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

Dr. Dean Kontinos, Entry Systems and Technology Division, NASA Ames Research Center

Dr. John Melton, Systems Analysis and Integration Branch, NASA Ames Research Center

Dr. Shon Grabbe, Systems Modeling and Optimization Branch , NASA Ames Research Center

Prof. Juan Alonso, Department of Aeronautics and Astronautics, Stanford University

Mr. Jeff Sinsay, Aeroflightdynamics Directorate, United States Army

Mr. Brendan Tracey, Department of Aeronautics and Astronautics, Stanford University

The Idea

- The objective of this study is to determine the technical feasibility of electric aircraft to provide a solution to regional mass transportation; a capability currently achieved through road and rail.
  - a compelling aspect is that air-connected nodes (station stops) could be dropped, added or reconnected to suit real-time traffic needs – a feature impossible to attain with a rail system
  - addresses NASA Strategic Goal 4 to advance aeronautics research for societal benefit

Study Elements

1. Definition of the transportation network
2. System simulation of passengers in the network
3. Design of electric aircraft
4. Definition of schedule
5. Airspace assessment
6. ~~Design of station~~*

* Descoped from original proposal because of rise of prominence of system simulation

Out of Scope Elements

- Cost
  - focus on technical feasibility and enabling technology thresholds
  - public transportation is a complex economic analysis involving government capital investment, recurring subsidy, and cultural habits
  - potentially to be part of Phase II study
- Availability
  - no consideration of all-weather operation
- Certification
  - such a system would likely require new regulation

Driving Questions

- Given a metro-regional network:
  - What would be the flight schedule (number and frequency) required to service a weekly commuter ridership, i.e. can throughput be achieved?
  - What size aircraft are required to operate within the schedule?
  - What are conceptual designs for the aircraft, do they close, and what technical barriers are there to them being electrically powered?
  - How would operation of the network fit into existing air traffic?
  - How do answers to above questions change as the total ridership is varied?

Approach

- Define a model network in a metro complex
- Devise a discrete event simulation of the passengers using the system
- Design aircraft of various size (passenger count)
- Devise a mixed fleet aircraft schedule that services the ridership
- Simulate the schedule in the local airspace to determine conflict

Element 1: The Network

San Francisco Bay Area Network

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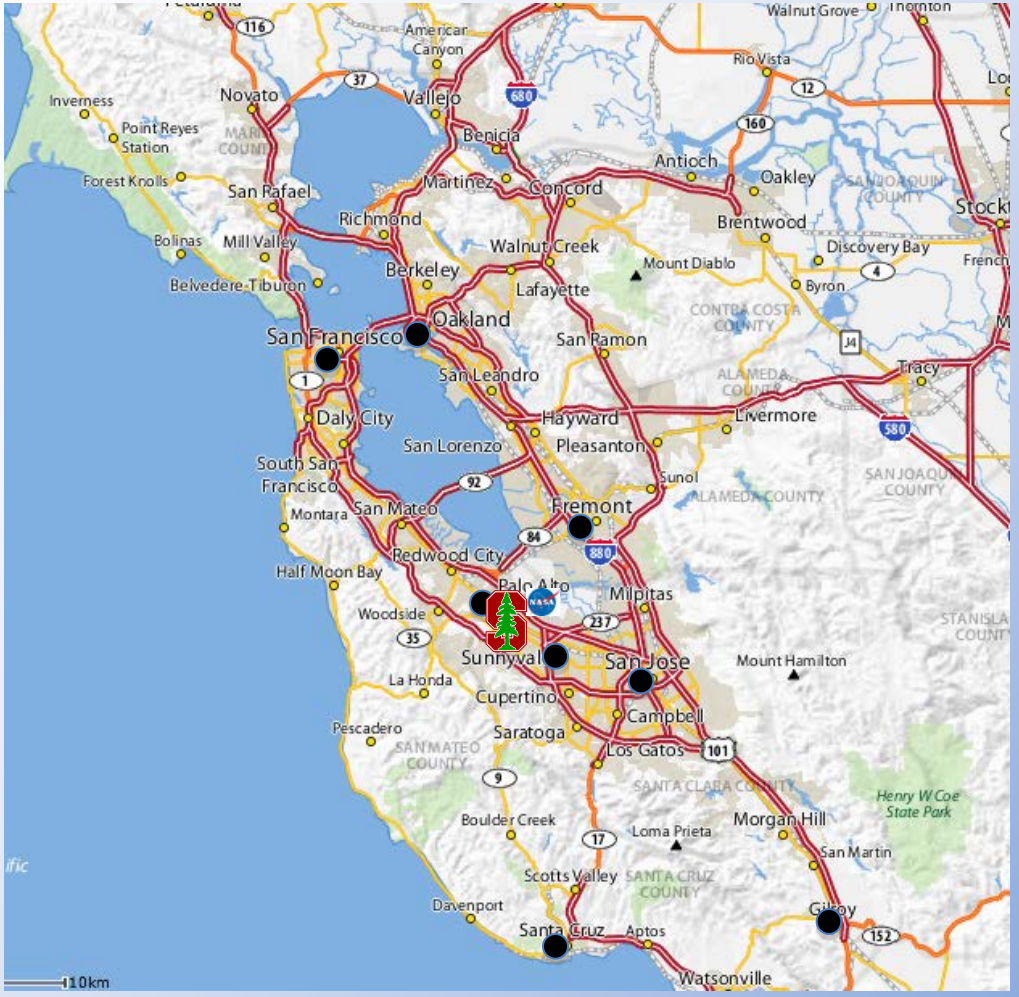

8 Network Nodes

San Francisco Cal Train Station

Palo Alto Cal Train Station

Sunnyvale Cal Train Station

San Jose Cal Train Station

Gilroy Cal Train Station

Oakland City Center BART

Fremont BART

Santa Cruz Metro Center

Element 2: System Simulation

Simulation Objective

- To generate a demand model based on population density, job density, and typical work hours
  - Currently using simple approximations
- Output of the simulation is number of passengers demanding a node-to-node connection as a function of time of day
  - Currently modeling week day commuter travel

BaySim

- Newly developed Discrete Event Simulator called BaySim
- Simulates daily commutes of individual passengers
  - Finite State Machine
  - 3.4K lines of JavaScript + DHTML with integrated graphics
  - 12 states of PX travel, including surfaceTransport, atWork, etc.
  - 3 states of flights, including LoadingPX, ReadyForTakeoff, EnRoute
- Aircraft fly direct between all 8 air nodes (no hub)
- Flight queuing and departure delay logic
- Gaussian randomness on most inputs and behaviors
- Approximated home and workplace locations
- Outputs specialized for fleet assignment and FACET

BaySim: PX Populations

- 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
- Starting Population Sizes: **5K, 15K, 45K**
- 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

BaySim: Live Demonstration

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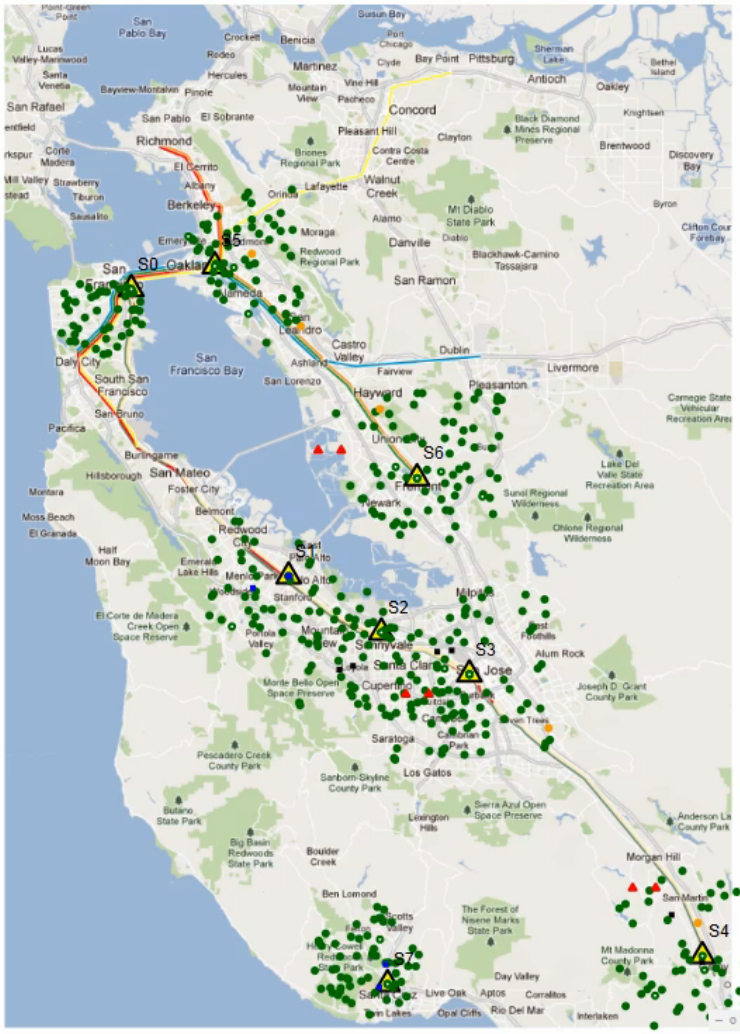
C:\Users\jmelton\Documents\NASA\DES_FSM\JSXGraph\BaySim_v33.0_PX_log_Q2.hta



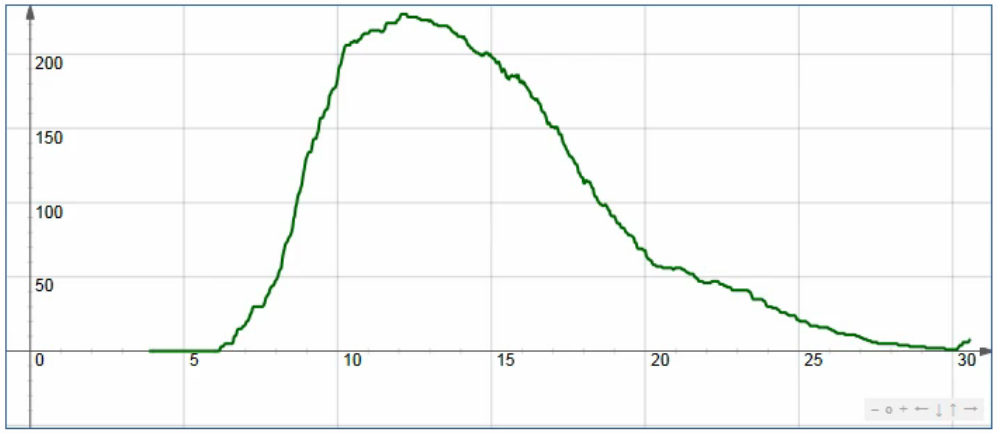
Timescale	Timestep (secs)	Days	Hours	FPS
46.84	20.00	1	06:34 AM	2.3
PX	**Stations**	**Avg Vel (mph)**	**PX-Depart**	**PX-Arrive**
500	8	46.5	2515	2482
At Home	**to Work**	**at Work**	**from Work**	**Total**
437	49	8	6	500
day Flights	**day Air PX**	**day Unqueued**	**day PX-time**	**day PX-mile**
15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

