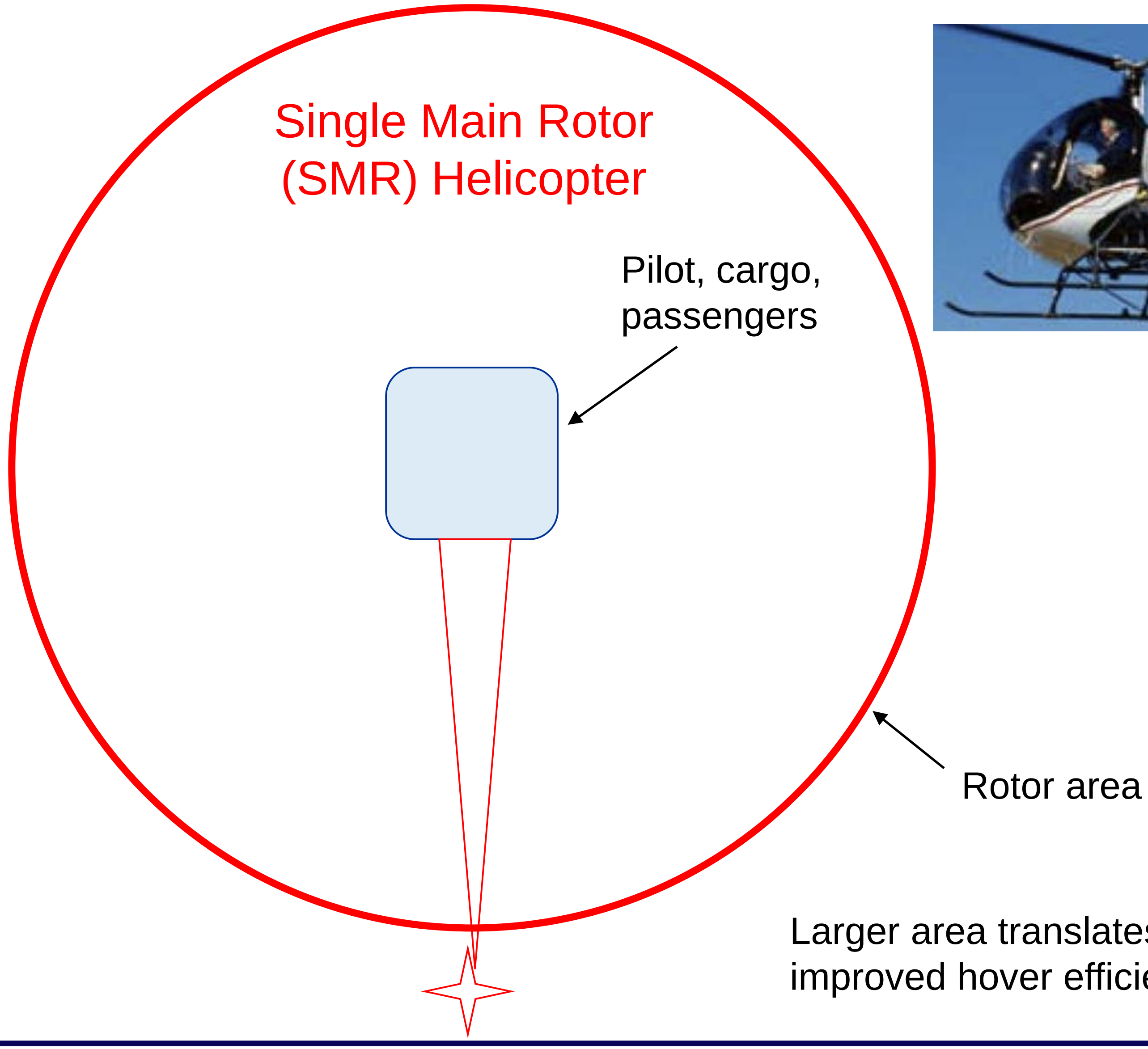
- Introduce baseline vehicles
- Review propulsion and energy systems
  - Electric motors / system parameters (Dever)
  - Compare and contrast traditional versus battery / electric motor systems
- Discuss analysis methodology and assumptions
- Present Results
  - Power required for various mission segments
  - Mission radius versus hover and loiter duration
- Summary
- Future work

Baseline vehicles
Single Main (SMR) Helicopter, Tilt Rotor and Vertical Take Off and Landing (VTOL) Aircraft

payload (450 lbs.
  passengers / luggage
+ 200 lbs. pilot
≈ 1 hour mission

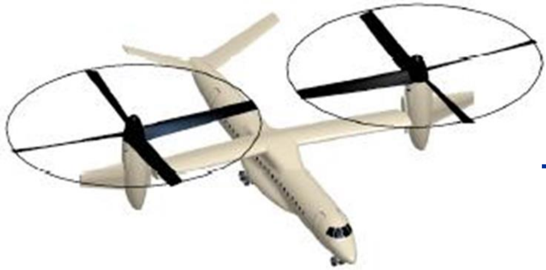
Images not to scale

Baseline vehicles (cont.)



