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Combined Electric Aircraft and Airspace Management Design for Metro-Regional Public Transportation

NASA Aeronautics Research Mission Directorate (ARMD)

2014 Seedling Technical Seminar

February 19–27, 2014

Project Contributors

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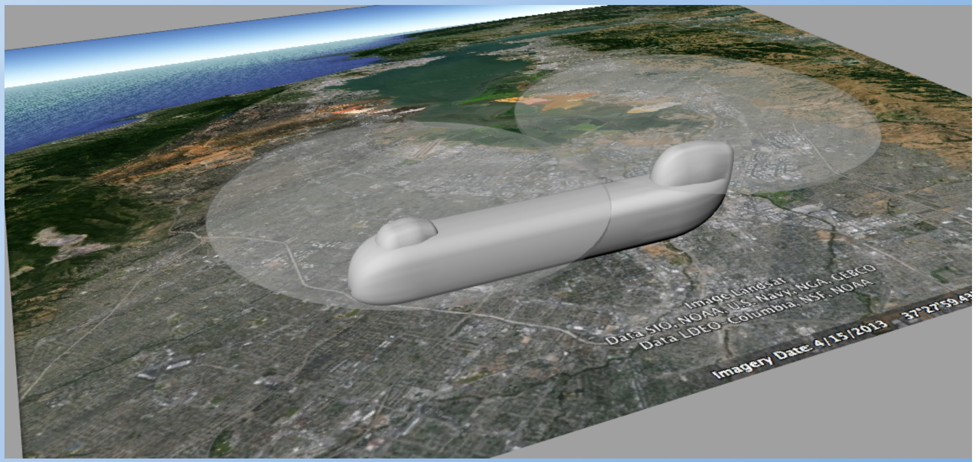
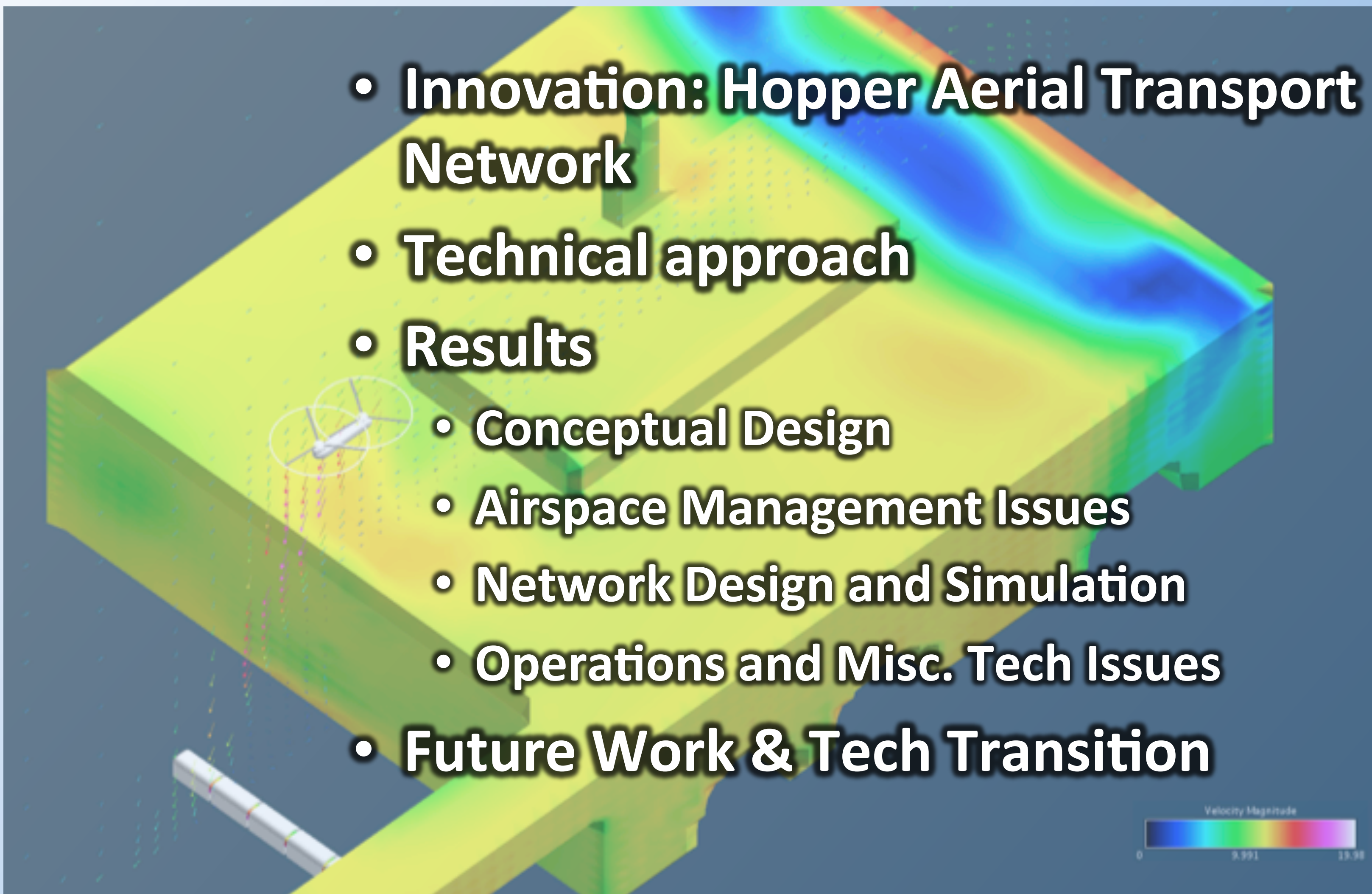
- **Juan J. Alonso, Prof., Stanford University**
- **Heather Arneson, NASA**
- **John Melton, NASA**
- **Jeffrey Sinsay, US Army Aeroflightdynamics Directorate**
- **Brendan Tracey, Stanford**
- **Michael Vegh, Stanford**
- **Cedric Walker, NASA**
- **Larry Young, NASA, PI**



Outline



- Innovation: Hopper Aerial Transport Network
- Technical approach
- Results
  - Conceptual Design
  - Airspace Management Issues
  - Network Design and Simulation
  - Operations and Misc. Tech Issues
- Future Work & Tech Transition

The Innovation

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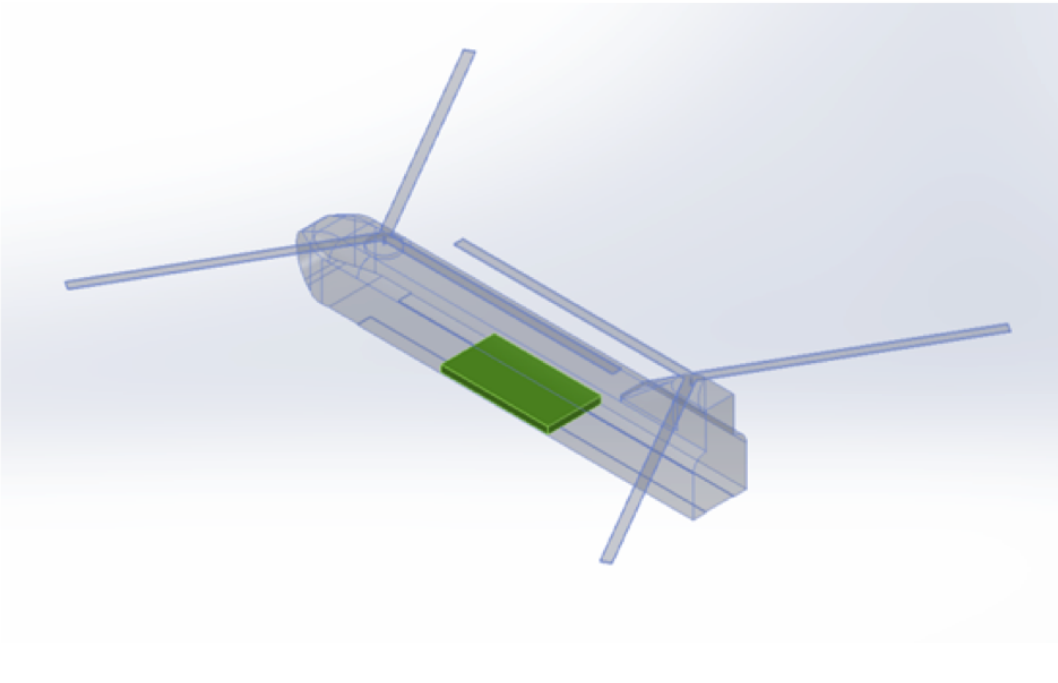
- Investigate technical feasibility of electric aircraft to provide a solution to metro/ regional public transportation

Hughes Helibus concept circa 1967 (Courtesy AHS International)



“Hopper” Metro/Regional Aerial Transportation System

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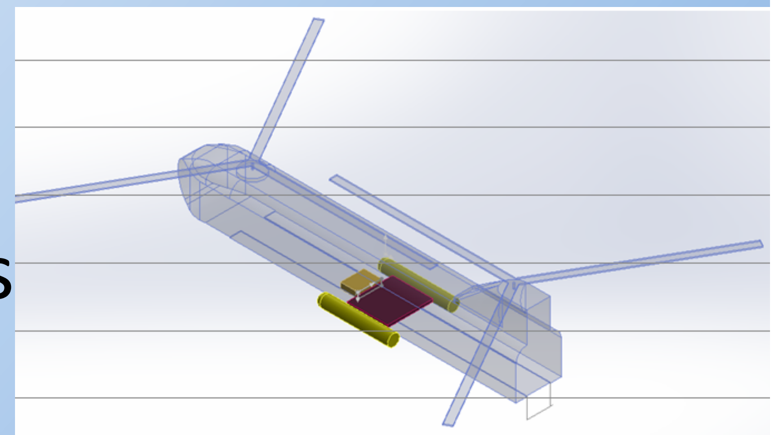
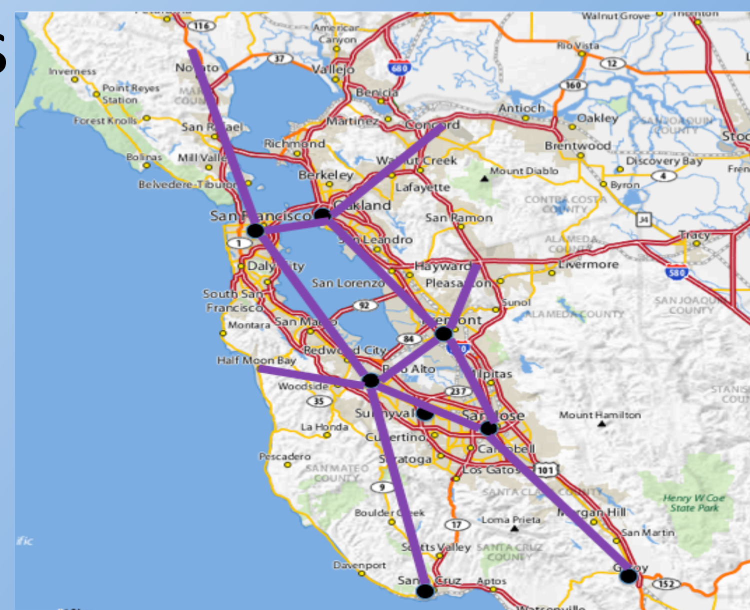
- Rotorcraft with electric-propulsion
- Extremely short haul vehicles (<100nm)
- Network of vertiport stations in San Francisco Bay Area
- Different network topologies studied
- An evolutionary build-up of networks studied





Technical Approach

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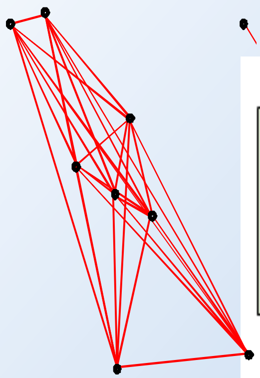
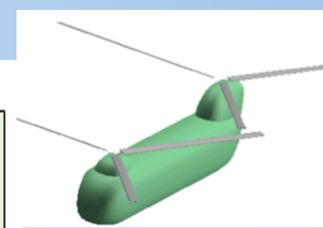
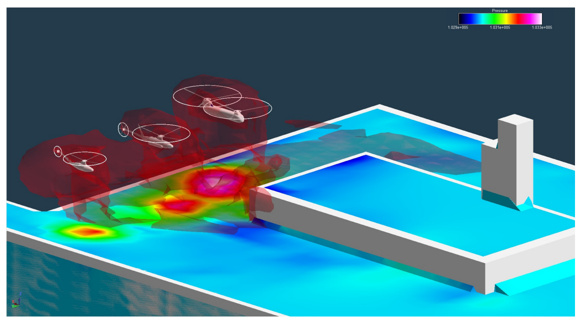




Network Topology Definition Tool

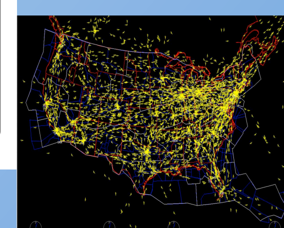
NDARC & Hopper Tool



RotCFD & Misc.