BaySim: Output Data

- Complete chronological information about all flights, including PX count, O-D pair, delays, transit times, speeds, etc.
- Specialized departure information tables ready for fleet assignment and FACET incoporation
- Plotting via GNUPLOT scripts

BaySim: Sample Plots

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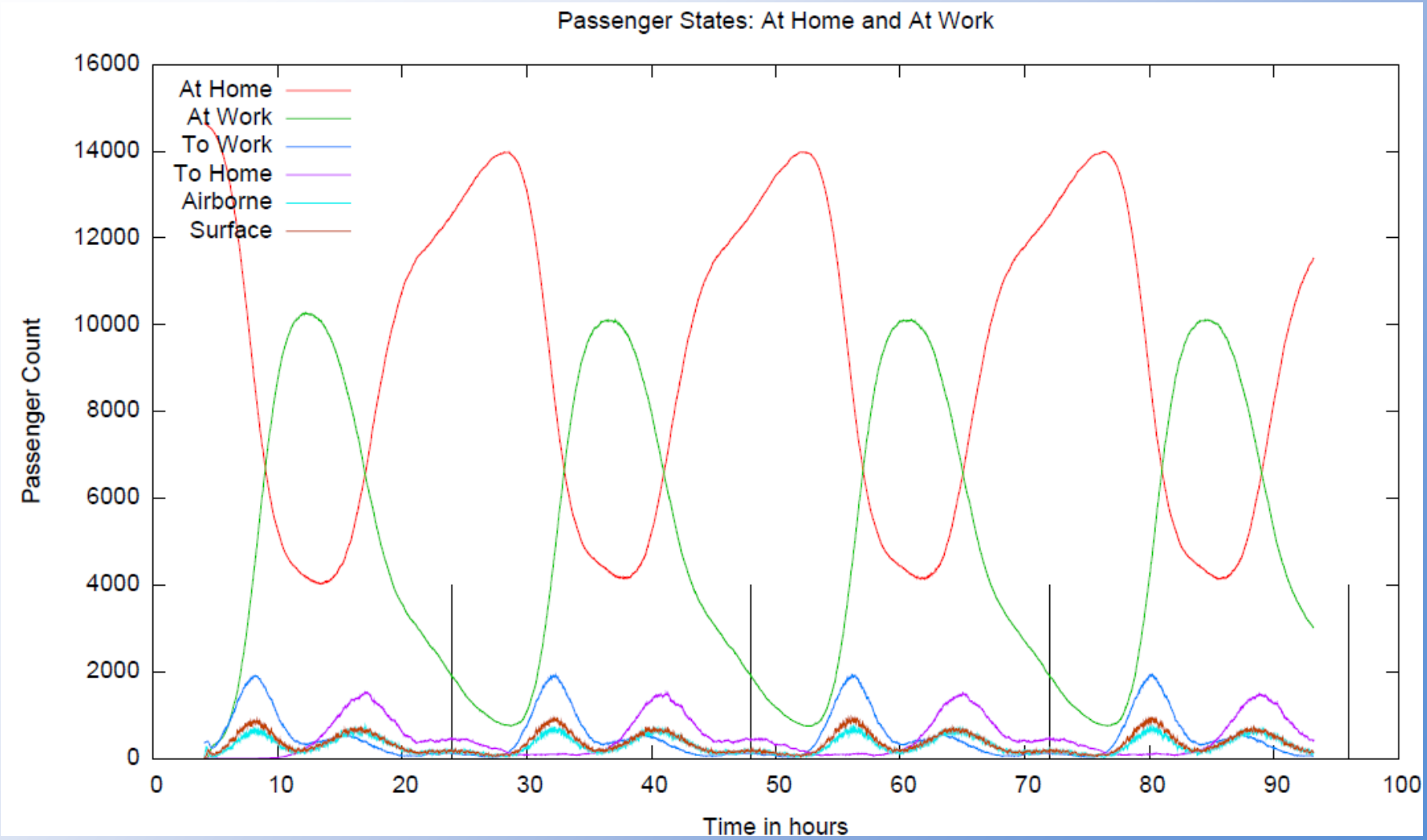

BaySim: Sample Plots

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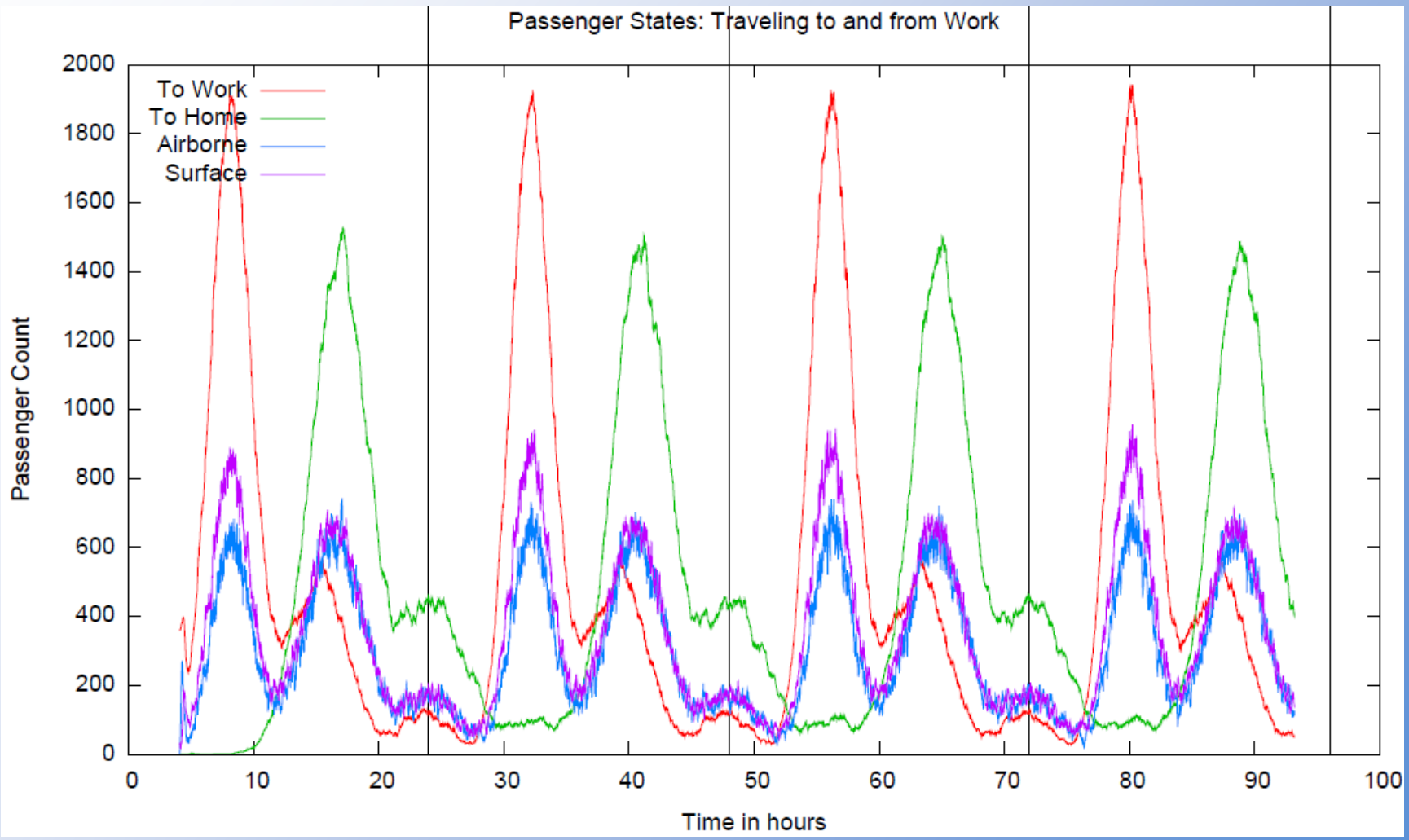

BaySim: Sample Results, 25 PX/AC

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Population	(minutes) MBD	Daily Flights	(maximum) Simultaneous Flights	(preflight) Max Delay	(daily) PX-miles
5K	3	1940	40	10	270K
15K	3	3140	47	***15***	834K
15K	1.5	4010	71	6	836K
45K	1.5	6250	84	***13***	2494K
45K	1	6850	100	3.5	2498K

Average Trip Length: 28 statute miles Average Air Time per Flight: 14 minutes

MBD (input): required minutes between departures from any single terminal

Simultaneous Flights (output): number of aircraft in flight at any one time

Max Delay (output): maximum departure delay due to MBD spacing restrictions

Caltrain provides 300M PX-mile/year or about 300M/(52*6) = 960K PX-miles/day

BART has 370K riders on weekdays traveling 13.45 miles = 4980K PX-miles/day

(6850 Departure + 6850 Arrivals) / 8 Stations = 1712 ops/day at each station

SFO does around 1100 ops/day (arrivals and departures) for 112K PX/day

Element 3: Aircraft Design

Current Electric Rotorcraft

1st Electric Manned Helicopter
Pascal Chretien, France, August 12, 2011
TOGW: 545 lb
Motor: 32 kW
Battery: Li-ion, 9.2 kWh

Sikorsky Firefly (Modified S-300C)
Awaiting First Flight
Motor: 142 kW
Battery: Li-ion, 45 kWh

Design Objectives

- Conduct sizing of three rotorcraft sizes: **6, 15, & 30** passenger
- Implement electric propulsion model in sizing tool
  - Implement motor, battery & power distribution models
  - Generate parametric relationships for sizing
  - Modify air vehicle sizing approach for electrics
- Identify technology needs for electric powered VTOL