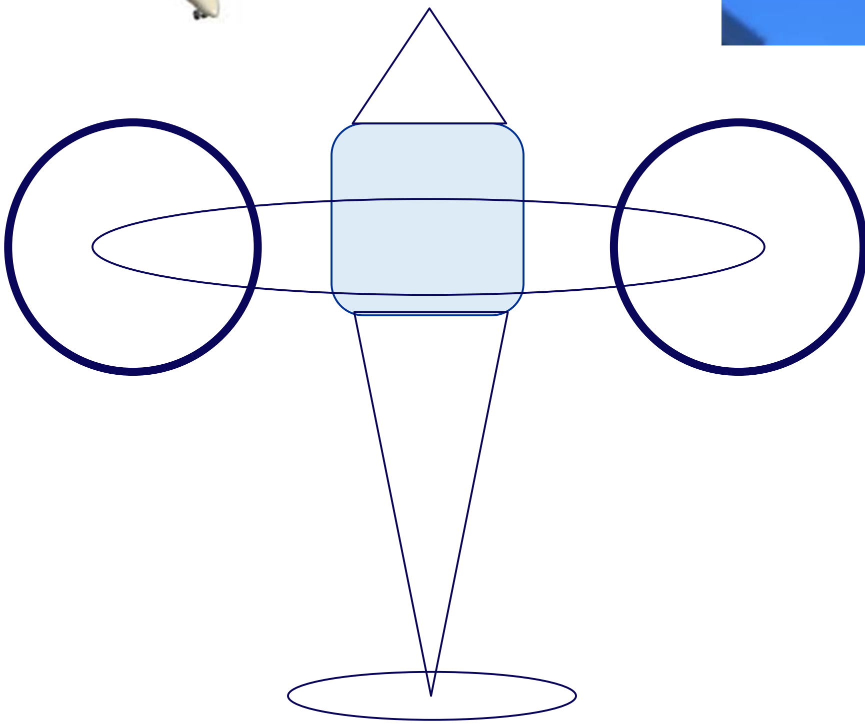
Larger area translates to
improved hover efficiency

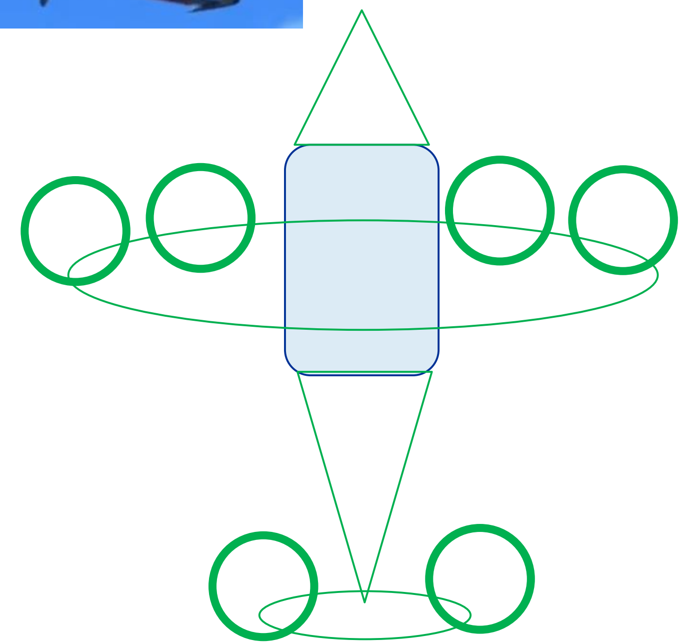
Baseline vehicles (cont.)