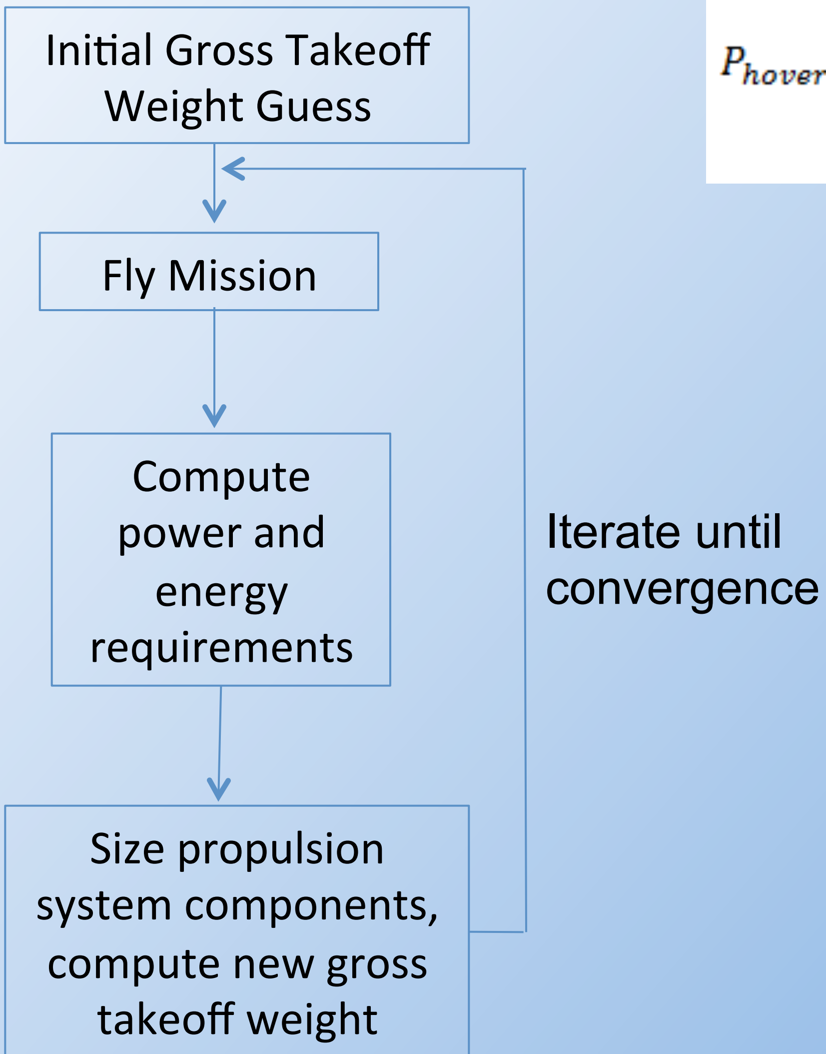
Bay Sim

FACET



Conceptual Design: Hopper/ Electric-Propulsion

"Hopper" Tool Architecture



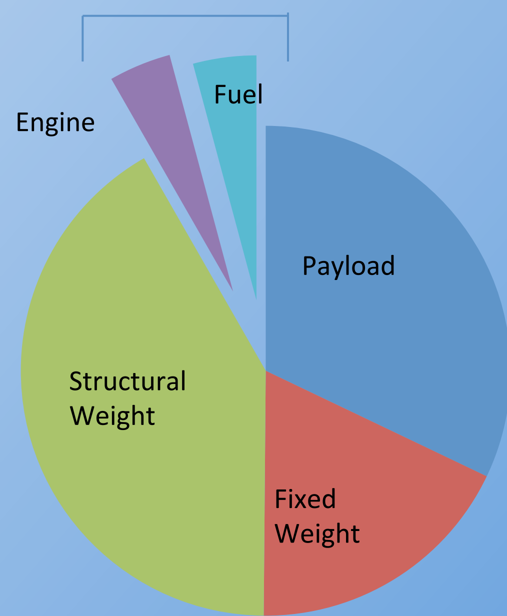
Power Requirements

$$P_{hover} = \frac{W * \sqrt{\frac{\{DL\}}{2\rho}}}{\{FOM_{AC}\} * \{\eta_{motor}\}} \qquad P_{cruise} = \frac{W * \{V\}}{\{\frac{L}{D_e}\} * \{\eta_{motor}\}}$$

{bold}=code inputs

Redesigned this section of the helicopter and observed effect on gross takeoff weight

Turboshaft Weight Breakdown



NDARC (Phase I) and Stanford Tool (Phase II) Validation Comparison

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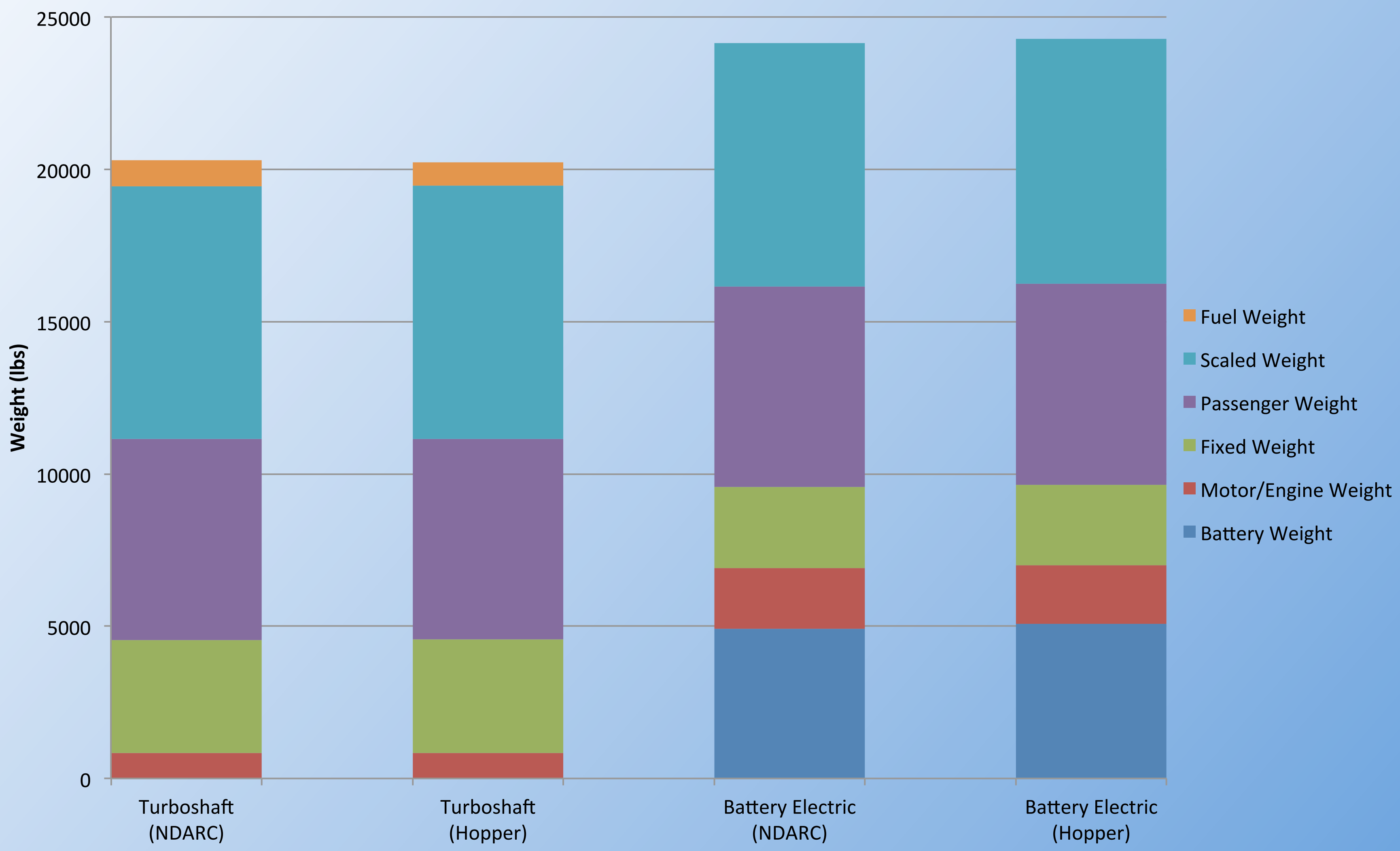
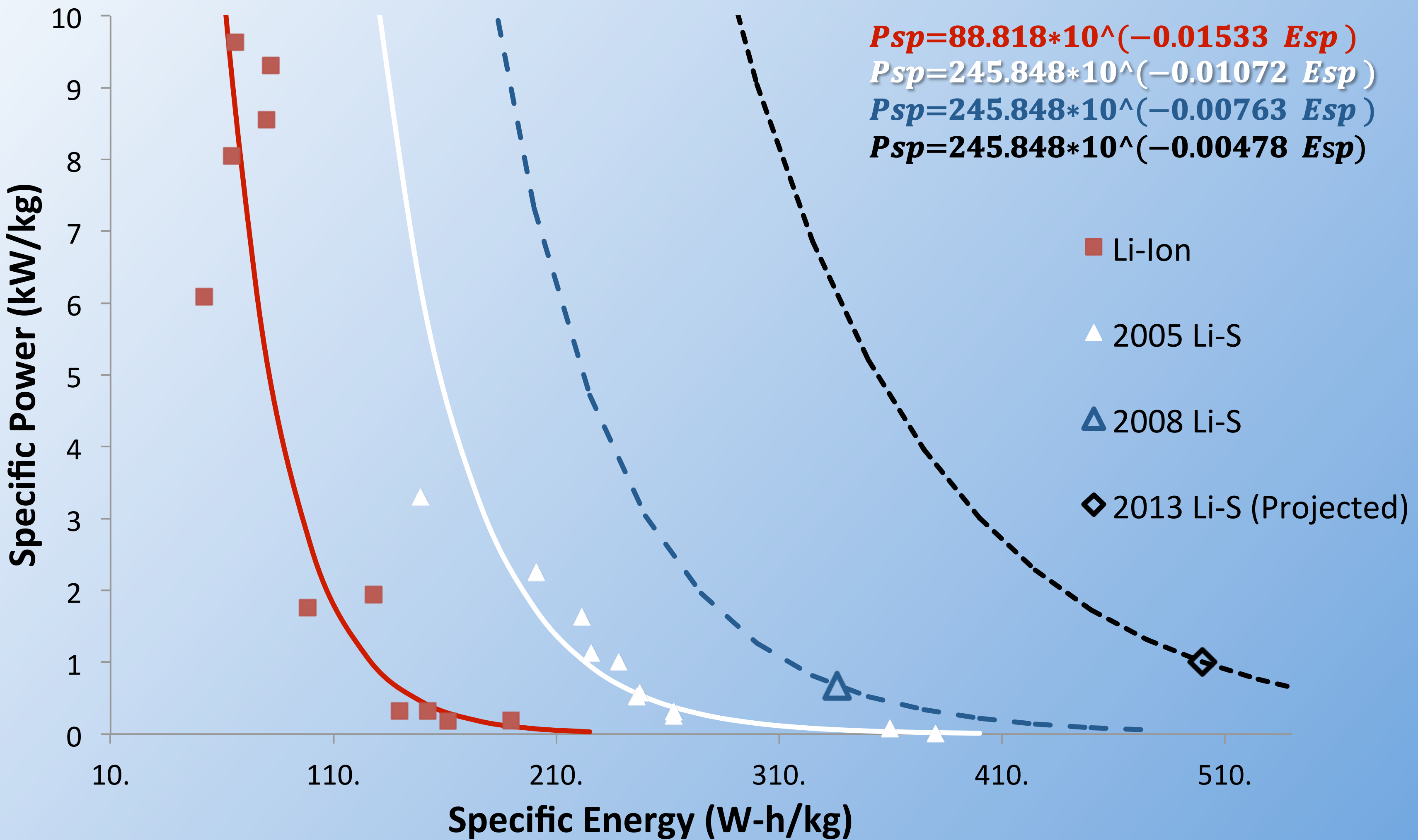


Ragone Plot: Battery Specific Power vs. Energy



Sizing Requirements

Mission Requirements	
Cruise velocity	130 kt.
Cruise altitude	3000 ft.
Disk Loading	4 psf
L/De	4.2
Aircraft Figure of Merit	0.5
Number of passengers	30
Range	25-65nm (with 20 minute reserve)

Sizing Assumptions	Gas	Battery	Hybrid	Fuel cell	Fuel Cell Hybrid
Structural Weight fraction	0.42	0.331	0.37	0.42	0.37
Fixed Weight	3710	2660	3000	3200	3200

Sample Battery Electric Design Results (25 nm)

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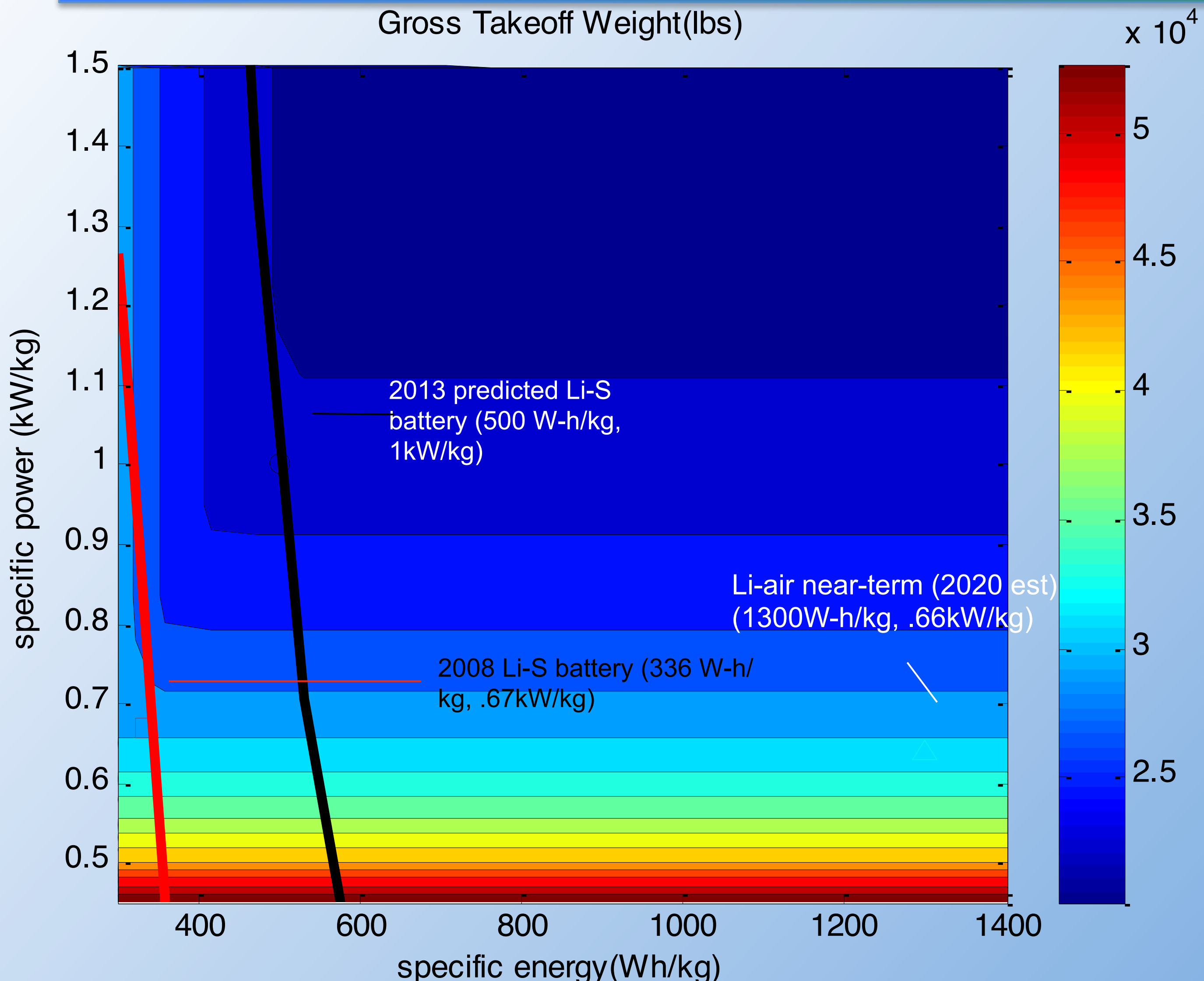