Vehicle Design Approach

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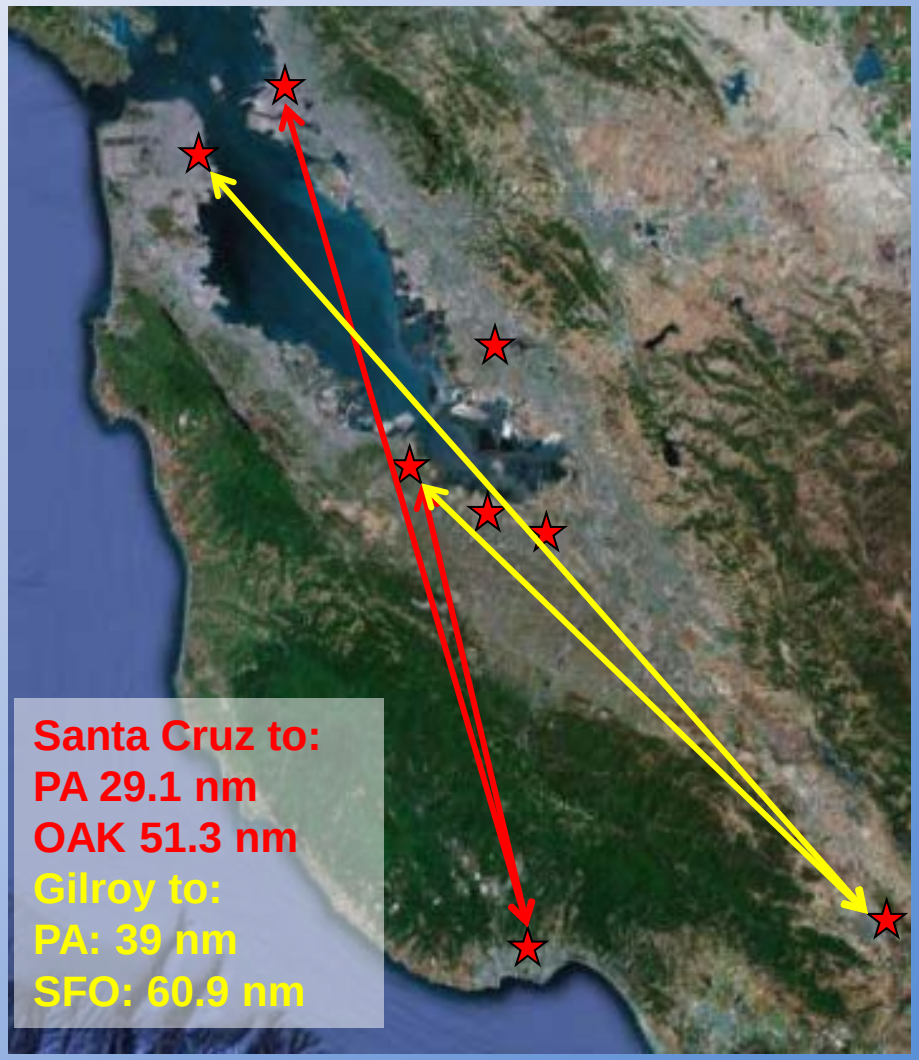
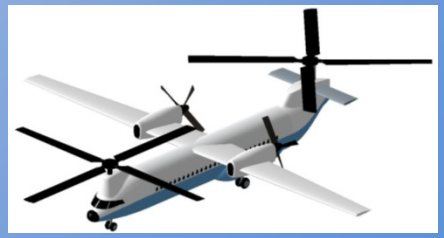
- Vehicles sized for longest point-to-point segment
- Baseline vehicles sized with gas-turbine propulsion
- Upfront assumptions /ground rules
  - Advanced structure, drive system & rotor tech
  - Single-pilot operation (path to full-autonomy?)
  - **20 min VFR reserve** (significant for short-haul)
  - No minimum One-Engine Inoperative performance requirement
  - 3k/ISA+20 ºC take-off condition



NASA Design and Analysis of Rotorcraft (NDARC)

- NDARC is a code developed by Wayne Johnson at NASA Ames in 2008
  - Designed for flexibility and modularity
  - Able to rapidly model wide array of rotorcraft concepts
- Critical to achieving this capability is decomposition of aircraft into set of fundamental components
- NDARC builds on legacy of U.S. Army conceptual design codes
- Fidelity similar to legacy government/industry tools
- Sizing:
  - Determines the dimensions, power and weight of a rotorcraft to meet a specified set of design conditions and missions
  - Critical parameters:
    - Rotor diameter or engine power
    - Take-off gross weight
    - Transmission size
    - Mission fuel / fuel tank size **(stored energy)**
    - Rotor design thrust
  - Uses method of successive substitutions to converge values to consistent design
    - User must define a well-posed design problem
    - Converged when parameters and aircraft weight empty are within tolerance



NDARC Modification

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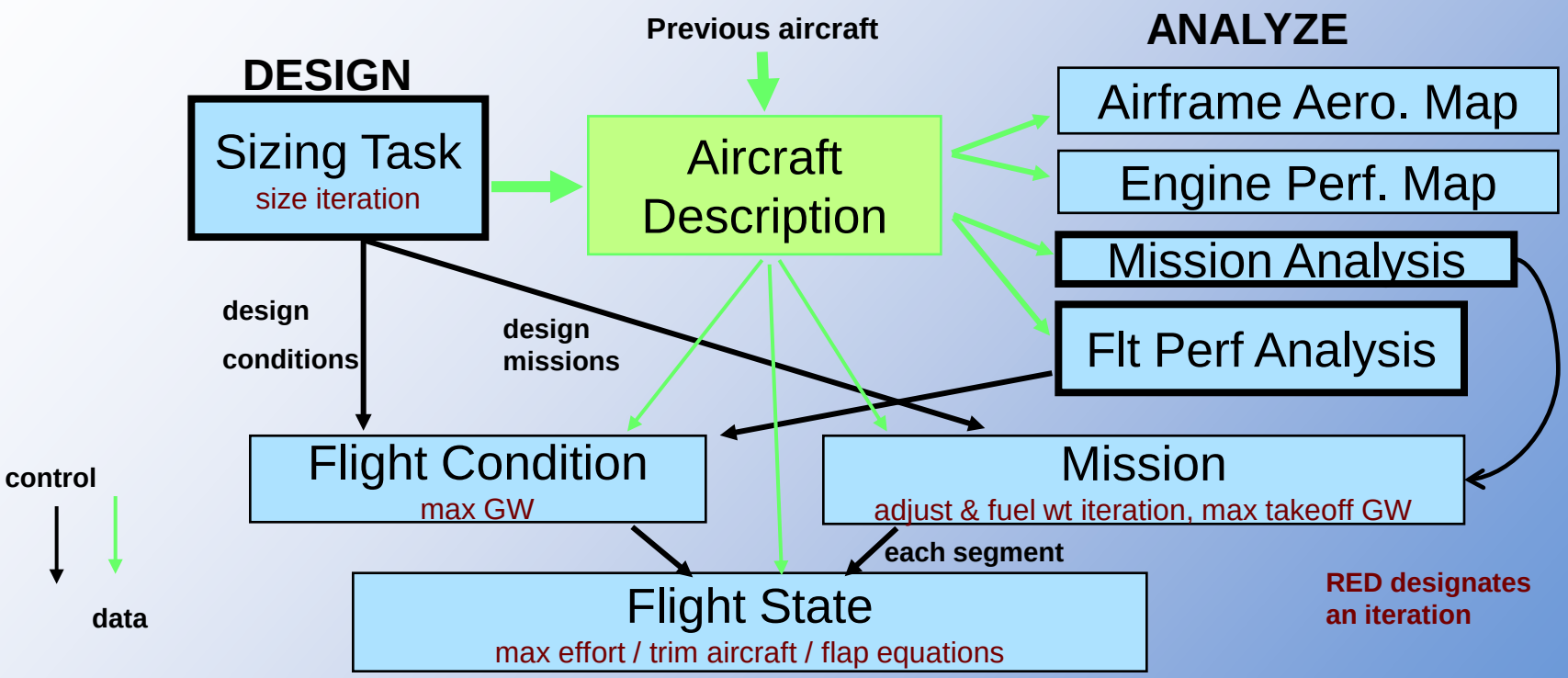

- Added Battery component to library of components
  - Specific Energy, Specific Power, Volumetric Energy Density inputs
  - Account for power distribution & control weight
- Modified engine components for electric motors
  - Updated weight parametrics
  - Include relevant efficiencies: motor, power distribution, battery, fuel cell
- Revised mission iteration scheme
  - Iterate on energy storage
- Adjusted sizing loop to scale battery to meet required storage capacity

Baseline Rotorcraft Designs

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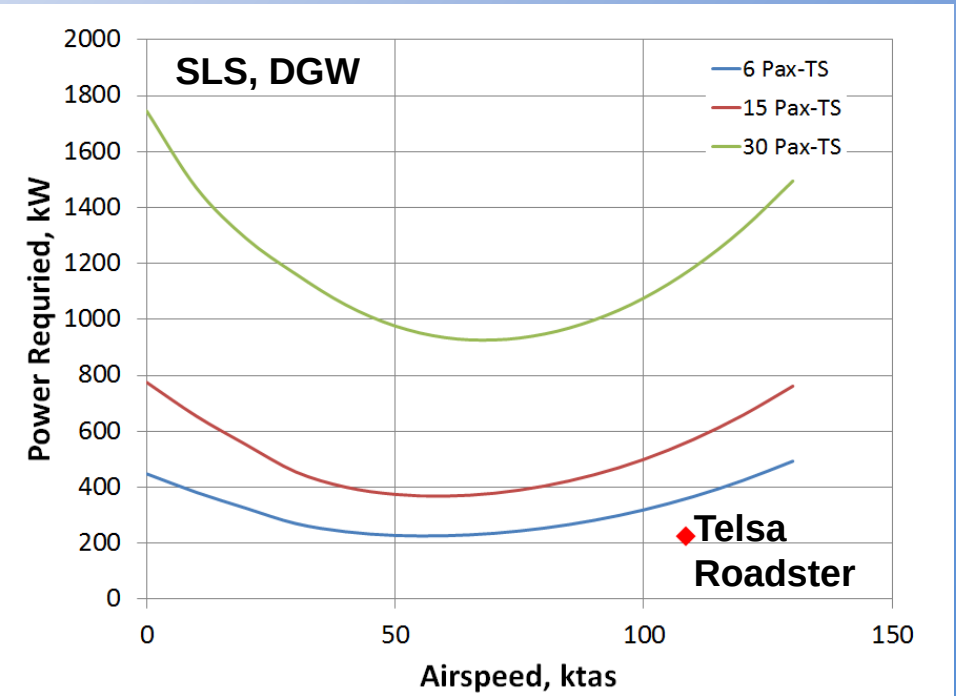
- Sized vehicles as baseline for study
  - Characterized performance for NAS simulation with FACET
  - Compare favorably to existing rotorcraft of similar size
- Mission unique considerations:
  - Lower disk loading to reduce installed power requirements
  - Fuel weight fraction is relatively small
  - Relatively low hover ceiling
  - Reduced tip speed for community noise