Tilt Rotor

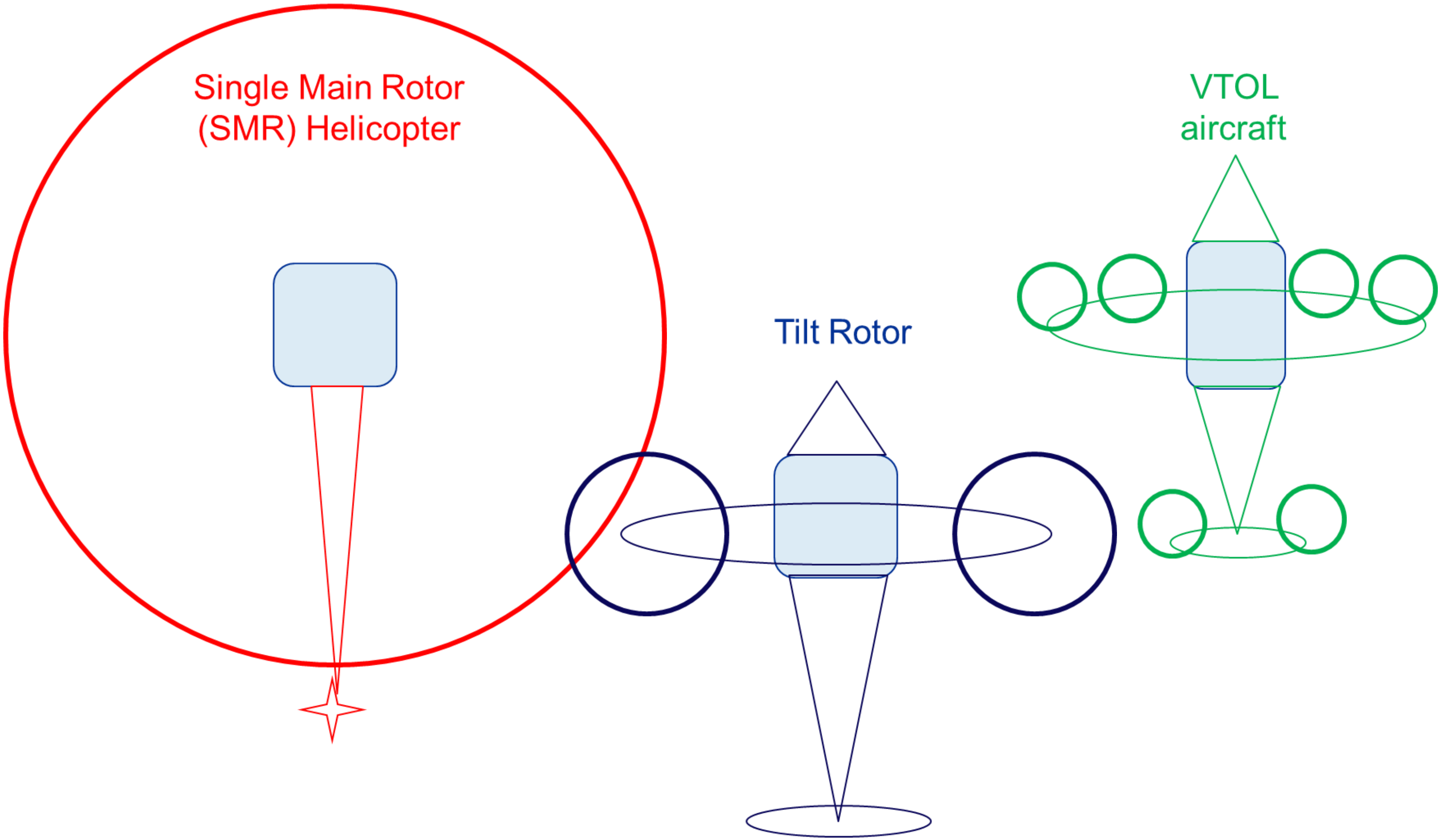
VTOL aircraft





Designs allow better cruise aerodynamics, fly on wing

Baseline vehicles (cont.)



Roughly similar scale, highlights rotor area variation → hover efficiency

Impressive weight and loss reductions for Electric Motor / Electronics are occurring

Technology year	**Power/weight, hp/lb. (kW/kg)**	Electric motor η, %	Controller η, %	Net η, %	**Net Loss, %**
State of the art	**1.9 (3.1)**	90	94	85	**15**
15 year	**3.4 (5.6)**	95	98	93	**7**
30 year	**4.9 (8.0)**	98	99	97	**3**
Non-cryogenic *Power-to-weight includes electric motor (3,8,16 hp/lb.) + controller (5,6,7 hp/lb.)*					

"15 year" power-to-weight goals are being demonstrated today

Efficiency goals are taking a little longer (power/weight first)

Reduced losses = less thermal management (less weight)

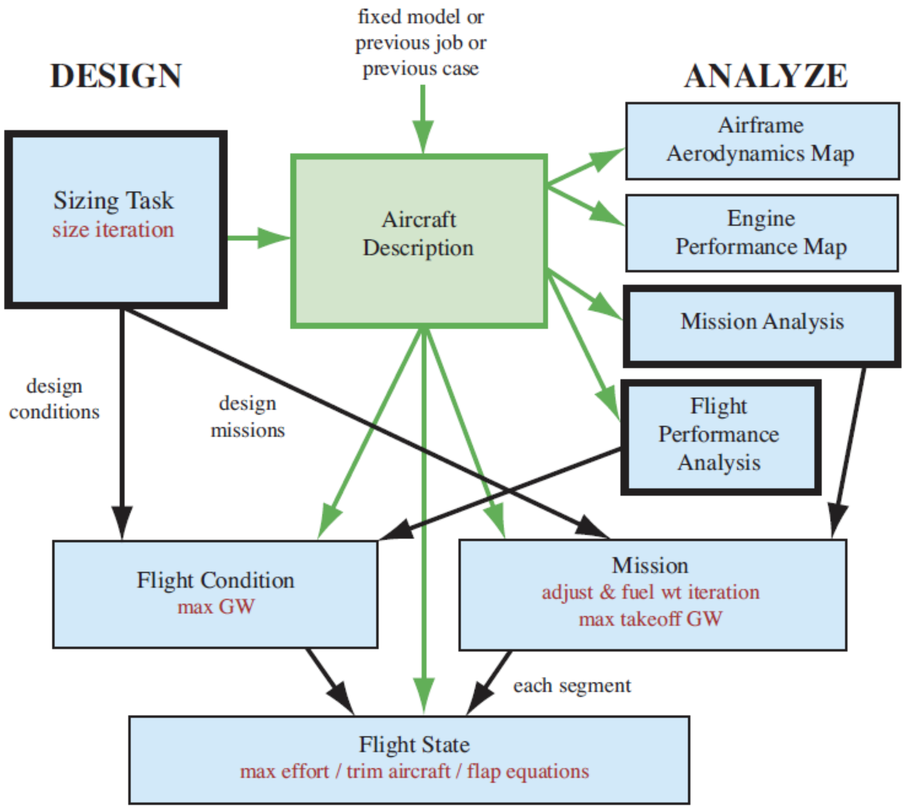
* Dever, T.P.; Duffy, K.P.; Provenza, A.J.; Loyselle, P.L.; Choi, B.B.; Morrison, C.R.; and Lowe, A.M. "Assessment of Technologies for Noncryogenic Hybrid Electric Propulsion", NASA TP-2015-216588, January 2015.