- $W_{gross_{2008}}$~26,640 lbs.
- $W_{gross_{2013}}$~22,000 lbs.
- $W_{gross_{2020}}$~31,000 lbs.
- Power and energy improvements make these configurations much more realizable in the near-term
- Sizing loop diverges for Li-ion technology

Hybrid Technology (Turboshaft with Battery

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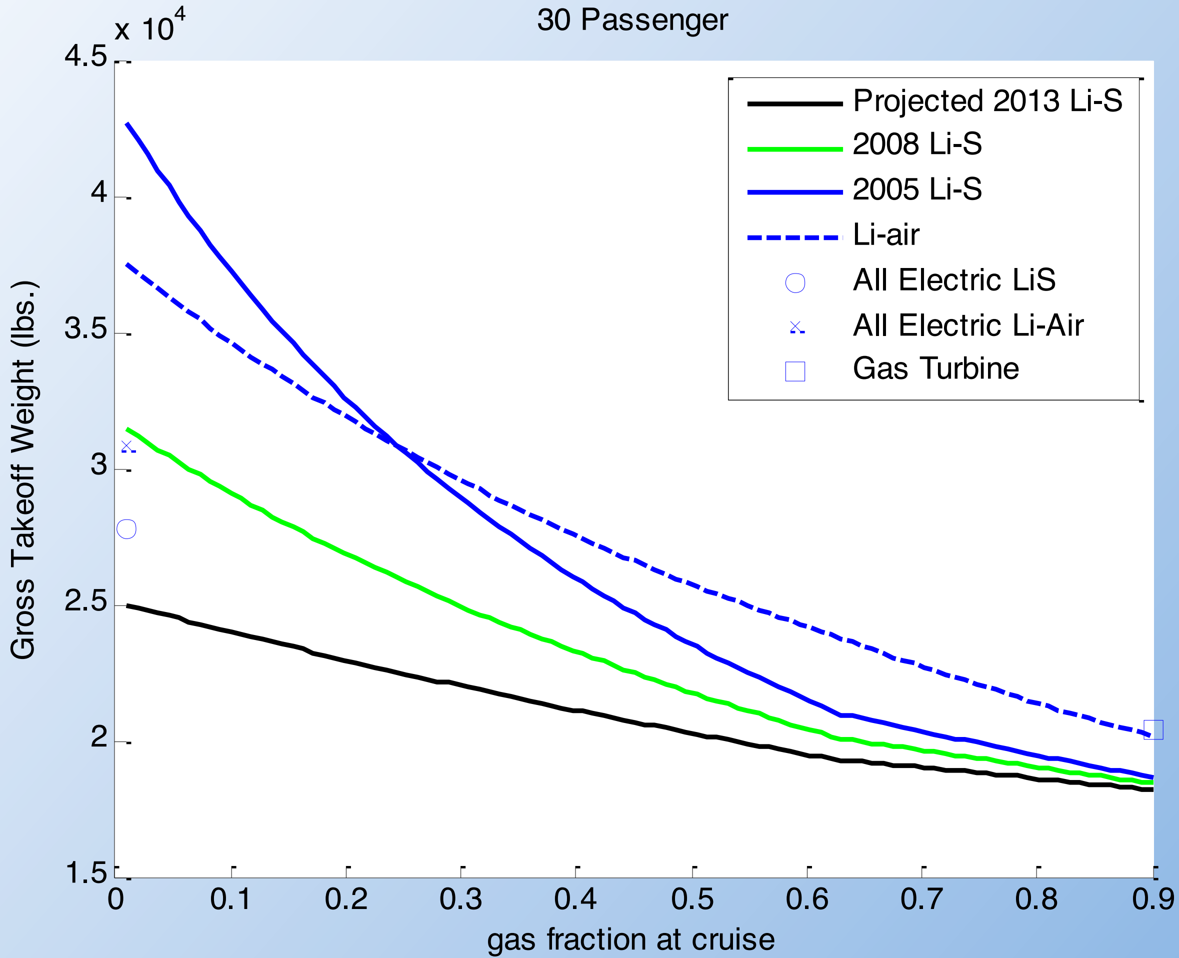

- Battery research tends to focus on improving specific energy, sometimes at cost of specific power
- Current technology outperforms future battery trends for most hybrid configurations, because power constraints tend to dominate these design

Sample Fuel Cell Results

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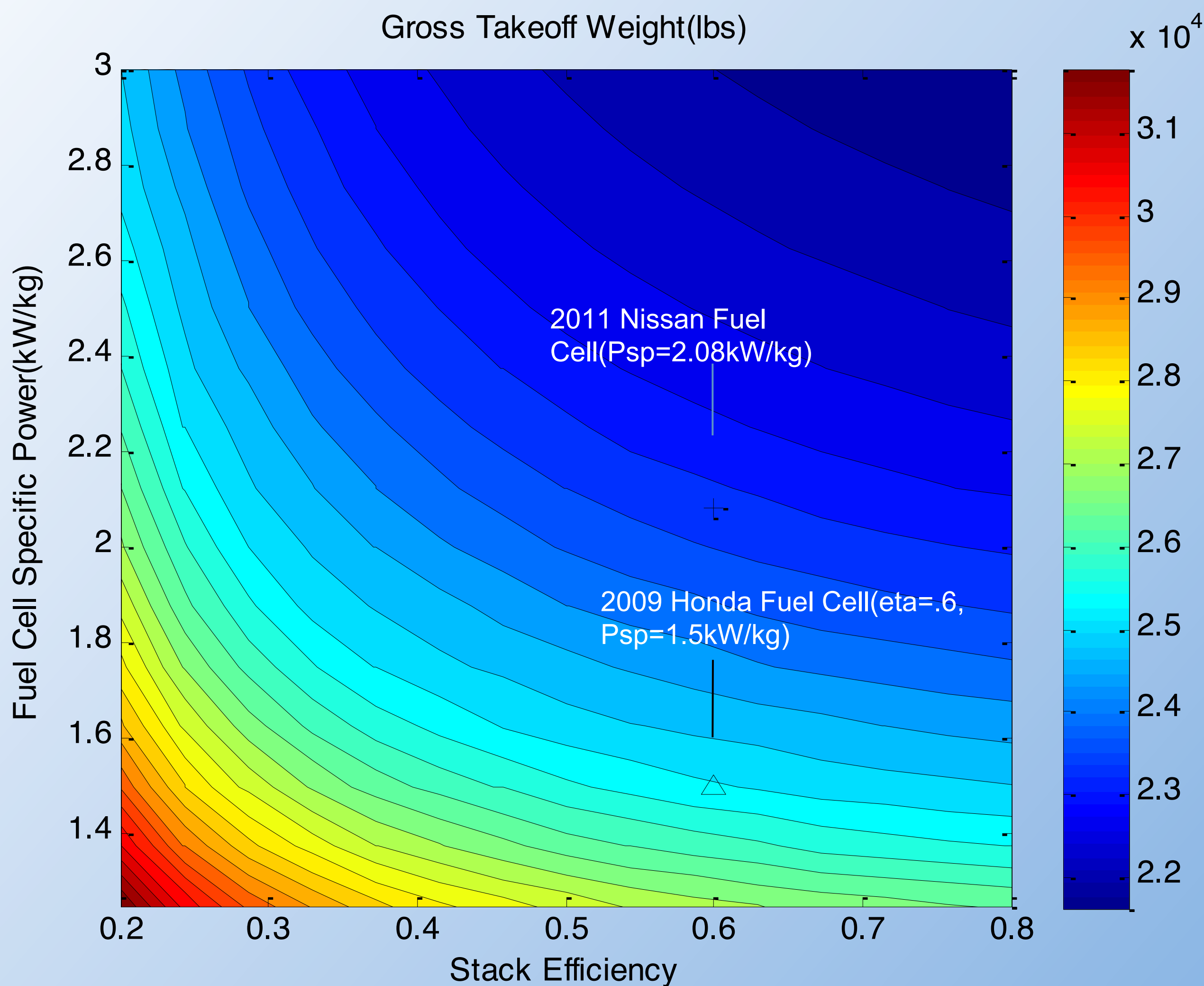
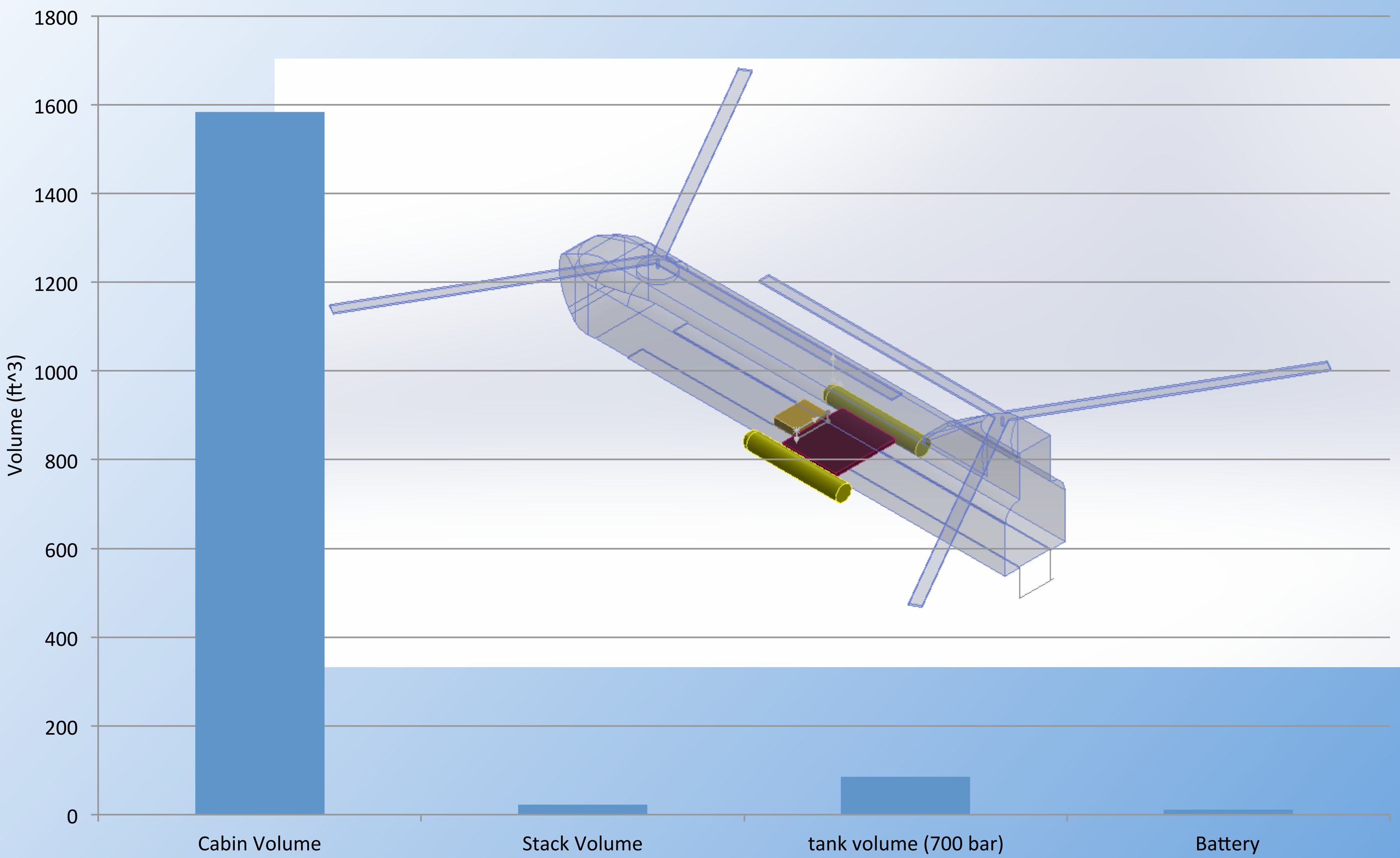


- Similar tradeoff between specific power and specific energy for fuel cell, although harder to quantify
- Efficiencies for H_2 Fuel Cells usually ~30-60%.
- Recent technology improvements result in cascading weight benefits
- 1999 technology (Psp~.4 kW/kg) results in gross takeoff weight ~300,000 lbs.