No. Pax		6	15	30
Design Gross Wt.	lb	5,421	9,770	20,313
Weight Empty	lb	3,547	5,763	12,364
Prop. Grp.+Fuel Wt.	lb	988	1,674	3,723
XMSN Power	kW	486	843	1,896
Prop Spec. Pwr	W/kg	224	229	231
Rotor Diameter	ft	39.16	52.58	53.6
Disk Loading	psf	4.5	4.5	4.5
Solidity (Geo.)	-	0.0524	0.0524	0.0524
No. Blades	-	4	4	3
Blade AR	-	24.3	24.3	18.2
Tip Speed	fps	650	650	650



Motor Scaling

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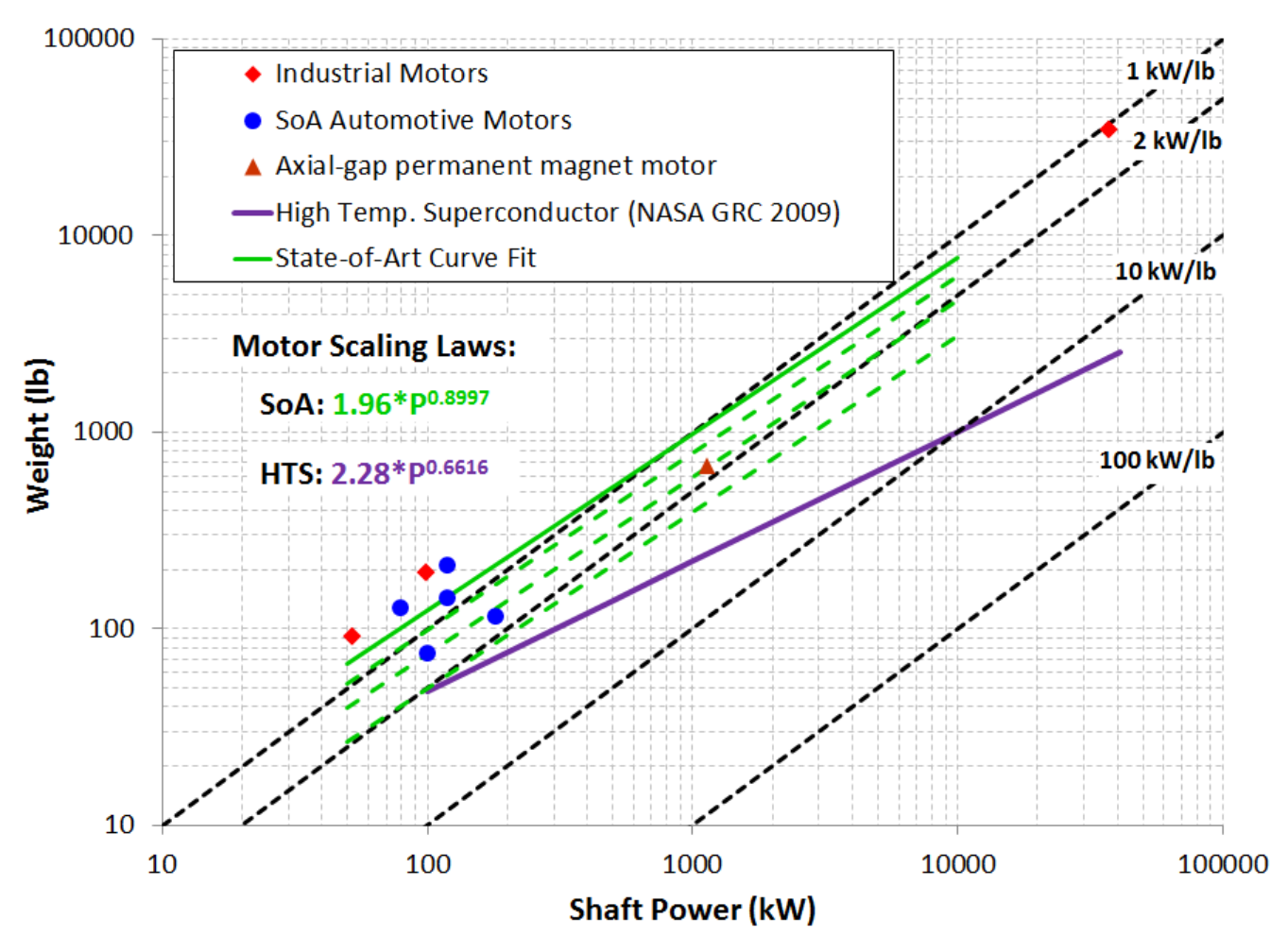

- Other potential scaling parameters: motor type, air/liquid cooling

Energy Storage (High Tech)

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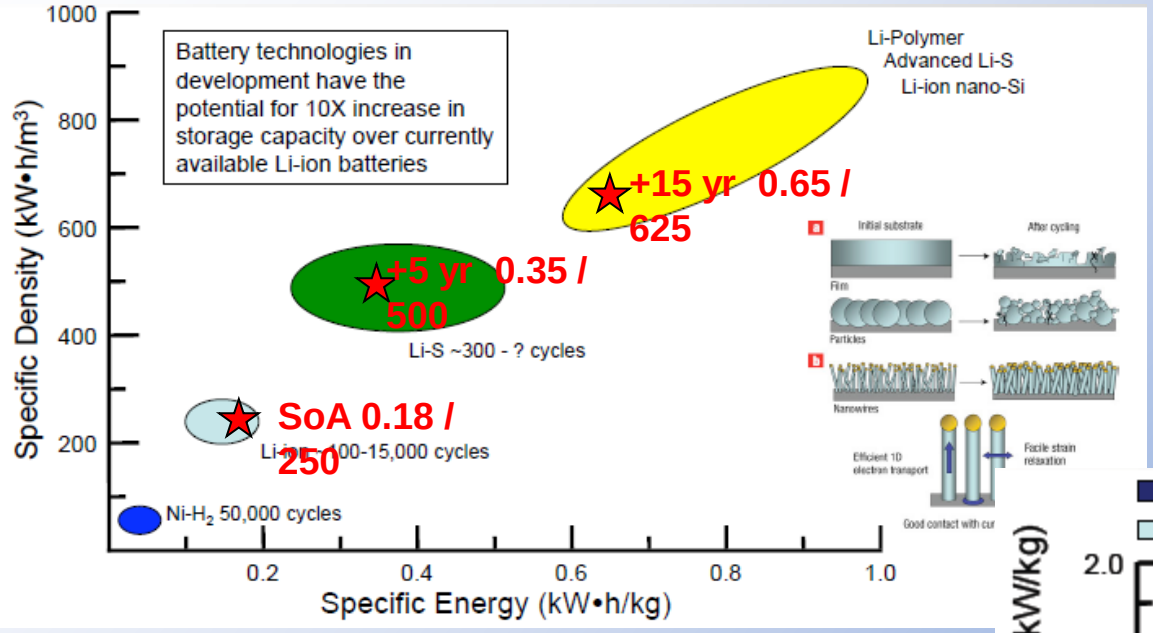