Electric motor's power-to-weight and efficiency are competitive or better than current systems;

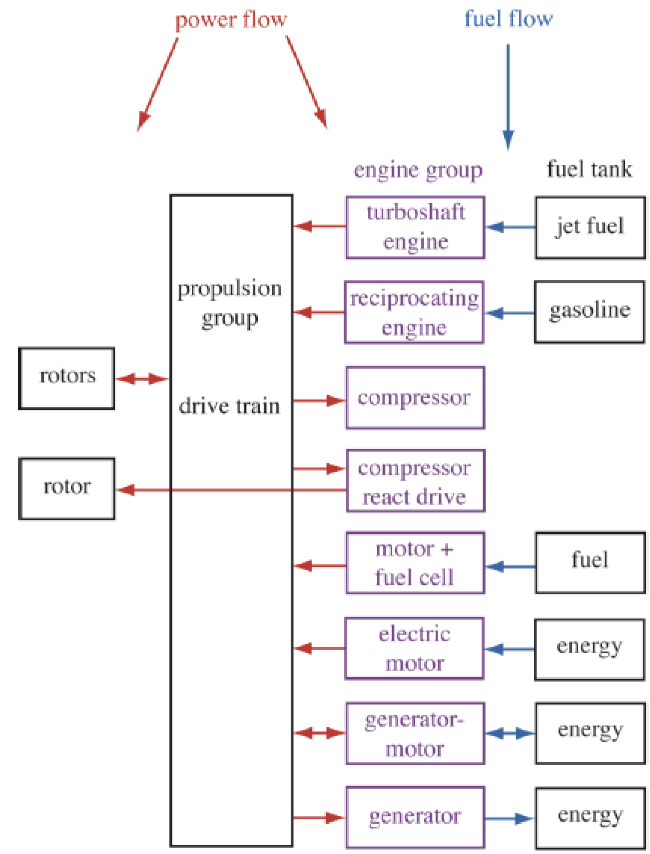
BUT efficiency doesn't overcome deficiencies in energy storage (critical for range / endurance)

Engine type	**Power / weight, hp/lb. (kW/kg)**	**Efficiency**	Fuel, energy density, MJ/kg	**Net energy density, MJ/kg**
Battery all-electric, SOA 15 year 30 year	**1.9 (3.1)** **3.4 (5.6)** **4.9 (8.0)**	**85** **93** **97**	0.70 1.75 3.15	**0.60** **1.63** **3.06**
Diesel cycle, SOA Advanced	**0.53 (0.9)** **1.06 (1.8)**	**37**	Diesel, 43.0	**15.9**
Reciprocating (IC) gasoline / Otto Cycle	**0.71 (1.2)**	**27**	Gasoline, 43.5	**11.7**
Advanced Gas turbine (500hp / 373kW class)	**5.0 (8.2)**	**24**	Jet-A, 42.8	**10.3**
For electric systems, "Fuel" is lithium battery, assuming average of lithium ion and sulfur, cell only (also from Dever)				

Analysis Tool: NASA Design and Analysis of Rotorcraft (NDARC)