Serial Fuel Cell Hybrid Volume Breakdown (65 nm)



Weight Breakdown (25 nm)

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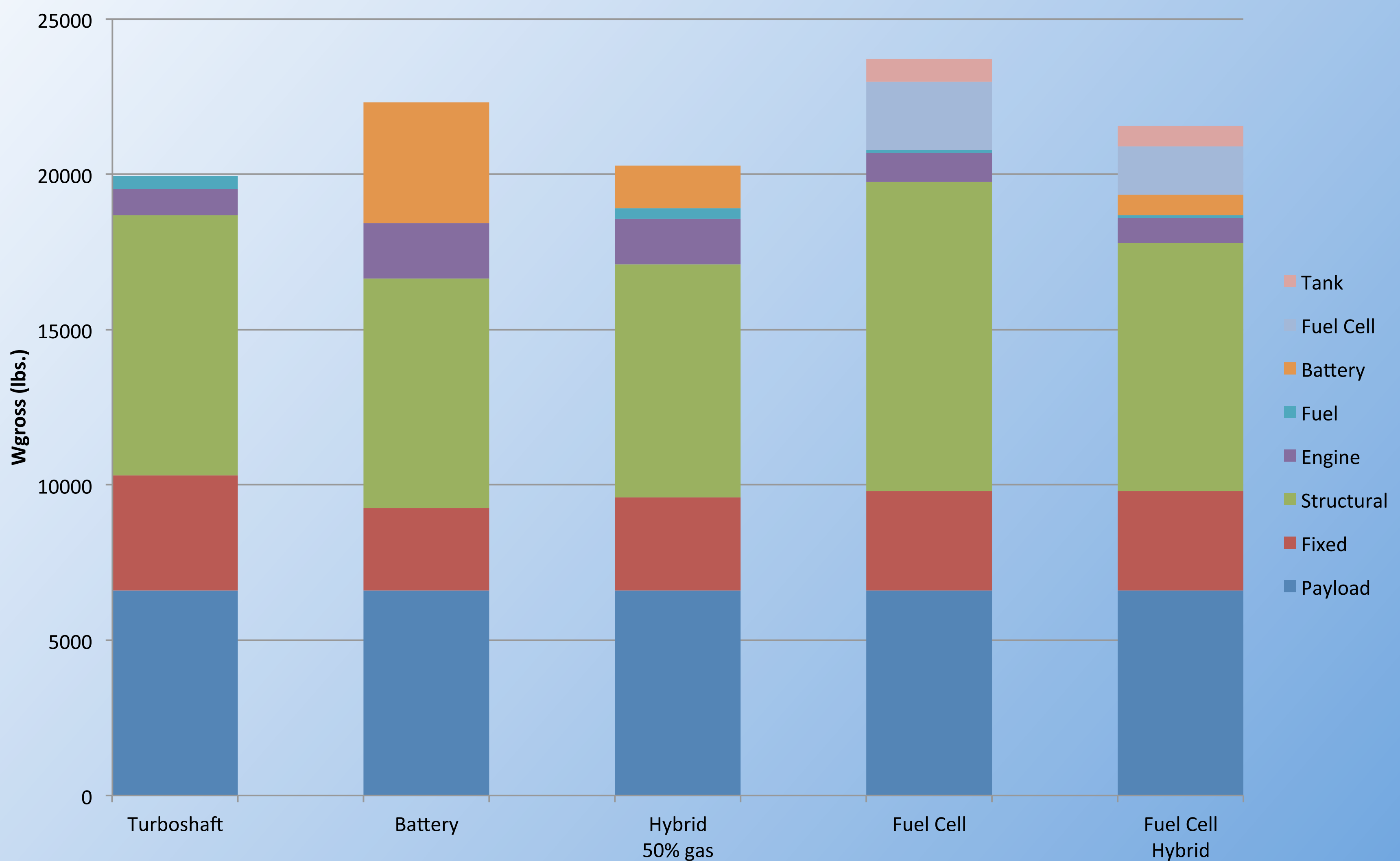
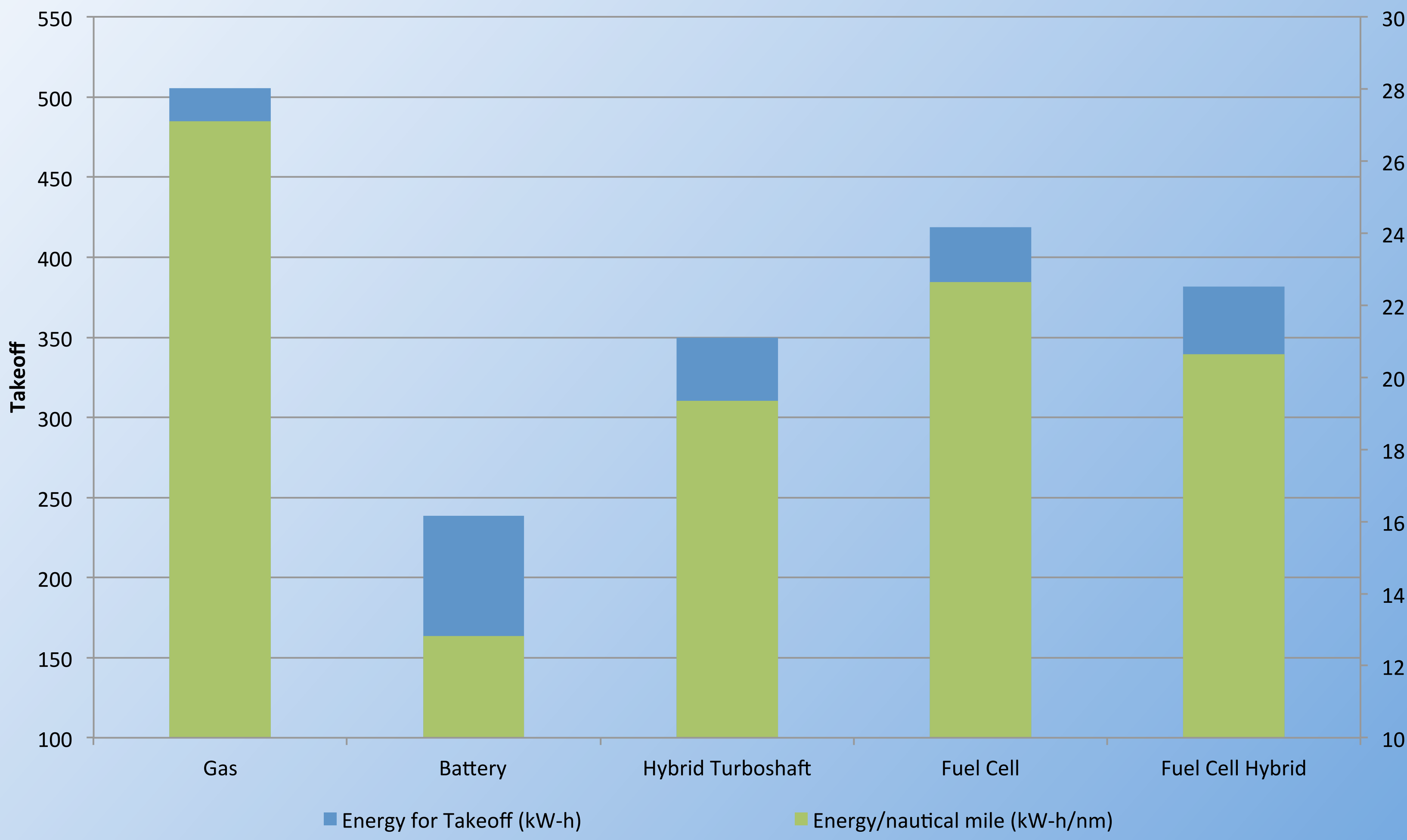


Energy Usage Comparison (Full)



Gross Takeoff Weight Comparison

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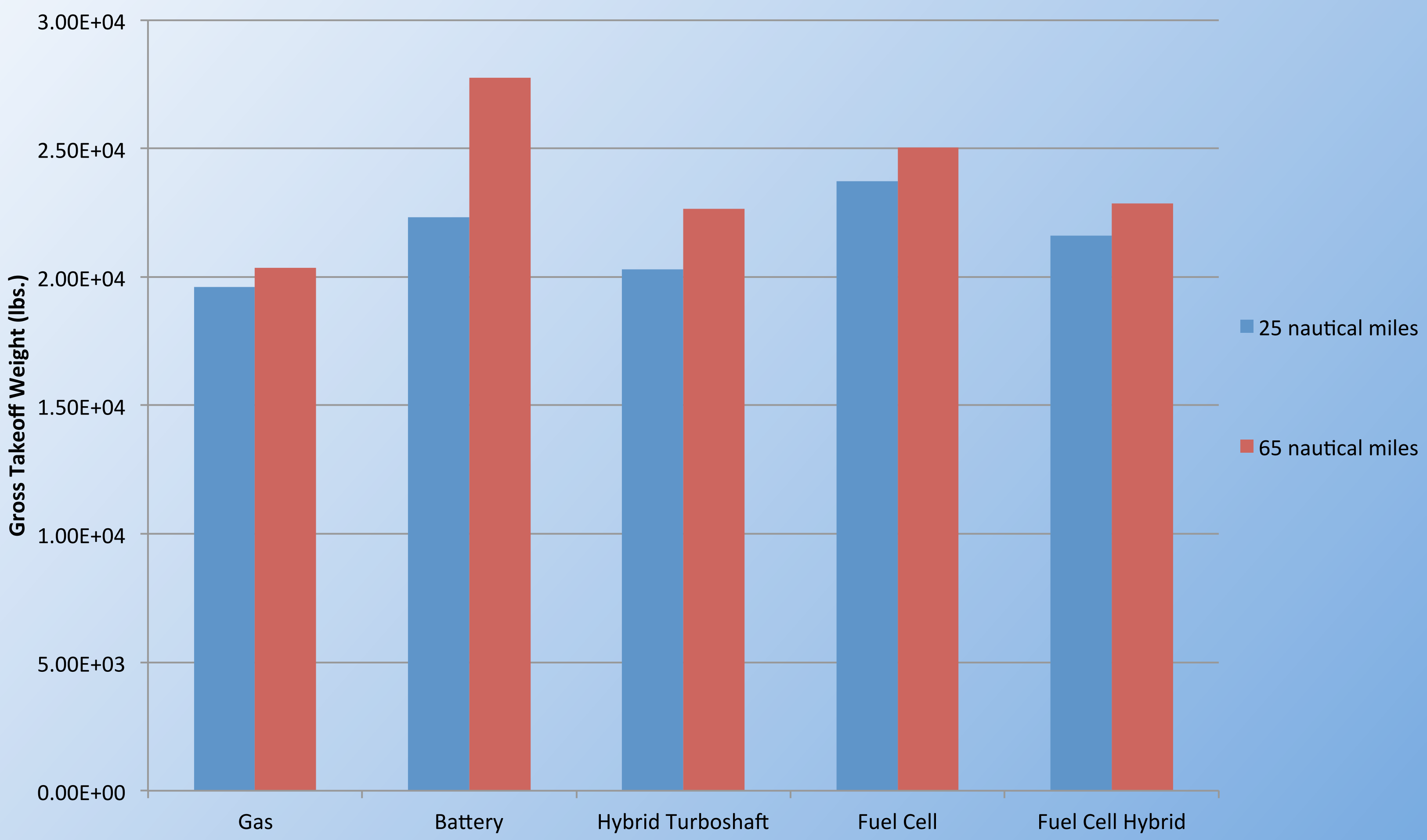

Airspace Management Issues

Bay Area Traffic Flows

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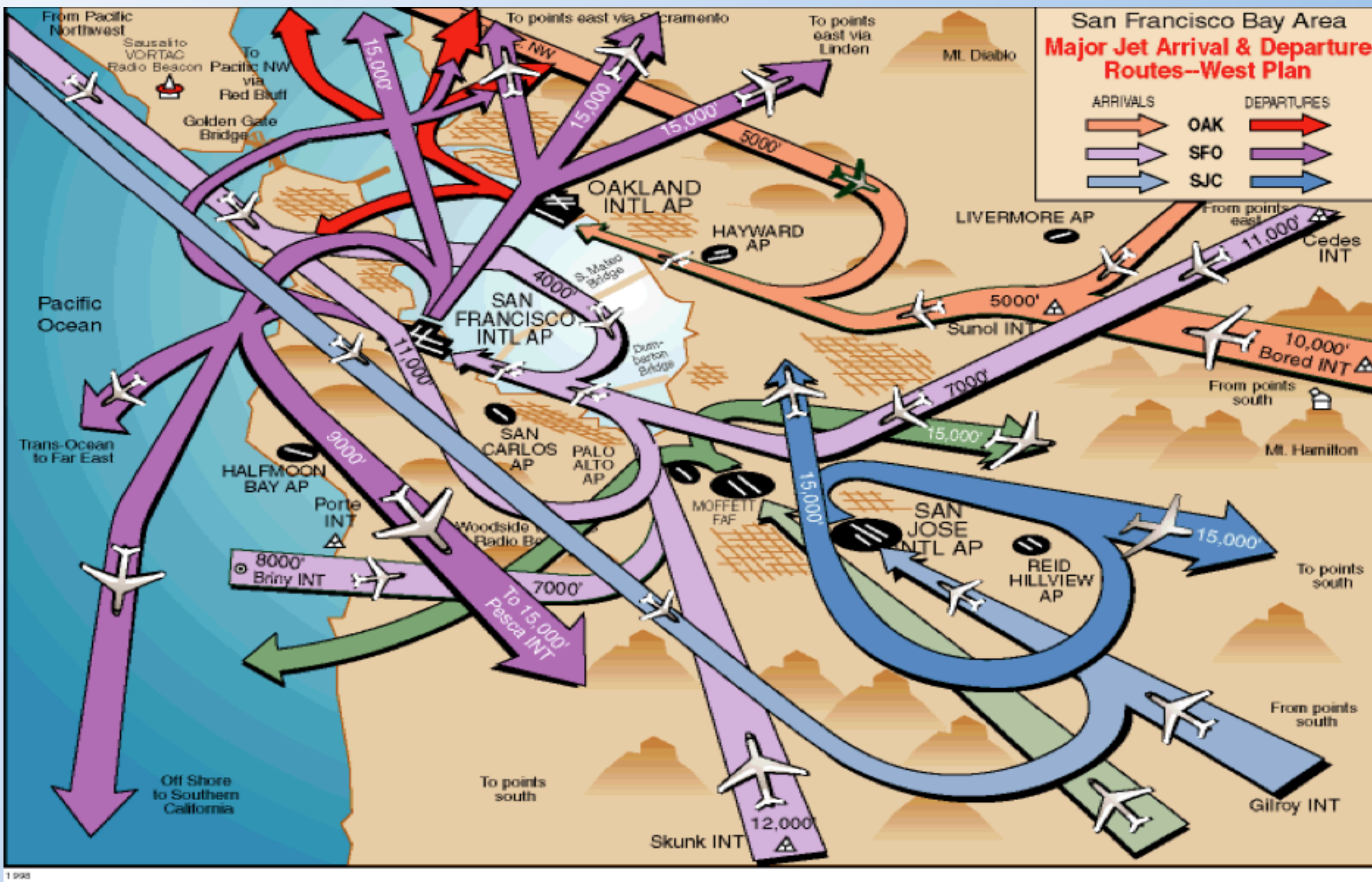