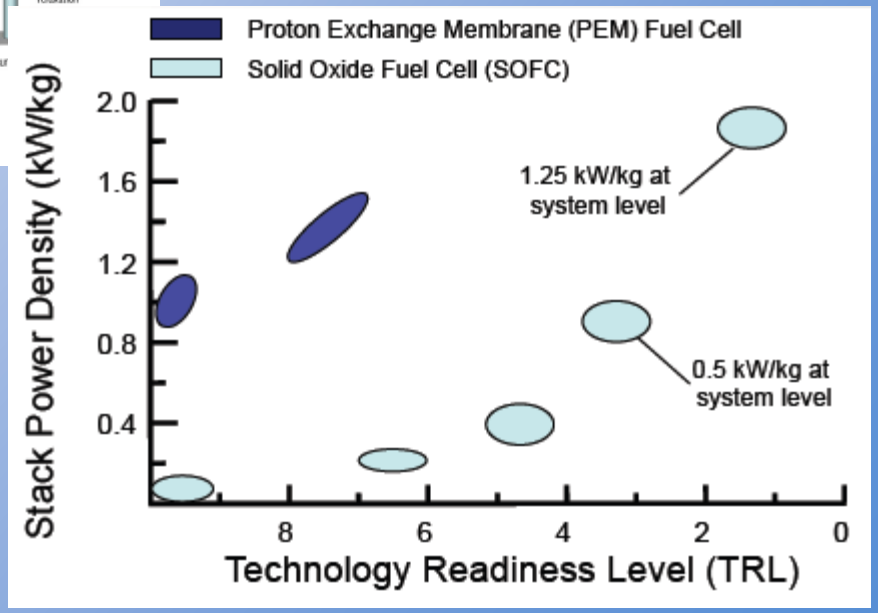

Source: M. Dudley NASA Ames
EAA Electric Aircraft World Symposium 2010

30 Passenger Electric Tandem

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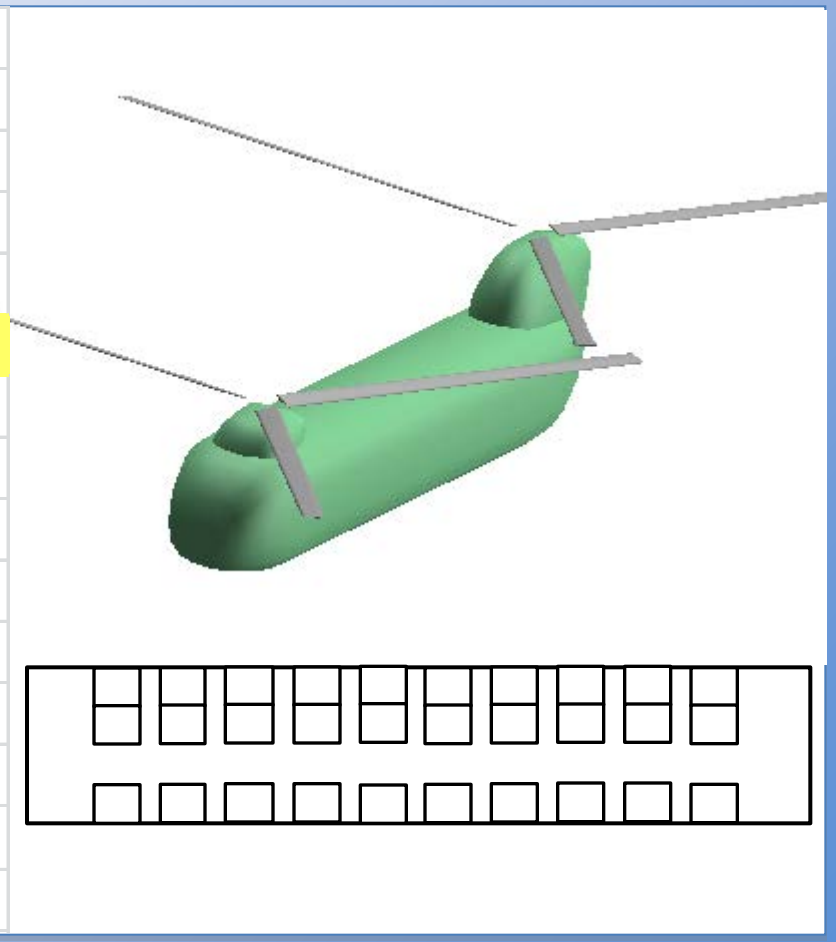
		TS	Electric	
No. Pax	-	30	30	30
Design Range	nm	65	65	40
Design Gross Wt.	lb	20,313	24,148	30,096
Weight Empty	lb	12,364	12,382	14,986
Wt. Empty Fraction		61%	51%	50%
Prop. Grp.+Fuel Wt.	lb	3,723	6,906	10,660
Max Rotor Pwr	kW	1,896	1,834	2,227
Prop. Grp. Spec. Pwr	W/kg	231	121	95
Stored Spec. Energy	kW-h/kg	12.0	0.650	0.350
Conv. Efficiency	-	28.1%	90.3%	90.3%
Storage Volume	gal	858	554	645
Rotor Diameter	ft	53.6	62.0	69.2
Disk Loading	psf	4.5	4.0	4.0
Tip Speed	fps	650	650	650



Aircraft Design Findings

- Gas turbine designs are realizable with current technology
  - Focus on O&S cost and noise required in design
- Electric Rotor
  - Battery technology key enabler
    - Specific energy density & specific power density need significant improvement
    - Li-air battery technology interesting
  - Poor empty weight fractions for smaller rotorcraft major obstacle
  - 30 pax tandem significantly reduced payload wt. fraction :
    - 0.32 (Gas Turb)
    - 0.27 (Li-Air Battery)
    - 0.22 (Li-S Battery)
  - Size vis-a-vis turbine unfavorable due to poor weight fraction (cost effective?)
  - Alternate approaches for energy storage/power deserve investigation
- Clear need for trade-off between network design & aircraft
  - Passenger capacity
  - Design range
  - Noise (cruise altitude / tip speed / blade design)

Element 4: Schedule

Schedule Optimization

- Inputs:
  - The list of required flights generated by BaySim
  - Capacity of each helicopter
  - Cost per mile to fly each helicopter type (DOC)
  - Cost per day to own each helicopter (Ownership costs)
- BaySim schedule modified to allow repositioning flights
- Outputs
  - A helicopter type assigned to each required flight
  - An output flight schedule for FACET airspace simulation

Schedule Optimization

Three different objectives examined:

1. Minimum DOC (no ownership costs, no repositioning flights)
   - Best case scenario for airspace
   - Worst case scenario for helicopter ownership
2. Minimum fleet size (lots of repositioning flights)
   - Worst case scenario for airspace
   - Best case scenario for helicopter ownership
3. Minimum total cost
   - Trades off cost of helicopter ownership with cost of repositioning flights
   - Most realistic scheduling approach

Schedule Optimization

Constraints:

- Every BaySim flight must be flown by exactly one fleet (repositioning flights optional)
- The capacity of the helicopter assigned to the flight must be greater than the number of passengers on the flight
- Cannot create or destroy helicopters (continuity)

Schedule Optimization

- The optimization problem is a variant of the *fleet assignment* problem
  - Used by airlines in their scheduling process
  - Modified to allow repositioning flights
- It is a *Mixed Integer Linear Program*
  - Objective is linear – sum of the costs of all the flights + sum of owning all the airplanes
  - Integer (0 or 1) because exactly one aircraft type flies each required flight
- Solved using the Gurobi optimization suite

Schedule Results

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# Pax	Opt Goal	# Flights Repositioning	# Flights Total	# Aircraft 6 Pax	# Aircraft 15 Pax	# Aircraft 30 Pax	# Aircraft Total	Max At SF
5K	DOC	0	1830	73	43	0	116	14
	Total $	36	1866	26	29	0	55	7
	Fleet size	1804	3634	-	-	-	46	6
15K	DOC	0	3155	64	84	57	205	25
	Total $	59	3214	3	17	37	57	7
	Fleet size	1959	5114	-	-	-	54	6
45K	DOC	0	6825	51	32	125	208	51
	Total $	35	6860	12	11	106	129	24
	Fleet size	3689	10514	-	-	-	109	18

Element 5: Airspace Assessment

Airspace: FACET Background

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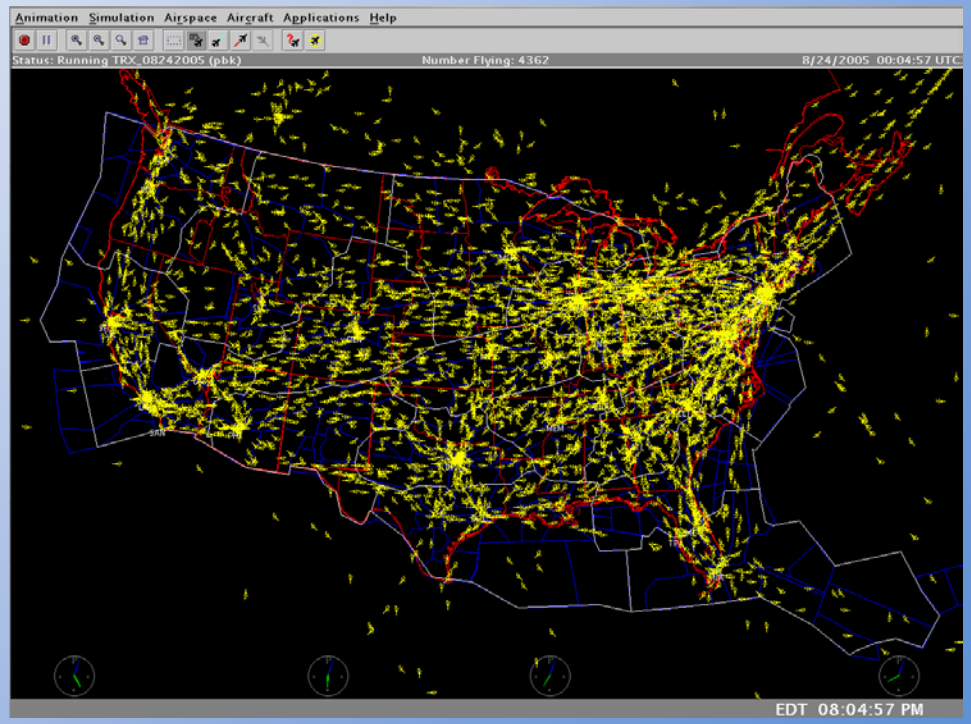
- NASA's Future ATM Concepts Evaluation Tool (FACET) used extensively to examine the interaction of the hopper flights with historical air traffic flows
- Enhancements include:
  - Module to parse TRACON Host Data
  - Updated airport definitions to define Hopper stations
  - Enhanced coastline database
  - Addition of three new vehicle databases