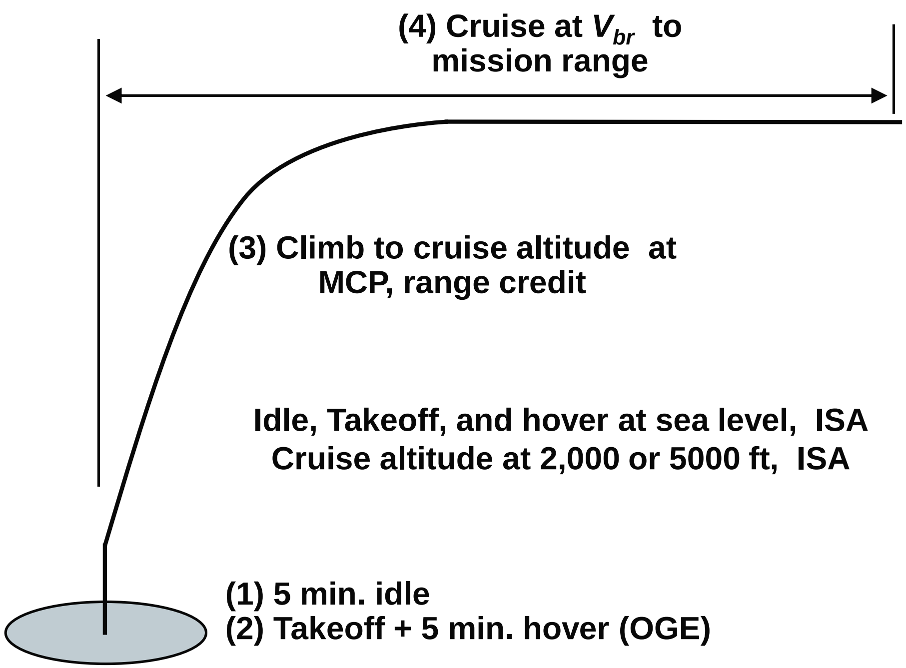


Overall Program Layout

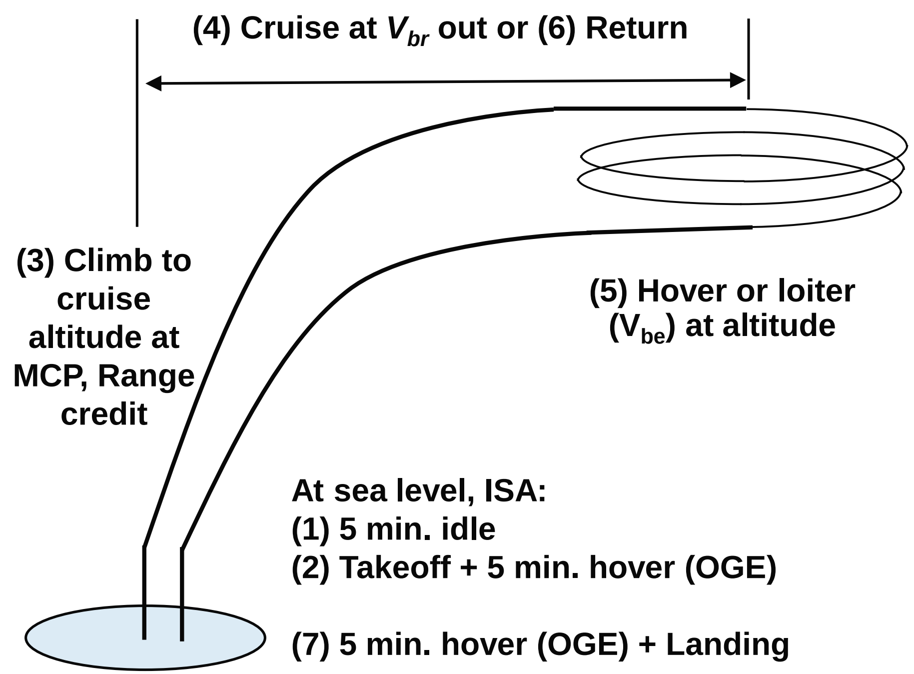


Propulsion / energy models

Mission Profiles



Vehicle sizing profile



Vehicle hover / loiter profile

Additional study assumptions

- For conversion of SMR helicopter and Tilt rotor to all-electric, maintain empty weight + fuel (retrofit).
  - Electric motor + battery = former propulsion + nominal fuel load
- Electric motors sized for mission requirements (no power lapse with high / hot).
- For Advanced VTOL: sized to meet 200 nmi. range. Electric motor sized to meet hover power requirements.
- Takeoff, determine range and endurance with:
  - Full payload (450 lbs. passengers / luggage)
  - 200 lbs. pilot
  - For all-electric, additional battery up to design gross weight
    - (SMR helicopter & Tilt rotor)