ATM Focus

- Generate Hopper flight plans to reduce potential conflicts with background traffic
  - Reduce controller workload by avoiding heavily used airspace
  - Adjust flight plans based on time of day as background traffic shifts
- Investigate emerging technologies which could enable Hopper

Traffic Density Maps

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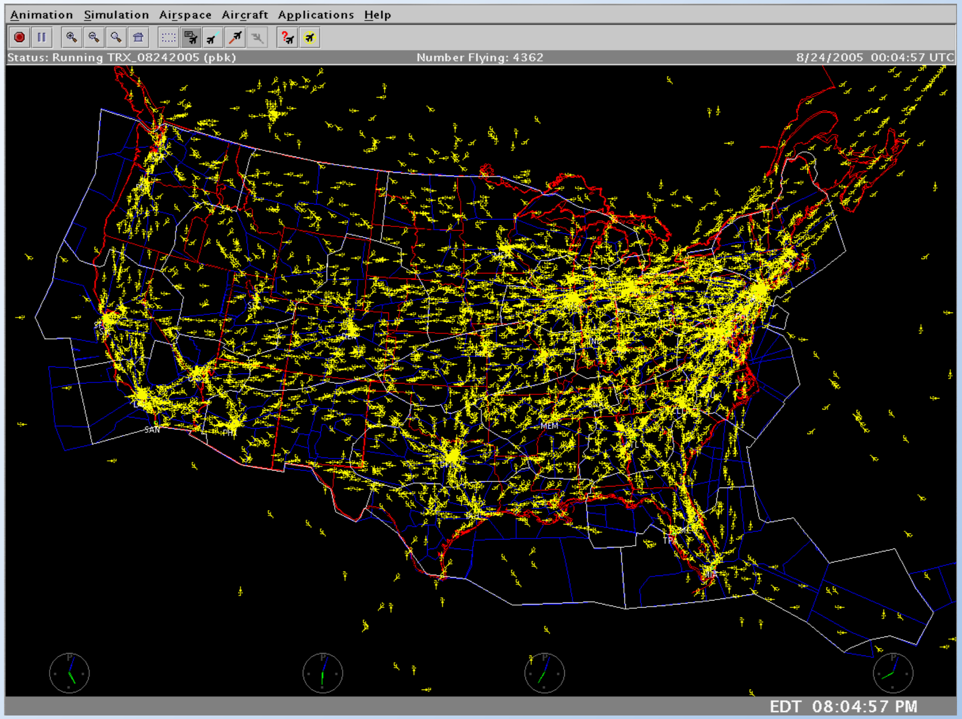

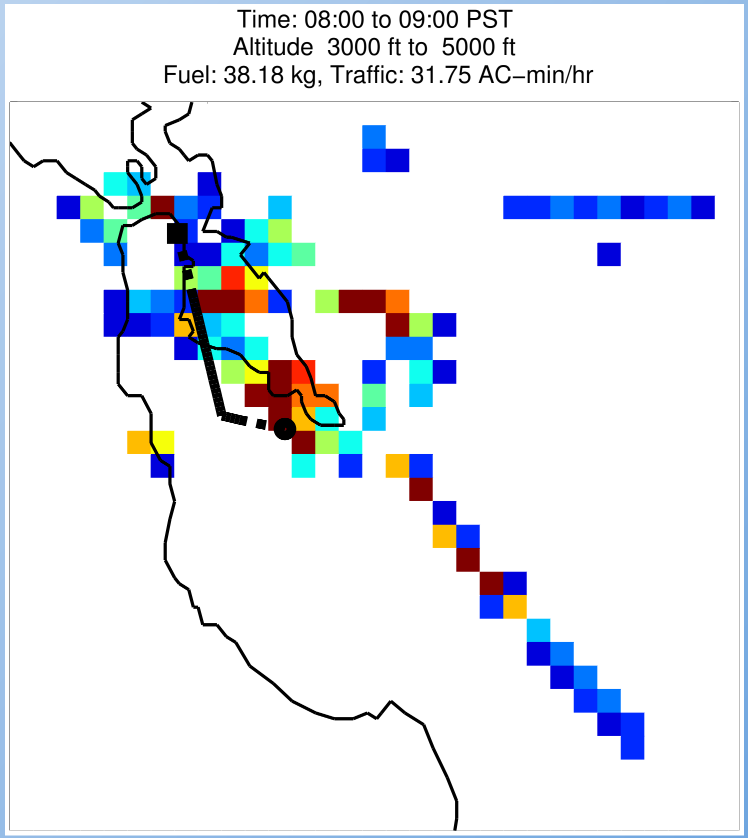

Time-of-Day Dynamic Flight Path Routing

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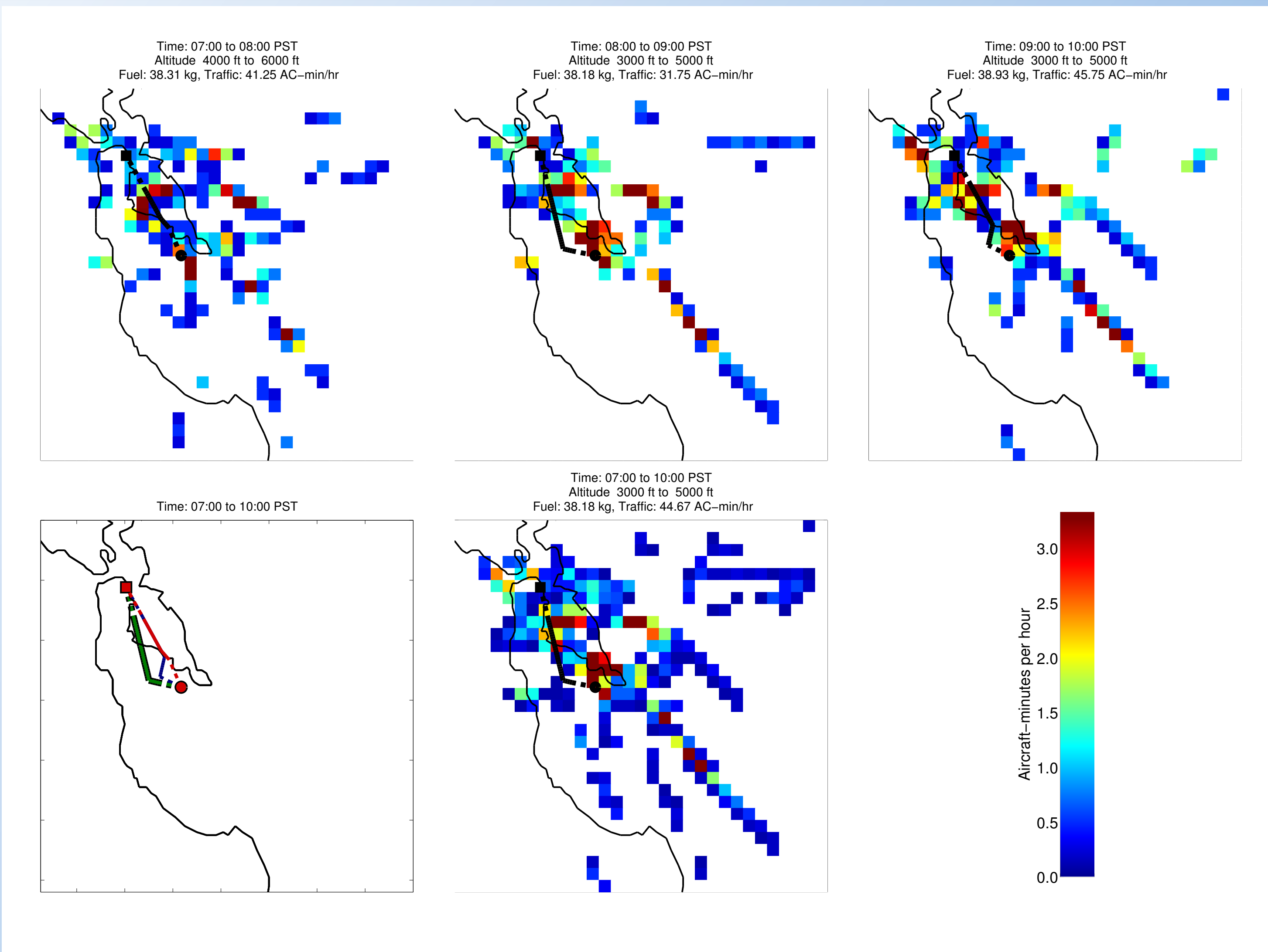

Traffic Interaction Decrease

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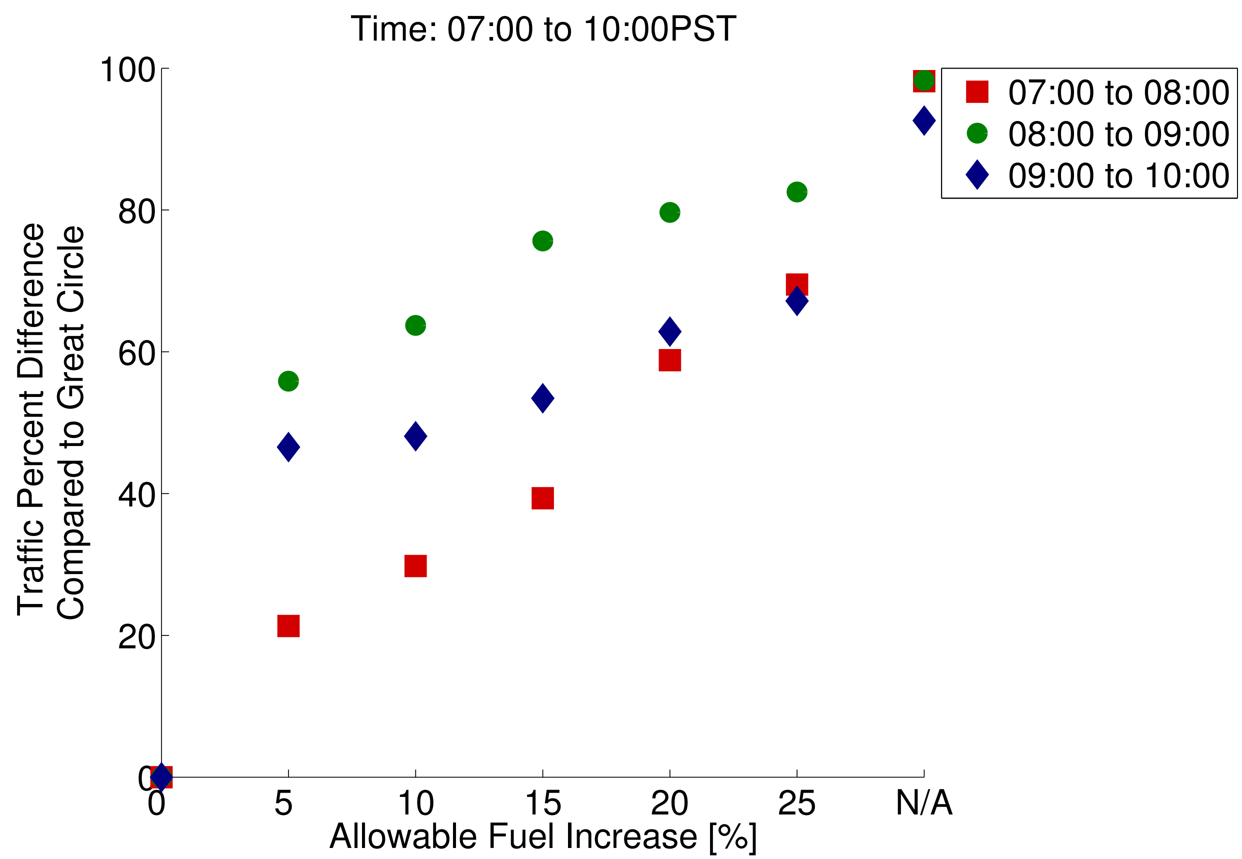

Airspace Emerging Technologies Applicable to Hopper

Domain	Emerging technologies
Communication	Widespread Data Link with limited human oversight
Ground operations	Precision Departure Release Capability (PDRC)
Terminal airspace	Traffic Management Advisor (TMA) Airborne Dependent Surveillance–Broadcast (ADS-B)
Weather avoidance planning	Dynamic Weather Routes (DWR)
Enroute	Airborne Dependent Surveillance–Broadcast (ADS-B) Strategic ground-based 4D trajectory planning Tactical airborne 4D trajectory execution

Network Design and Analysis

BaySim: Discrete Element Simulation

- Individual passenger and flight agents
- Fast-time simulation of surface and air travel
- PX transition through 12+ daily states from
  - home – work – home
  - Queue up for flights
- Heuristic rules
- Gaussian inputs
- Creates estimates of demand for flights and subsequent inputs for fleet optimization