Airspace: Major Bay Area Traffic Flows

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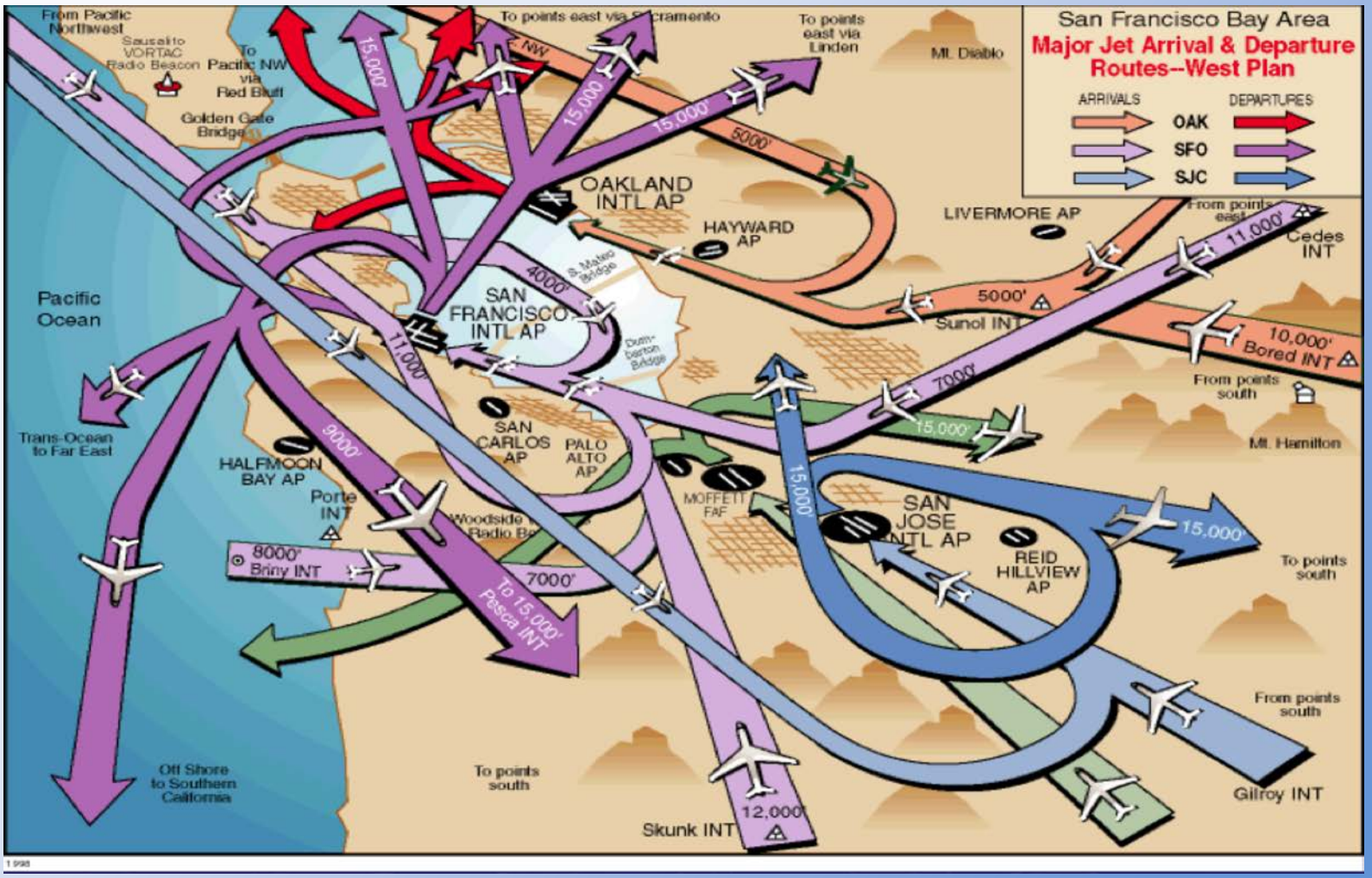

Airspace: Historical and Hopper Traffic

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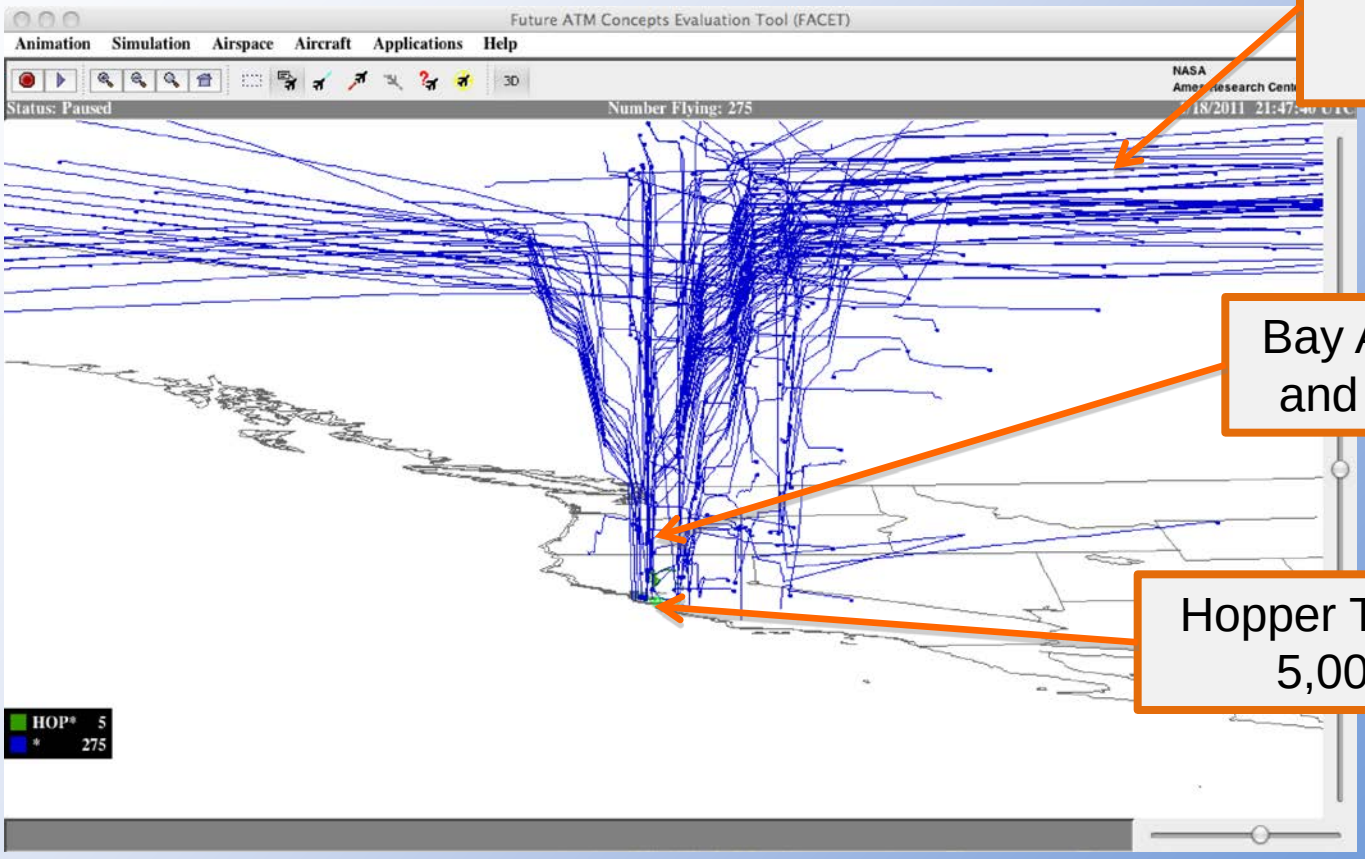

En route over-flight traffic at ~30,000 ft

Bay Area Arrivals and Departures

Hopper Traffic at 5,000 ft

Airspace Results: Loss of Separation Counts

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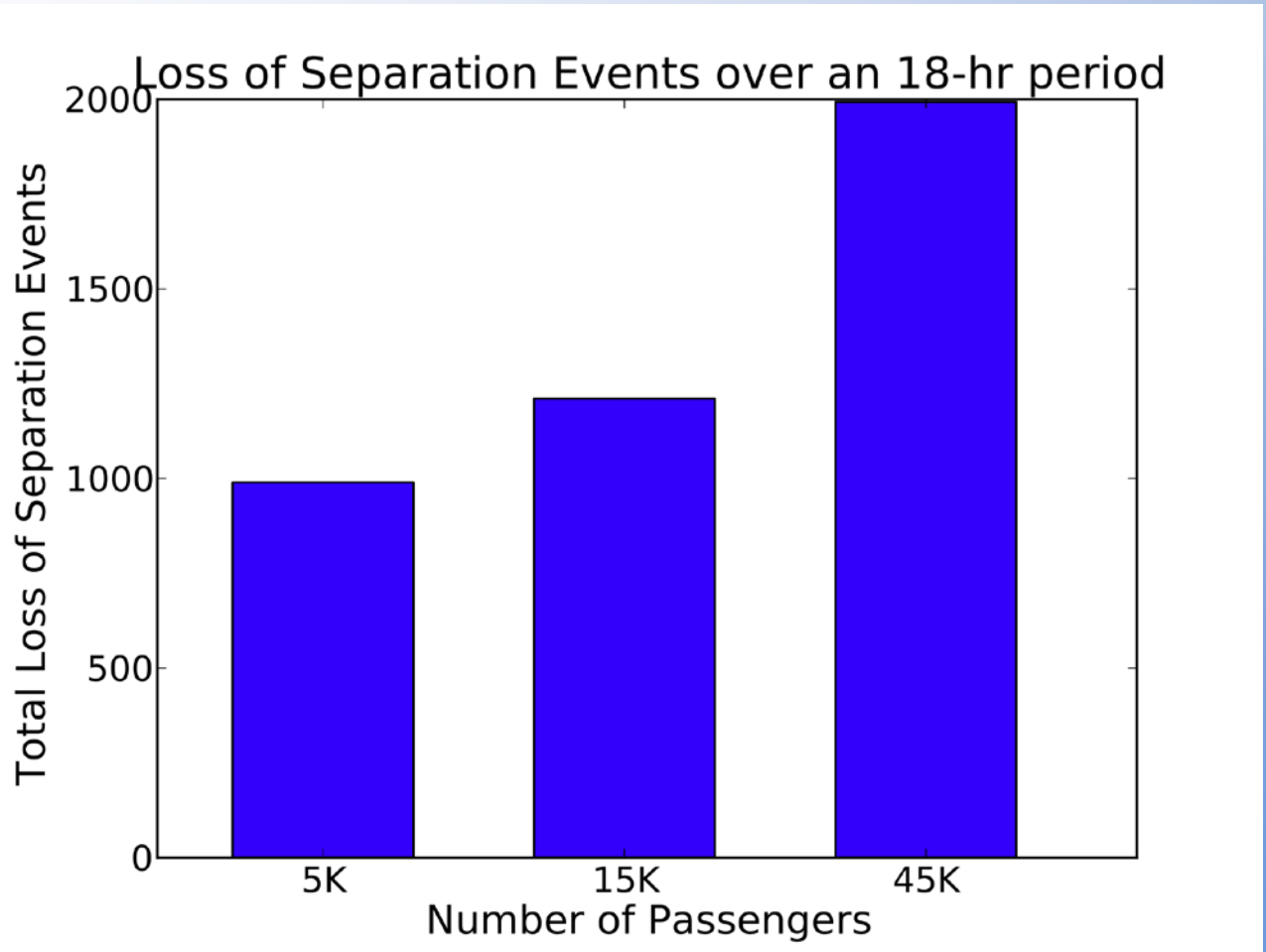