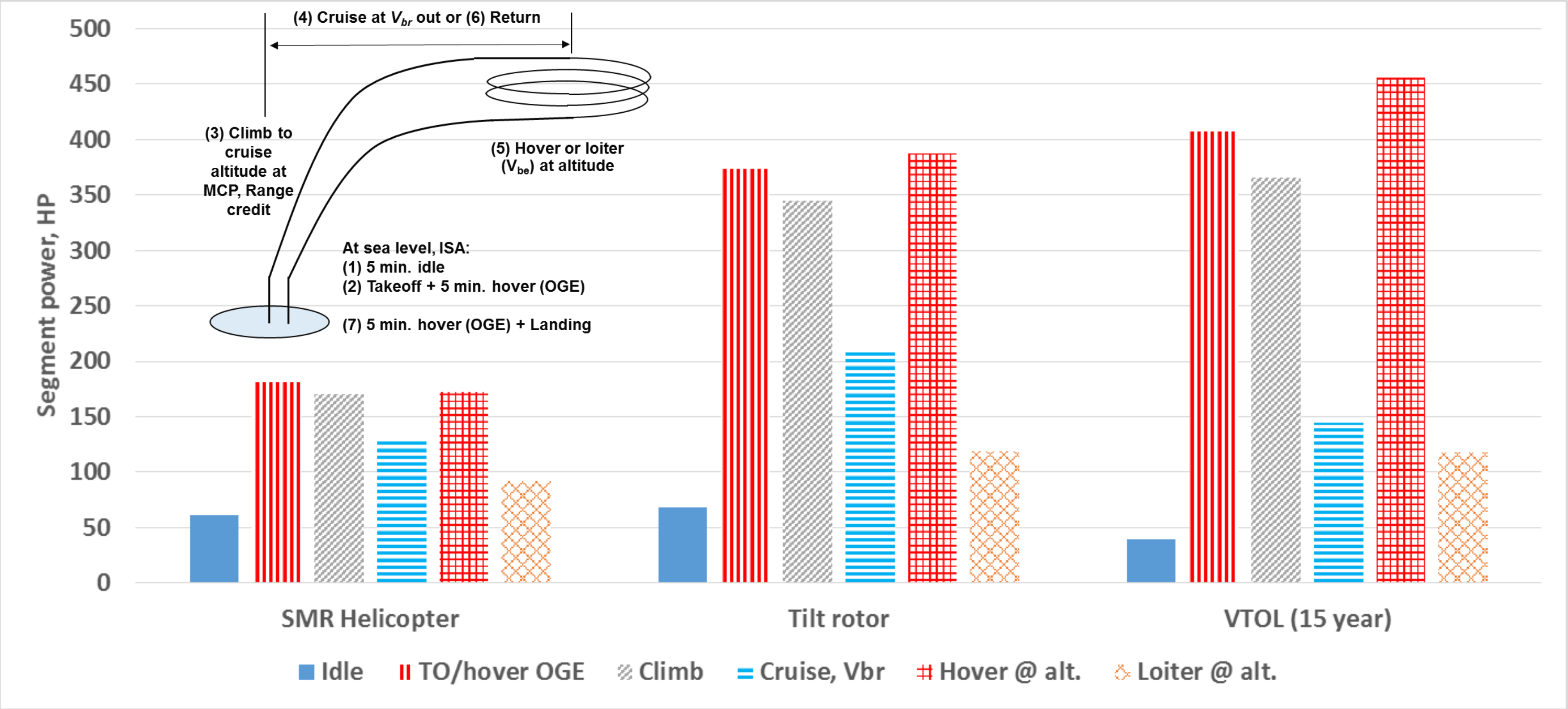
Results

Baseline vehicles

Parameter ↓ / Vehicle →	Single Main Rotor (SMR) Helicopter	Tilt Rotor	All-Electric VTOL Aircraft, 15 year technology	All-Electric VTOL Aircraft, 30 year technology
Design gross weight (DGW), lb. (kg)	2,050 (932)	2,545 (1,157)	2,785 (1,266)	2,200 (1,000)
Disk loading / wing loading, lb/ft^2	3.6 / N.A.	14 / 50	16 / 50	16 / 50
Nominal fuel weight, lb. (kg), % DGW *	160 (73), 8%	200 (91), 8%	630 (286), 23% (590 MJ battery)	270 (123), 12% (456 MJ battery)
Sea level maximum rated power (MRP), hp (kW)	190 (142)	470 (350)	456 (340)	350 (262)
Engine type	Reciprocating (Otto cycle)	Advanced turboshaft	All-electric, 15 year technology	All-electric, 30 year technology
Engine weight, lb. (kg), % DGW	270 (123), 13%	310 (141), 12%	105 (48), 4%	60 (27), 3%
Power / DGW, hp/lb. (kW/kg)	0.09 (0.15)	0.18 (0.30)	0.16 (0.27)	0.16 (0.27)
Cruise velocity (V_{br}), knots (km/h) *	95 (176)	185 (343)	200 (370)	200 (370)
Range, nmi (km) *	195 (360)	200 (370)	150 (280)	150 (280)

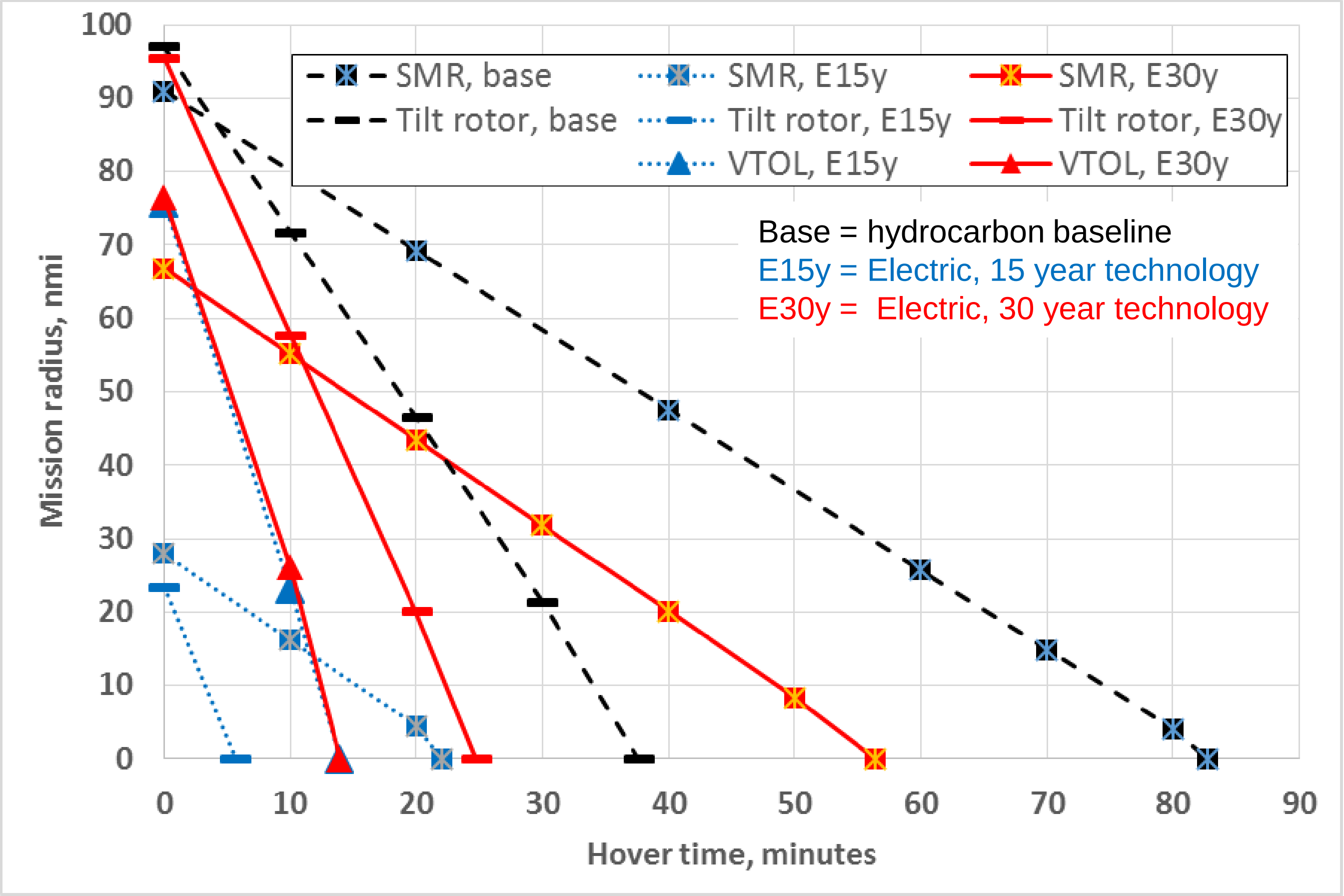
Power requirements vary greatly with vehicle design