Network Build-out

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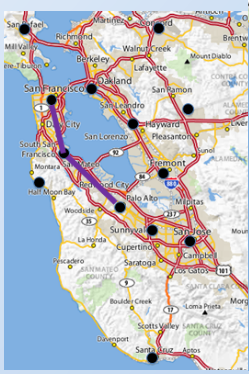
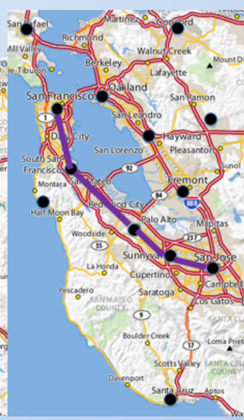
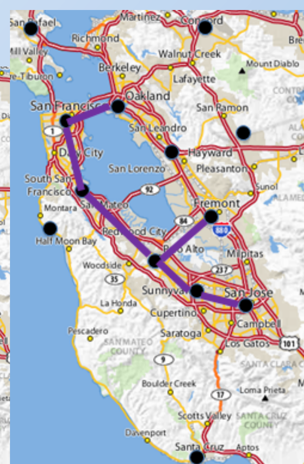
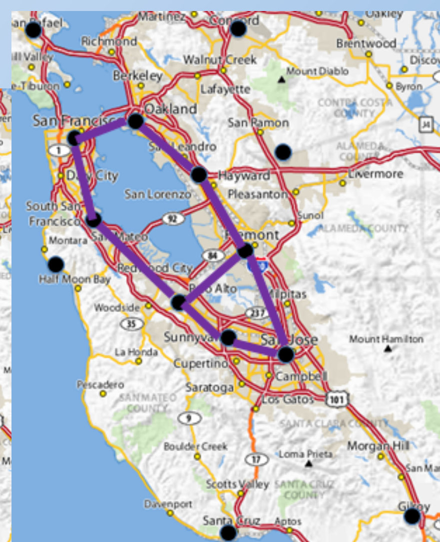
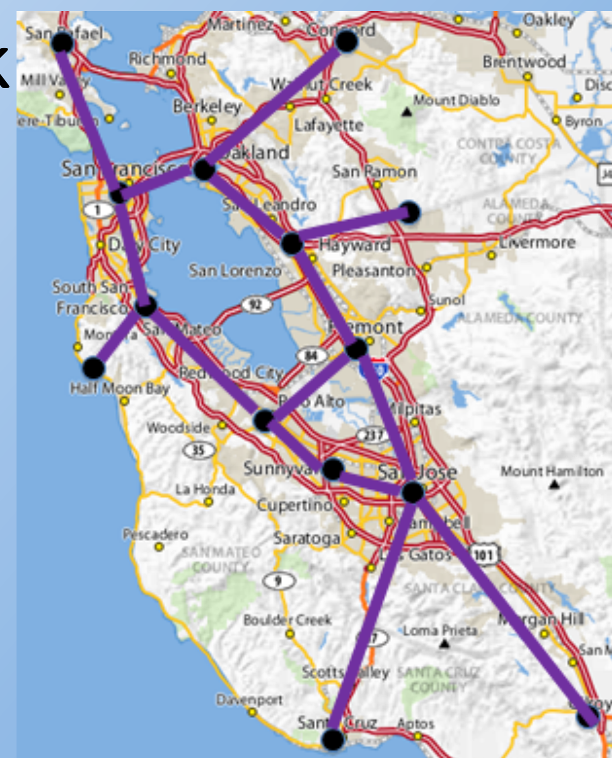
- Phase II considers practical network expansion
- Replace Phase I "n x n" network with "ring-spoke"

BaySim: Passenger Populations

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- How many daily passengers?
  - “Tech Industry” employs 386K workers in Bay Area
  - CalTrain serves roughly 42K passengers per day
  - BART serves roughly 370K passengers per day
- Population Sizes: **5K, 10K, 15K, 20, 25K, 30K**
- PX Distribution, starting times, workday length

– 65% Day	4 to 10 AM	7 to 9 hours
– 20% Swing	1 to 6 PM	7 to 9 hours
– 5% Graveyard	9 to 2 AM	7 to 9 hours
– 10% Other	8 AM to 3 PM	4 to 5 hours

Population Improvements

- Extensive use of Census and Zip Code databases
  – Zip codes provide appropriate geographic granularity
  – Zip and Census data readily available via websites (i.e., FREE!)
  – 2010 Census data includes commute and business employment demographics
  – Populations within zip codes created via iterative process according to several constraints:
    - Homesite network node != Worksite network node
    - Estimated Flying time < Estimated Driving Time
    - Number of workers at jobsite scaled and limited using local zip code employment statistics
    - Residents and worksites within user-specified distance from station nodes

30K PX Sample Population

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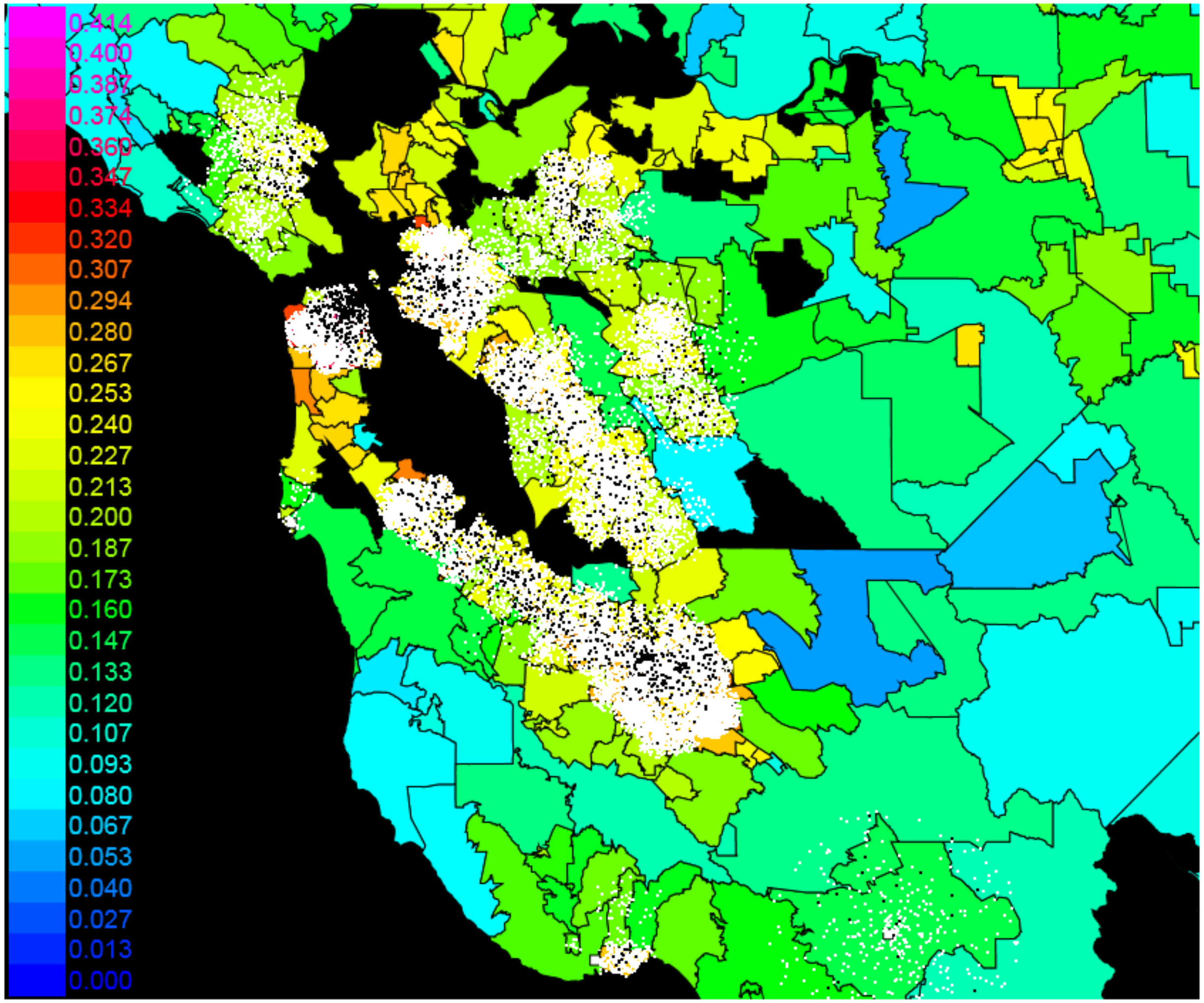

Stations

- ☑ 0: San Francisco CalTrain
- ☑ 1: Palo Alto CalTrain
- ☑ 2: Sunnyvale CalTrain
- ☑ 3: San Jose CalTrain
- ☑ 4: Gilroy CalTrain
- ☑ 5: Oakland BART
- ☑ 6: Fremont BART
- ☑ 7: Santa Cruz
- ☑ 8: Half Moon Bay
- ☑ 9: Walnut Creek BART
- ☑ 10: Dublin BART
- ☑ 11: San Rafael
- ☑ 12: San Carlos
- ☑ 13: Hayward

	Residents	Businesses	Employees
Candidate:	1537468.2700000007	102120	1830587
Population:	30000	1675	29999

	Min	Avg	Max	Extra	Check
Emplys/Biz:	0	17.910	45	7	30000

0	2
1-10	256
11-20	817
21-30	575
31-40	22
41-50	3
51-60	0
61-70	0
71-80	0
81-90	0
>90	0

ShowTrip Up 15200 Down

Colorbar | Stations | Residents | Businesses | Path | Borders | Scale 3 | Residents/Area | Q-power 0.2 | Pop 30000 | D_R 4.70 | D_W 3.50 | Update Pop | Output

Dijkstra and Speed Tables

- Each passenger chooses flights attempting to minimize transit time between home and work (including estimates of queue times)
- Dijkstra leg weights (transit times) updated immediately after each flight arrival and best route made available to each passenger before queuing
- Leg transit times from hourly table lookup, based on routes that minimize traffic conflicts with current SJC, SFO, and OAK patterns

BaySim Phase II Sample Movie

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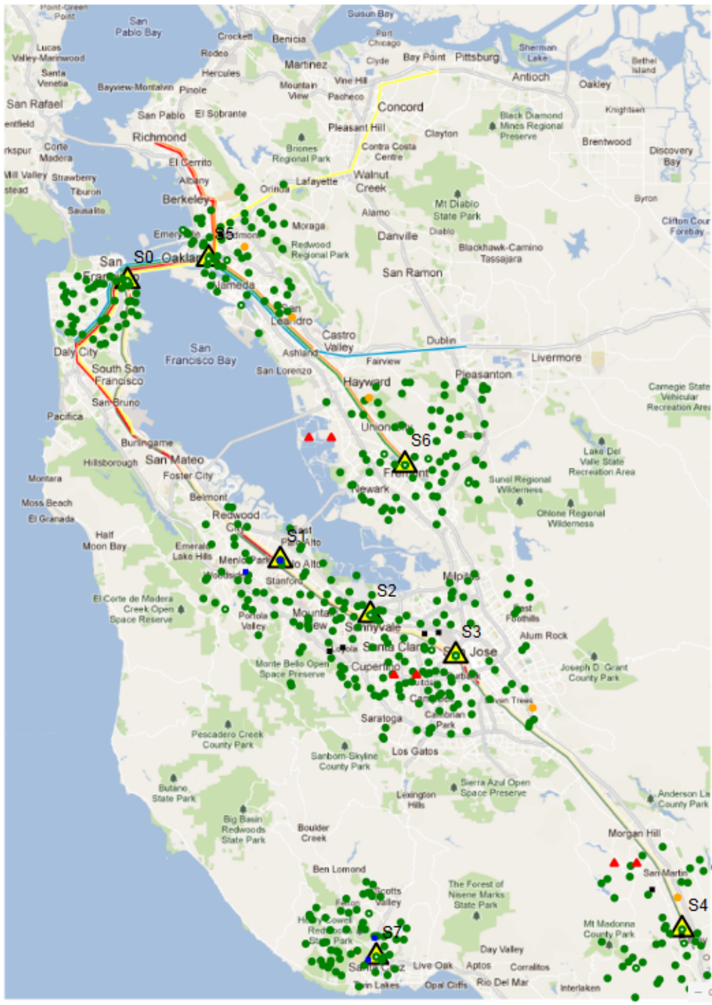


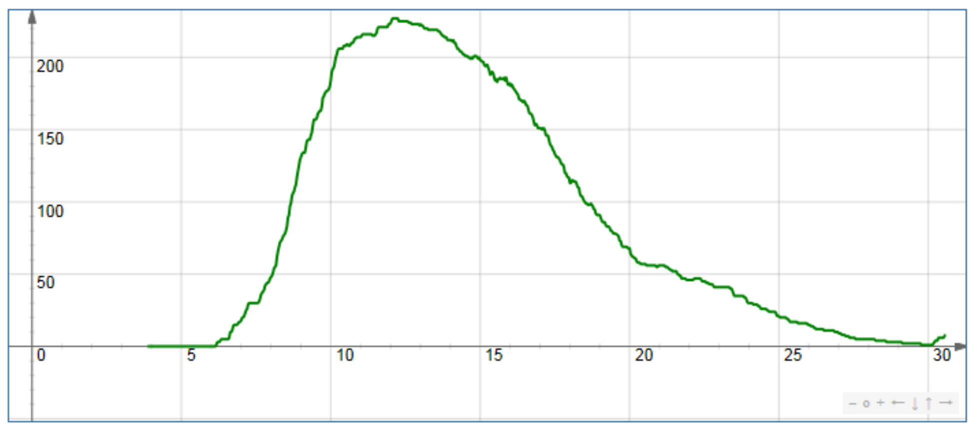
Timescale	Timestep (secs)	Days	Hours	FPS
46.84	20.00	1	06:34 AM	2.3
PX	**Stations**	**Avg Vel (mph)**	**PX-Depart**	**PX-Arrive**
500	8	46.5	2515	2482
At Home	**to Work**	**at Work**	**from Work**	**Total**
437	49	8	6	500
day Flights	**day Air PX**	**day Unqueued**	**day PX-time**	**day PX-mile**
15	32	67	7.3	858.1

	Total	SFC	PAL	SVA	SJC	GIL	OAK	FMT	SCZ
Queued	27	4	5	4	5	2	1	3	3
Wait Sum	6.11	0.52	0.94	1.02	1.11	0.28	0.52	0.41	1.31
Max Wait	0.61	0.22	0.39	0.42	0.33	0.16	0.52	0.17	0.61
Avg Wait	0.23	0.13	0.19	0.26	0.22	0.14	0.52	0.14	0.44