Hopper flights operating at 5,000 ft

Airspace Results: Loss of Separation Locations

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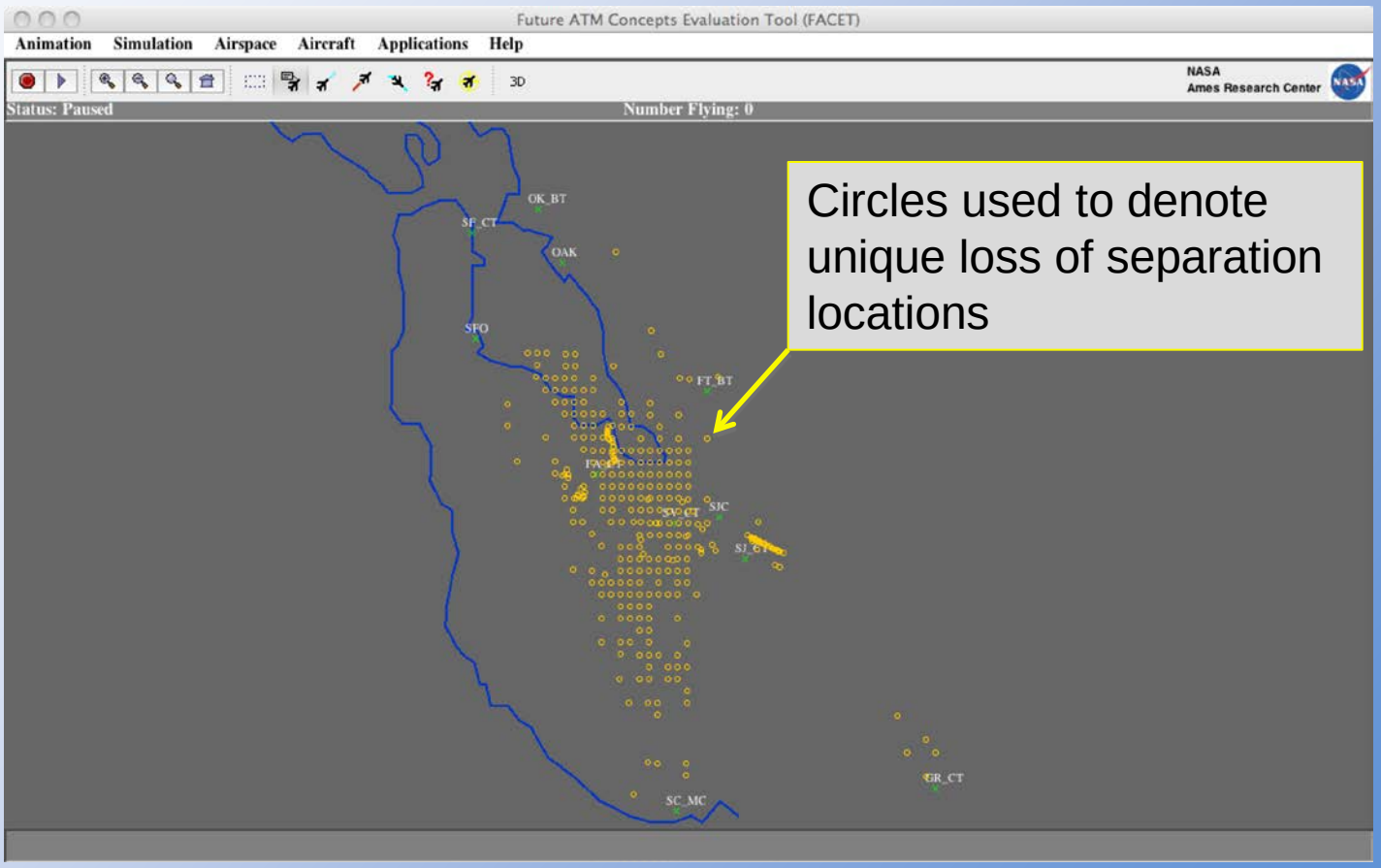
- 5K Minimum Aircraft Schedule integrated with Northern California TRACON traffic from Jan. 18, 2011
- Loss of separation assumed to be less than 3 nmi horizontal and 1,000 ft vertical
- Hopper vehicles cruising at 5,000 ft
- 990 unique events



Significant interactions with SFO and SJC arrival and departure traffic flows

Airspace Summary

Current Airspace Modeling Approach:

- Hopper vehicles fly a great circle trajectory from origin to destination
- Vehicles cruise at 5,000 ft to reduce noise impact
- Current trajectory have a significant interaction with SFO and SJC arrival and departure traffic flow

Future Airspace Modeling Enhancements:

- Optimal path planning algorithms will likely identify 4D trajectories that minimize interactions between the hopper flights and the background traffic flows
    - Vertical and horizontal trajectory changes required by the algorithm may be unrealistic for a vehicle designed for mass transit
    - Temporal changes to the trajectory may impact the schedule

Overall Findings (1/2)

- Models, tools, and processes have been created to simulate a baseline airborne commuter transportation system
  - The baseline is set to identify issues, trends, and focus; it is not an optimal system
- Rotorcraft have been designed specific to the extreme short haul routes in the system
  - conventional propulsion designs close at 6, 15, and 30 passenger
  - electric propulsion designs in the 15-30 passenger count are projected to close using +30 yr technology development;

Overall Findings (2/2)

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- Without optimizing the network topology and while servicing 24-7 ridership,
  - larger ridership drives toward a uniform fleet of 30 passenger vehicles
  - the system optimization will be driven by aircraft at-station (footprint)
  - large airspace conflict at 5k ft; lower altitude ops will have less conflict but greater community noise; trade altitude and noise
  - **have simulated up to 45k daily riders equal to CalTrain, however we are transporting them over 2.5 times the miles!**

It seems possible that extreme-short haul rotorcraft could be an element of commuter travel infrastructure. Conventional propulsion rotorcraft could be employed today. Electric propulsion will require technology development and a limited size variance of O(15-30) passengers for closed designs. There is head-room in the network design to transport thousands of daily riders.

Next Steps

- Update the BaySim demand model with more accurate demographical data
- Pare down the schedule to less than 24-7 ops
- Investigate alternate network topologies
  - consider the system as sole transport mode
  - synergize with existing commuter modes
- Design in-station operations
- Understand impact of design requirements (e.g. 20 min reserve) on design closure
- Understand airspace conflict as a function of topology

Dissemination

"Air Vehicle Design and Technology Considerations for an Electric VTOL Metro-Regional Public Transportation System"

Jeffrey Sinsay; Juan Alonso; Dean Kontinos; Shon Grabbe; John Melton; Jeremy Vander Kam

Presentation Type: Technical Paper Eligible for Student Paper Competition Session: ATIO-01, Aircraft Design, September 17

12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference

17 - 19 September 2012

Enduring Product of Study

- Electric propulsion modules added to NDARC
- New discrete event simulator created
- Aircraft and NORCAL data added to FACET
- Greater understanding of metro-regional transportation system design and network optimization

Backup

Evaluation Criteria

- For a given total ridership
  - Are fleet logistics possible?
    - Are there sufficient number of flights?
    - Do aircraft pile-up?
    - OTHER
  - Do the conceptual aircraft designs close?
  - Are the flights compatible with existing air traffic?

BaySim: Final Steps and Phase II

- Improve home and workplace distributions
- Add altitude constraints (Santa Cruz Mountains)
- Modify for Hub-and-Spoke operations
- Specialize for other Metro regions
  - New York – Philadelphia – Washington DC
  - Chicago – Milwaukee
  - Los Angeles – San Diego
- Generate Histograms

BaySim: Main Loop Pseudo Code


```
Loop RunSim()
{
    clock = clock + dt;     // dt ~ 1 second
    LOOP over flights
      Update and transition between 3 flight states;
    NEXT flight
    LOOP over passengers
      Update and transition between 12 passenger states;
    NEXT passenger
    Update queues of passengers awaiting flights;
    Update graphics and system statistics;
}
```

BaySim: PX State Pseudo Code


```
LOOP over passengers
    STATE "AtHome"
    {
            if SimClock > GoToWorkTime[i] then
                px_state[i] = "SurfaceTravelFromHome"
               end if
     }
    STATE "SurfaceTravelFromHome"
    STATE "QueuedAtHomeStation"
    STATE "QueueDelayReturningHomeFromHomeStation"
    STATE "HomeStationToWorkStation"
    STATE "SurfaceTravelToWork"
    STATE "AtWork"
    STATE "SurfaceTravelFromWork"
    STATE "QueuedAtWorkStation"
    STATE "QueueDelayReturningHomeFromWorkStation"
    STATE "SurfaceTravelFromWork"
    STATE "WorkStationToHomeStation"
    STATE "SurfaceTravelToHome"
NEXT passenger
```

BaySim: PX Queuing Pseudo Code

NARI

```
LOOP over queued O-D lists of passengers   // "PX" = passengers
   WHILE ( #_of_PX_in_O-D_queue > max_#_of_PX_per_A/C ) {
      create a new flight_event with state = "ReadyForTakeoff";
      assign PX to this flight_event;
   compute departure time based on the greater of ( the time due to loading and pushback ) OR ( next available
     departure time for this origin station );
      remove PX from O-D queue;
         compute next available departure time slot for this origin station;
     }
     IF [ (#_of_PX_in_O-D_queue > required_LoadFactor * max_#_of_PX_per_A/C ) OR (#_of_PX_in_O-D_queue > 1
     AND avgQueueWait > 0.5 hrs ) ] {
     create a new flight_event with state = "SeatsAvailable";
      assign PX to this flight_event;
   compute departure time based on the greater of ( the time due to loading and   pushback ) OR ( next available
     departure time for this origin station )
      remove PX for O-D queue;
         compute next available departure time for this origin station;
     }
NEXT O-D queue list
```

BaySim Flight State Transitions

NARI

Flight State: flight_State[i]	*Next State*	Transition Condition	Notes
SeatsAvailable	ReadyForTakeoff	SimClock > DepartureTime, #PX == TotalSeats	Load passengers from queue up until departure time, being careful to assure adequate boarding time
ReadyForTakeoff	EnRoute	SimClock > DepartureTime	PX loaded, awaiting scheduled departure time
EnRoute		p_foundARide[i] == true	Queued at the departure node, queue meets load factor requirements for departure flight, load/departure time delay has passed