- Engines sized by hover, loiter power much less
- Significantly lower hover power for SMR Helicopter than other vehicles, cruise / loiter power also less, but at ½ their speed
- Tilt rotor and VTOL loiter effectively on their wings (large area coverage)



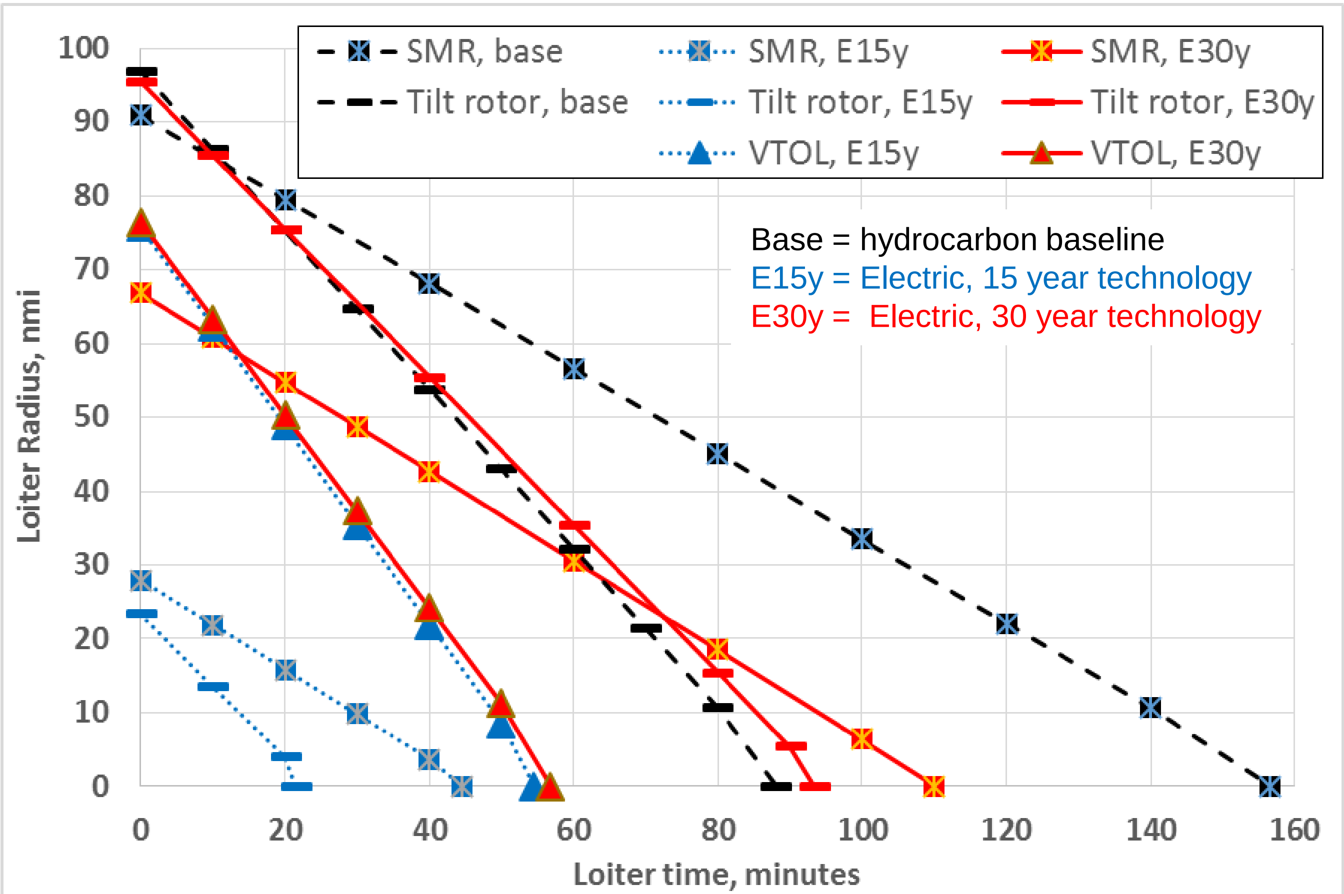
High hover power requirements significantly reduce range