\# PX: 500 Timestep: 20 Load Factor: 0.50 PX/AC: 6 AC Speed: 120

Max Queue Wait (mins): 60 Surface Speed: 30

Start Calculator Capture Help Graphics Step Exit



Report Interval (mins): 2 x-axis: Hours y-axis: At work

Network Statistics

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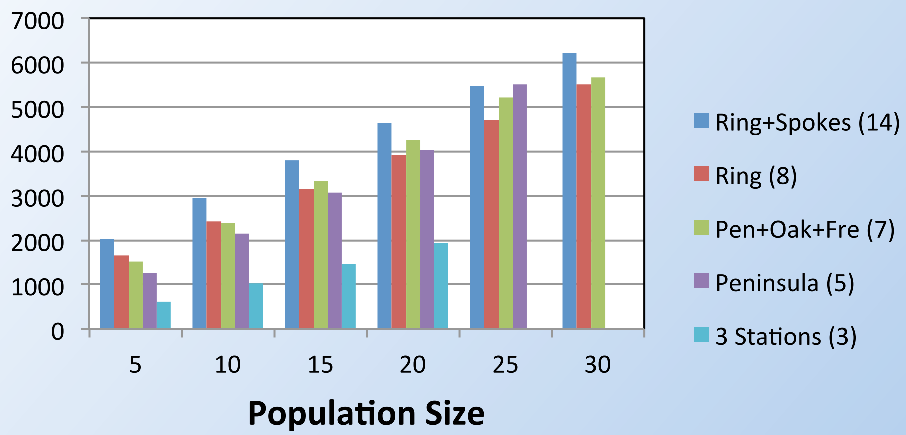
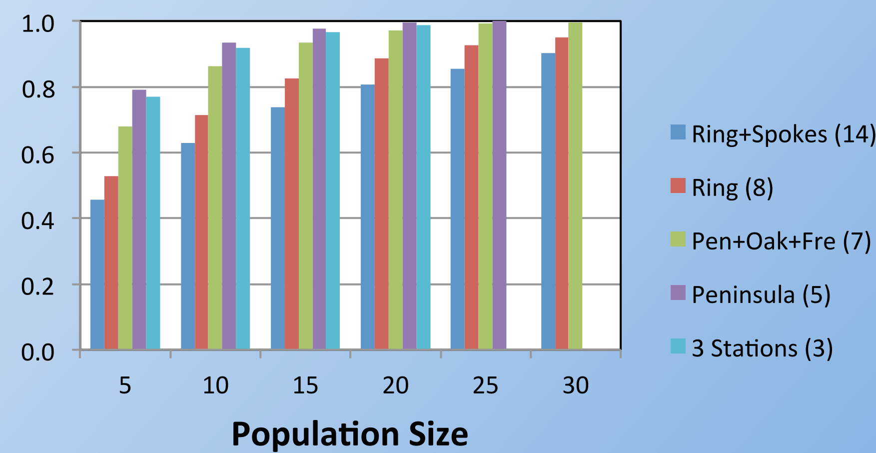
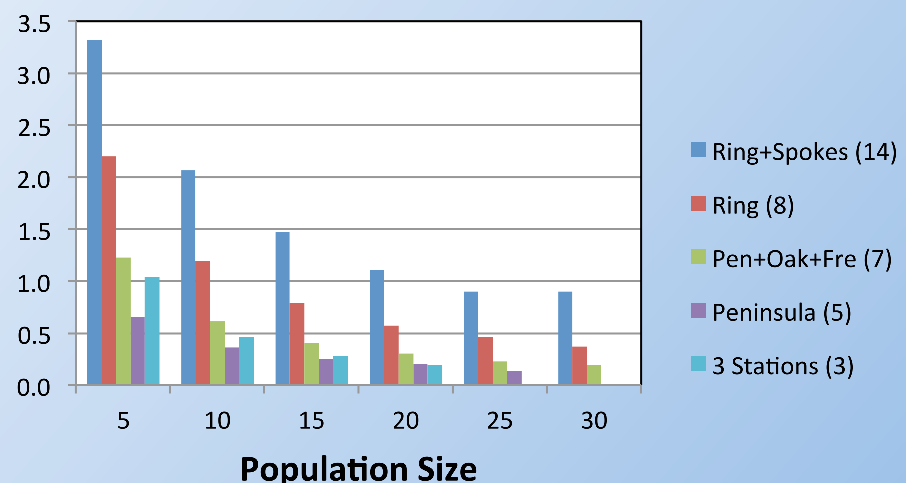
Number of Flights per Day



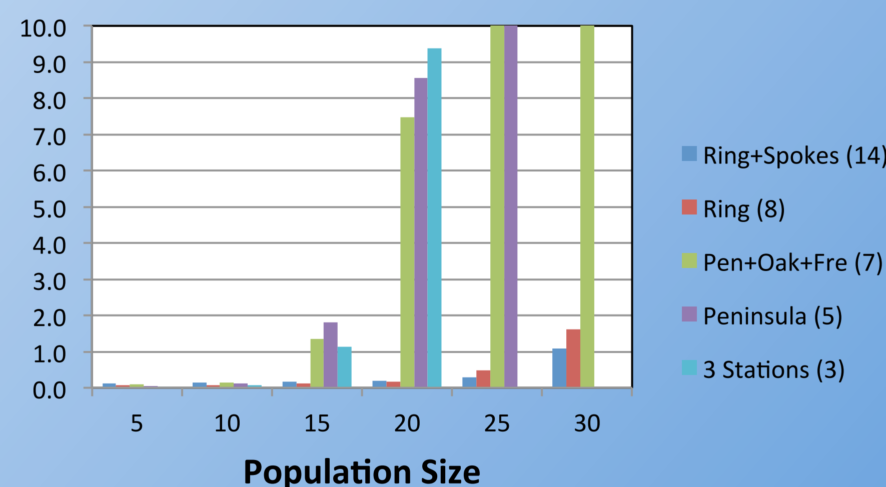
Average Load Factor



Average PX Queue Delay in Minutes



Average Flight Departure Spacing Delay in Minutes



Results with minimum departure spacing of 60 seconds

Network Energy Usage

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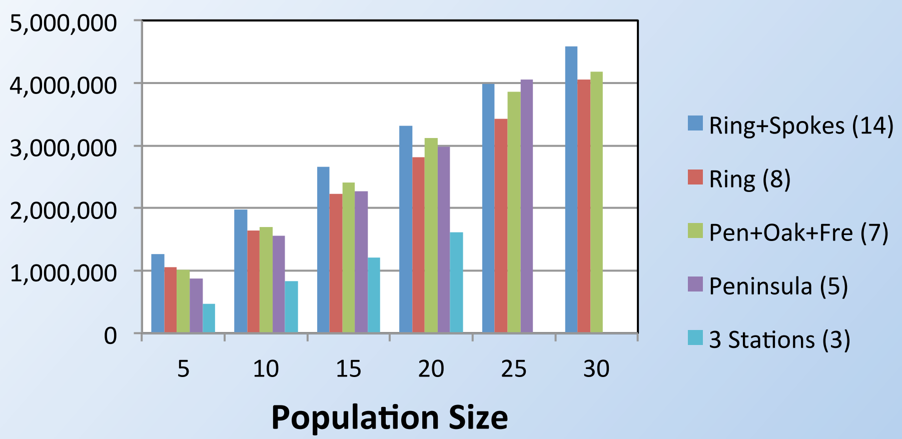
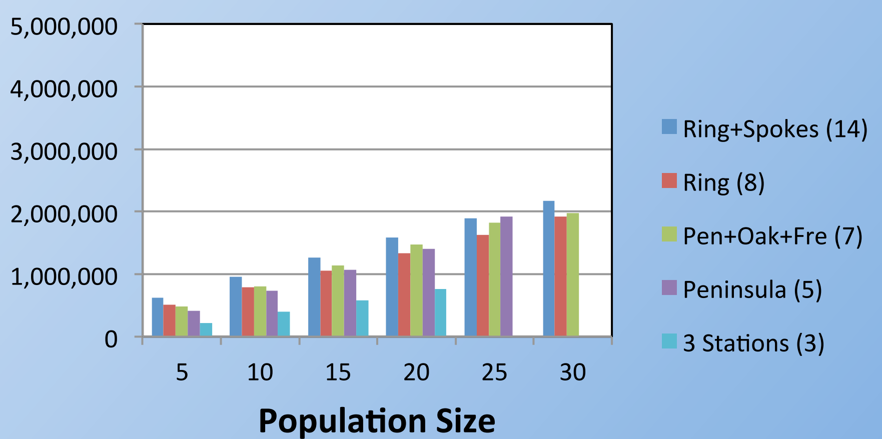
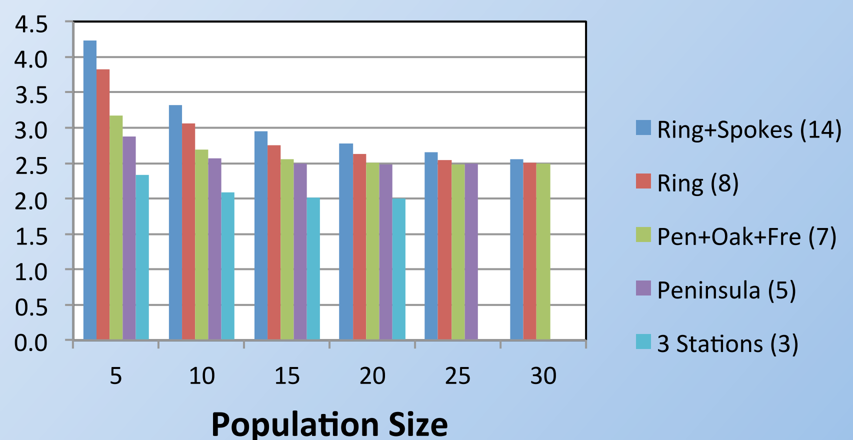
Total Energy Use in kW-h: Gas



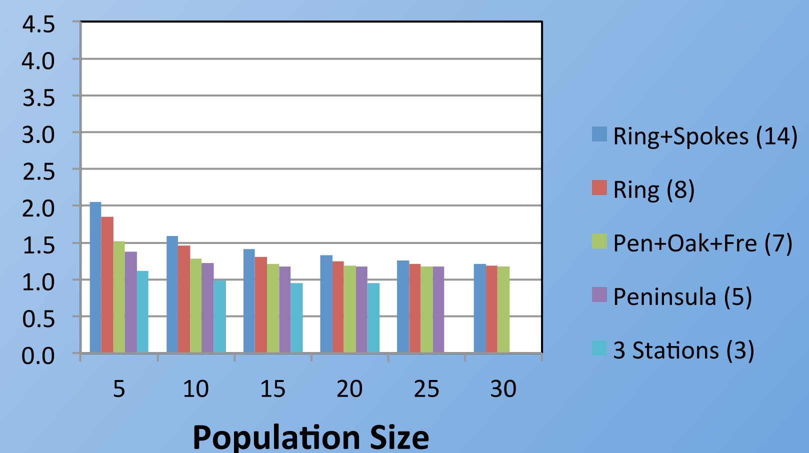
Total Energy Use in kW-h: Battery



kW-h/(PX-mile): Gas



kW-h/(PX-mile): Battery



Results with minimum departure spacing of 60 seconds

Operations & Misc. Tech Issues

Vertiport Station Operations

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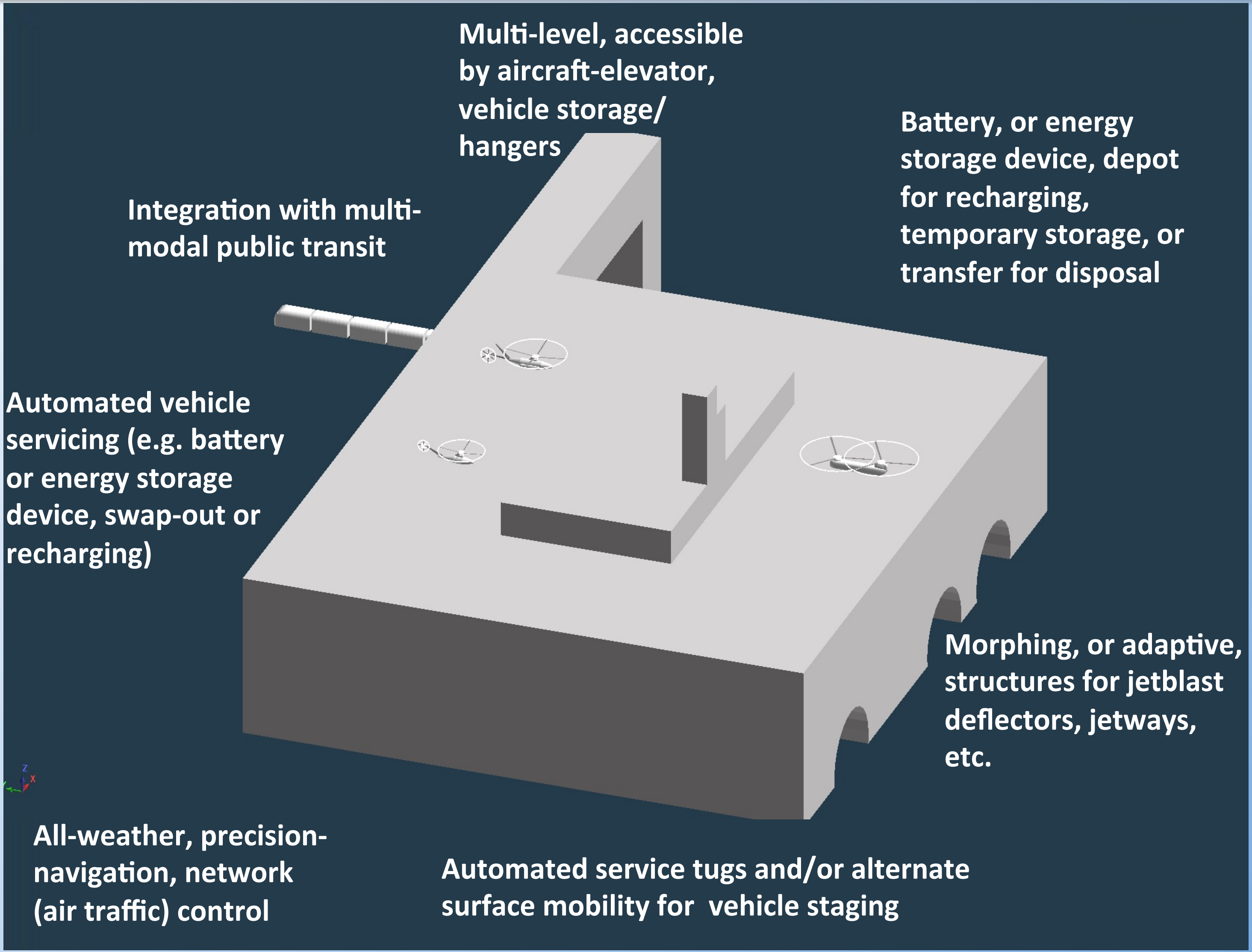

Rotor Wake Interactions

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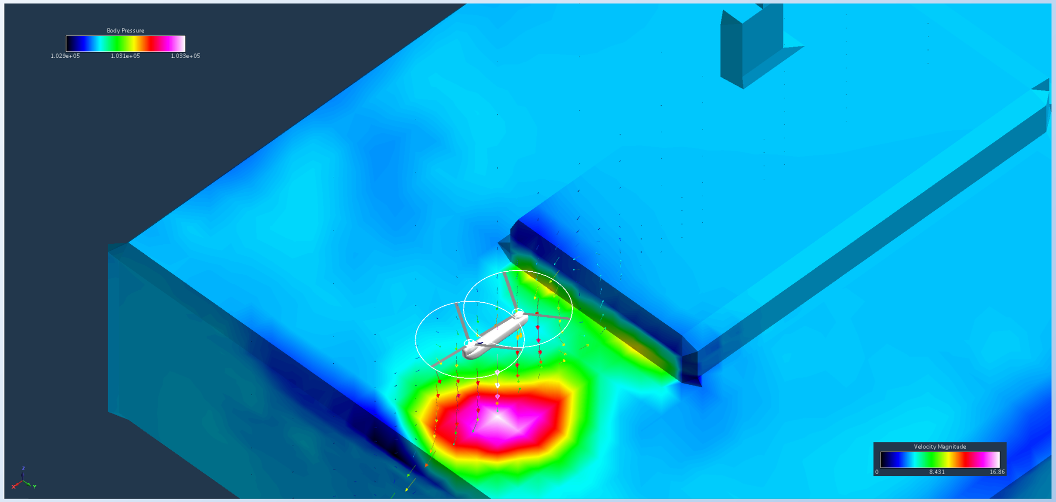

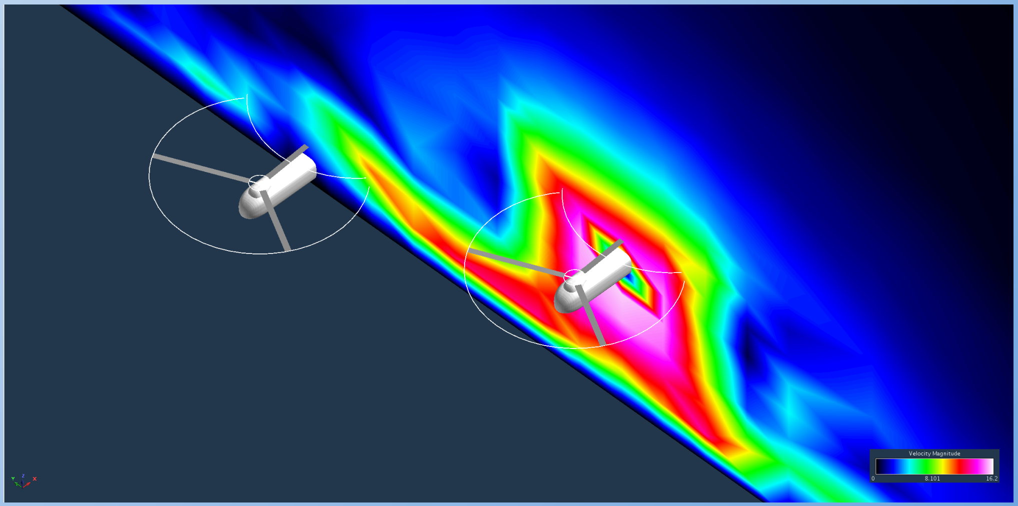

Preliminary Noise Assessments

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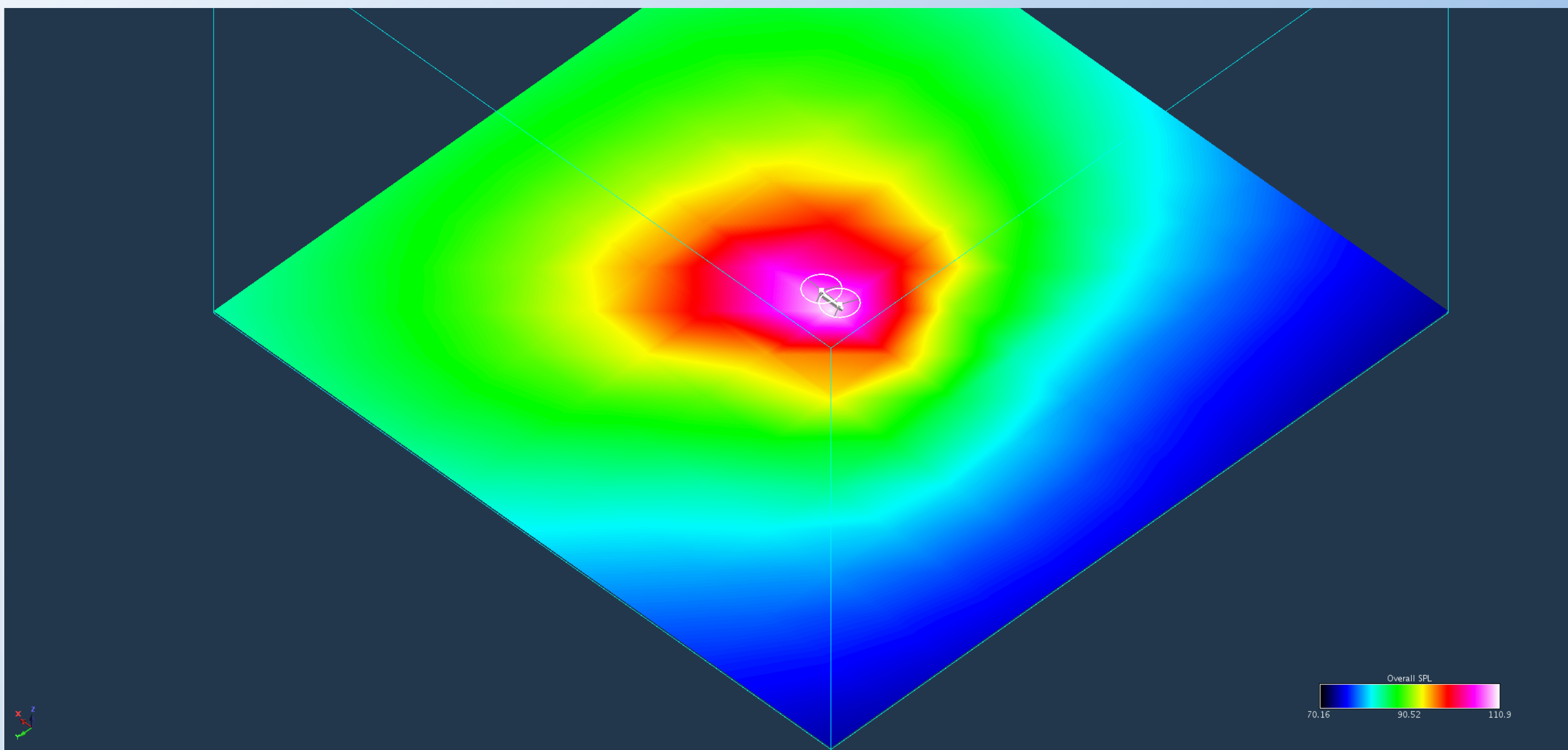

Future Work & Tech Transition

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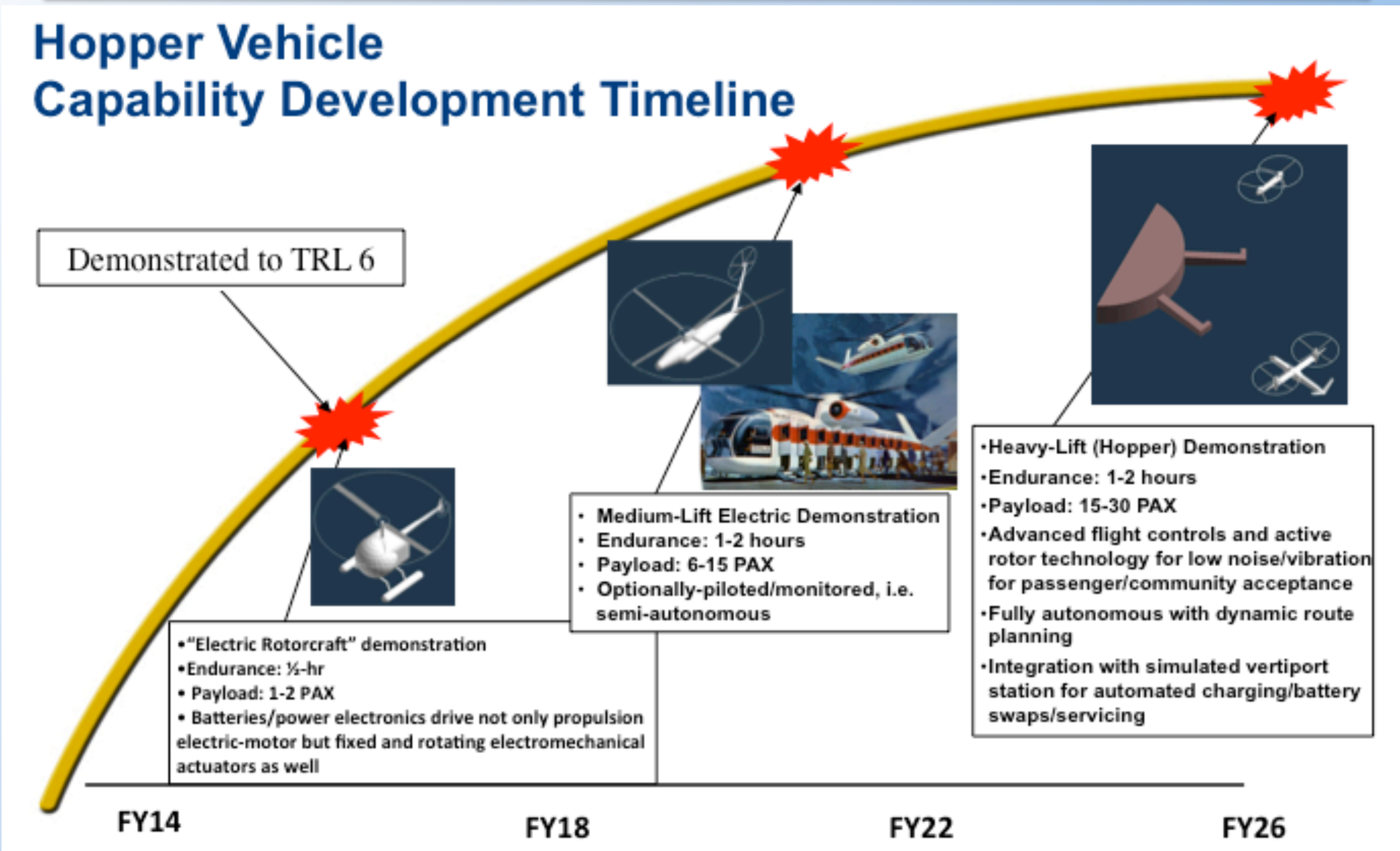
- Some of the electric-propulsion models developed are finding their way into Stanford's SAUVE vehicle conceptual design tool and NASA's NDARC
- Two NASA TM's are being drafted for publication
- Internal electric-propulsion discussion within ARMD Rotary-Wing project
- Hopper helps make a case for vehicle/systems autonomy research

Hopper Capabilities



Concluding Remarks

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- Large numbers of medium- to large- A/C are required to serve assumed passenger levels
- Flying and VTOL are energy intensive transportation modes for short distances and, yet, represent a potential way to bypass urban surface transportation congestion
- While originally conceived as "light infrastructure" (no new roads/rail-lines), the vertiport station power requirements and real estate footprints of ramps and terminals may require requite more infrastructure than initially anticipated when large numbers of aircraft are involved
  - Trucks will be required if charged batteries are to be delivered to stations (and discharged batteries removed for offsite recharging);
  - high-power electrical transmission must be provided to stations if charging is onsite.

Concluding Remarks, Cont.

- Acoustics and other over-flight issues will require technology innovations and public/neighborhood outreach. Will neighborhood populations accept a new type of traffic noise?
- The development of Discrete Event Simulations has value not only in producing quantitative design tradeoff information, but also in 1) uncovering and examining detailed operational policies surrounding transportation networks, and 2) understanding behavioral and demographic issues for the populations they are intended to serve.

Concluding Remarks, Cont.

- May be best to operate network independently of other air transport that transits outside of the Bay Area, instead of "actively intermeshing"
- Emerging technological and procedural advances, currently being proposed under the Next Generation Air Transportation System (NextGen), could be leveraged to facilitate the realization of the Hopper concept.

Concluding Remarks, Cont.

- Relatively near-term battery / hybrid / fuel cell technologies could make these short range vehicles realizable within the next 10 years
- Near-term battery technology (500-600 W h / kg at reasonable power densities) will satisfy power and energy requirements for these short range vehicles: more advanced Li-air batteries will not lead to further weight reductions.

Concluding Remarks, Cont.

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- Discrete event simulations and schedule optimizations reveal the possibility of carrying a substantial daily passenger load within the Bay Area.
- Study has identified challenges in integrating Hopper flights and Bay Area commercial traffic that can be partially tackled with Hopper aircraft time-of-day dynamic routing as well as NextGen technologies