- Improved hover efficiency mitigates range penalty for hover endurance
- 30 year battery retains significant fraction of baseline capability
- 15 year battery (equal DGW) achieves minimal range
- Advanced VTOL (vehicle resized) shows similar characteristics



Lower loiter power requirements roughly 2x time at range

- Most trends very similar to hover range / duration results
- Reduced gas turbine efficiency at part power results in less loiter capability than 30 year battery electric



Summary

- High hover power requirements can dominate vehicle design, constrains other segment characteristics.
- Loiter power levels are much lower; vehicles optimized for cruise mission retains significant loiter capability.
- Electric motors seem to be already competitive (or better) than traditional HC-fueled engines (weight & η).
- However, energy storage (battery) technology is limiting factor. 30 year technology projections are getting close to parity for some vehicles / missions. Suggests a hybrid solution. (Paper discusses HC range extenders.)

Future Work

- Just scratched the surface, new vehicles and missions are being developed and analyzed to better understand and exploit the potential for these systems.
- Tools / various performance models are being upgraded. Capture inter-dependencies among systems and components (such as hydrocarbon range extenders).
- Push / pull of research and technology:
  - What is the potential for various, future technologies?
  - Which future technology (or suite of technologies) have the best promise?

Acknowledgments

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Questions?

NASA

Backup Slides

Baseline vehicles

Vehicle → Parameter ↓	Single Main Rotor (SMR) Helicopter	Tilt Rotor	All-Electric VTOL Aircraft, 15 year technology	All-Electric VTOL Aircraft, 30 year technology
Design gross weight (DGW), lb. (kg)	2,050 (932)	2,545 (1,157)	2,785 (1,266)	2,199 (1,000)
Empty weight, lb. (kg)	1,100 (500)	1,690 (768)	2,135 (970)	1,549 (704)
Disk loading / wing loading, lb/ft^2	3.6 / N.A.	14 / 50	16 / 50	16 / 50
Nominal fuel weight, lb. (kg), % DGW *	160 (73), 8%	200 (91), 8%	628 (285), 23% (589 MJ battery)	270 (123), 12% (456 MJ battery)
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Engine weight, lb. (kg), % DGW	267 (121), 13%	312 (142), 12%	105 (48), 4%	60 (27), 3%
Engine power / weight, hp/lb. (kW/kg)	0.71 (1.2)	1.50 (2.46)	4.34 (7.1)	5.6 (9.2)
Sea level power specific fuel consumption, lb./hp-h (kg/kw-h)	0.500 (0.305)	0.574 (0.350)	N.A.	N.A.
Power / DGW, hp/lb. (kW/kg)	0.09 (0.15)	0.18 (0.30)	0.16 (0.27)	0.16 (0.26)
Cruise velocity (V_{br}), knots (km/h) *	95 (176)	185 (343)	200 (370)	200 (370)
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Hydrocarbon Range Extenders significantly lighter than 15 year batteries or for extended endurance (> 1 hour)

Advanced diesel hardware weight is slightly higher than the gas turbine, but its fuel efficiency results in the lightest system

Engine type	Hardware weight, lb. (kg)	Fuel weight, lb. (kg)	Total weight, lb. (kg)
Advanced diesel - 15 year - 30 year	127 (58) 114 (52)	41 (18) 39 (18)	167 (76) **153 (70)**
Gas turbine - 15 year - 30 year	101 (46) 89 (41)	81 (37) 77 (35)	181 (82) **167 (76)**
Lithium Battery - 15 year - 30 year	-	337 (153) 188 (85)	337 (153) **188 (85)**
100 hp (74.6 kW) output electrical power for 1 hour (for scaling purposes) Assume advanced hydrocarbon-fueled engine: Diesel 1.1 hp/lb. (1.8 kW/kg), 0.377 lb./hp-h (0.23 kg/kw-h) Gas Turbine 1.5 hp/lb. (2.46 kW/kg), 0.75 lb./hp-h (0.457 kg/kw-h)			

Mission power versus segment and cruise / loiter speed

	HP	HP	HP	HP	HP	HP	knots	knots	% of total power for segments 1,2,7
segment	idle	TO/ HOGE	Climb	Cruise (Vbr)	hover	loiter (Vbe)	Vbr	Vbe	
SMR Helicopter	61	181	170	130	172	92	95	53	11.4
Tilt rotor	68	374	345	208	387	119	185	95	21.3
VTOL (15 year)	39	407	366	145	456	118	199	138	35.5
VTOL (30 year)	34	317	281	114	351	92	194	133	34.9

Idle and Take Off / hover OGE 5 minute duration each
Climb segment generally about 2 minutes duration

END