BaySim Passenger State Transitions

NARI

Passenger State: px_State[i]	Next State	Transition Condition	Notes
AtHome	SurfaceTravelFromHome	SimClock >= p_DayStart[i] + 0.5 * Math.random()	Leave home for work after a certain time each day
SurfaceTravelFromHome	QueuedAtHomeStation	p_distToGo[i] <= 0	Travel from home to the departure node
QueuedAtHomeStation	HomeStationToWorkStation	p_foundARide[i] == true	Queued at the departure node, queue meets load factor requirements for departure flight, load/departure time delay has passed
QueuedAtHomeStation	QueueDelayReturningHomeFromHomeStation	SimClock - p_QueueStartTime[i] > p_GoBackHome[i]	Exceeded time limit for finding a flight after queueing at node, decide to return home
QueueDelayReturningHomeFromHomeStation	AtHome	p_distToGo[i] <= 0	Destination is home, surface transport
HomeStationToWorkStation	SurfaceTravelToWork	p_distToGo[i] <= 0	Fly between nodes (home to work), Arrival delay has passed
SurfaceTravelToWork	AtWork	p_distToGo[i] <= 0	Travel to workplace from arrival node
AtWork	SurfaceTravelFromWork	SimClock >= p_WorkUntil[i]	Stay at workplace for a predefined time
SurfaceTravelFromWork	QueuedAtWorkStation	p_distToGo[i] <= 0	Travel from workplace back to arrival node
QueuedAtWorkStation	WorkStationToHomeStation	p_foundARide[i] == true	Queued at the arrival node, queue meets load factor requirements for return flight, Departure time delay has passed
QueuedAtWorkStation	QueueDelayReturningHomeFromWorkStation	SimClock - p_QueueStartTime[i] > p_GoBackHome[i]	Exceeded time limit for finding a flight after queueing at node, decide to return home via ground transport
QueueDelayReturningHomeFromWorkStation	AtHome	p_distToGo[i] <= 0	Surface travel from arrival node back to home
WorkStationToHomeStation	SurfaceTravelToHome	p_distToGo[i] <= 0	Fly between nodes (work to home), unload /arrival delay has passed
SurfaceTravelToHome	AtHome	p_distToGo[i] <= 0	Travel from the departure node back to home

BaySim: PX Queuing and Departure

- Flights restricted to max # departures per hour from a single node
- Flights receive departure time once minimum load factor is met or 2+ PX have been waiting more than 30 minutes
- Passengers are allowed to fill partial flights up until scheduled departure time

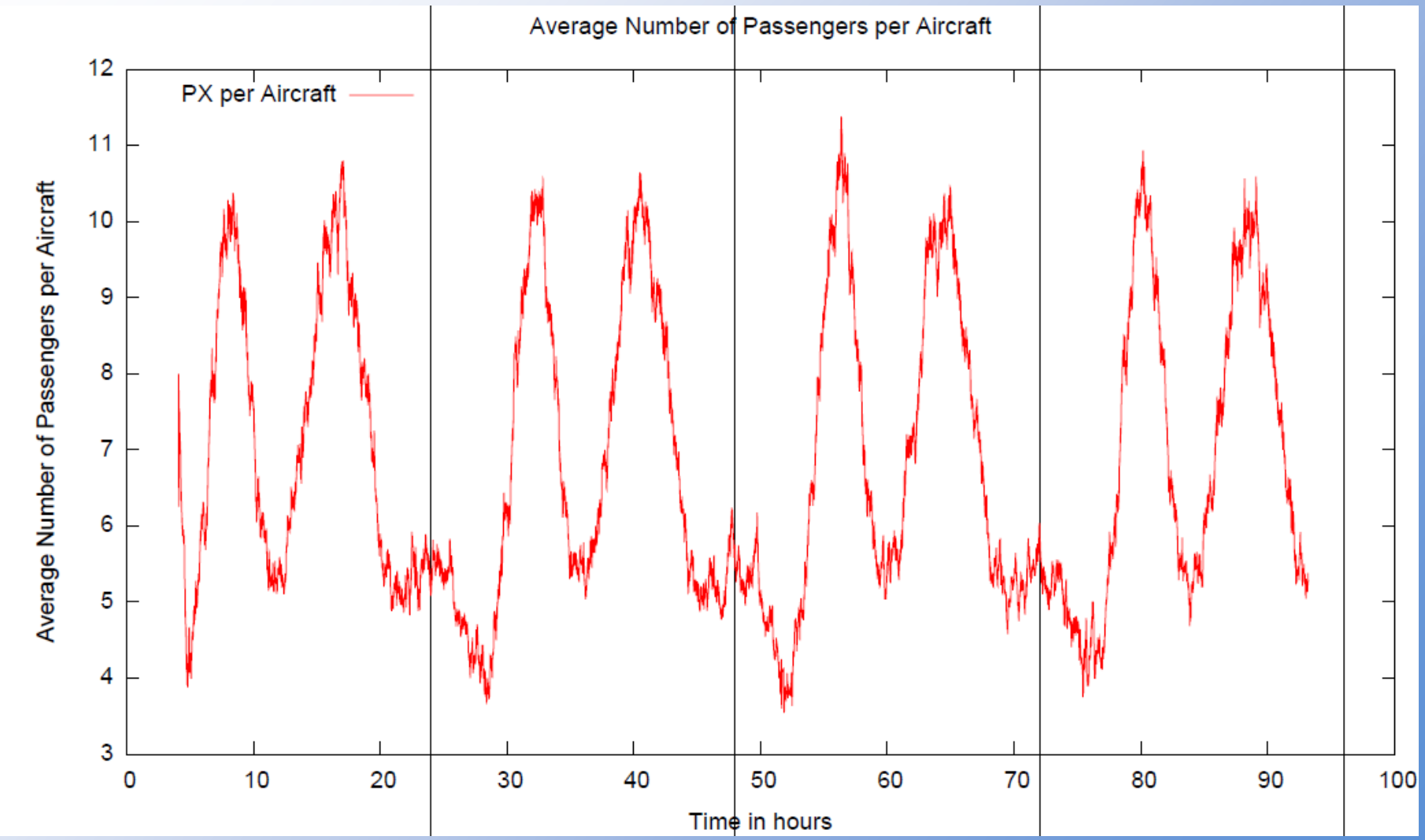
BaySim: Departure Pseudo Code

NARI

```
LOOP over flights
   STATE "ReadyForTakeoff"
     …
   STATE "SeatsAvailable"
     IF ( clock + dt >= flightDepartureTime[i] ) {    // departure at next timestep
       flightState[i] = "ReadyForTakeoff";
     }
       ELSE
       {
          IF new passengers have come into the queue for this flight O-D pair {
             IF there is time available for boarding {
                compute number of passengers that can be loaded before pushback;
                   add these passengers to the flight and remove them from the queue;
             }
             IF the flight is now full {
                flightState[i] = "ReadyForTakeoff";
             }
          }
       }
   STATE"EnRoute"
     …
NEXT flight
```

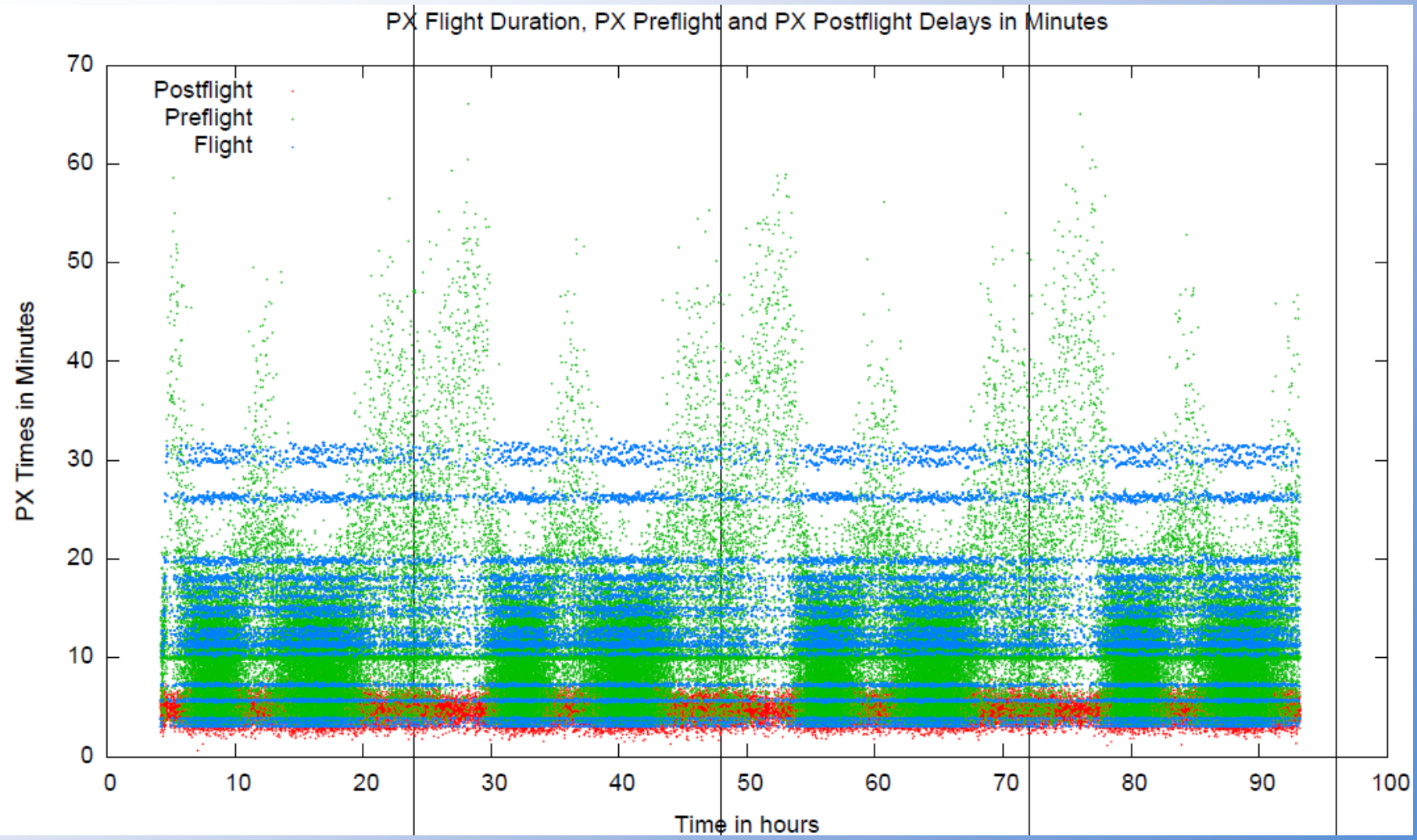
BaySim: Sample Plots

NARI



BaySim: Sample Plots

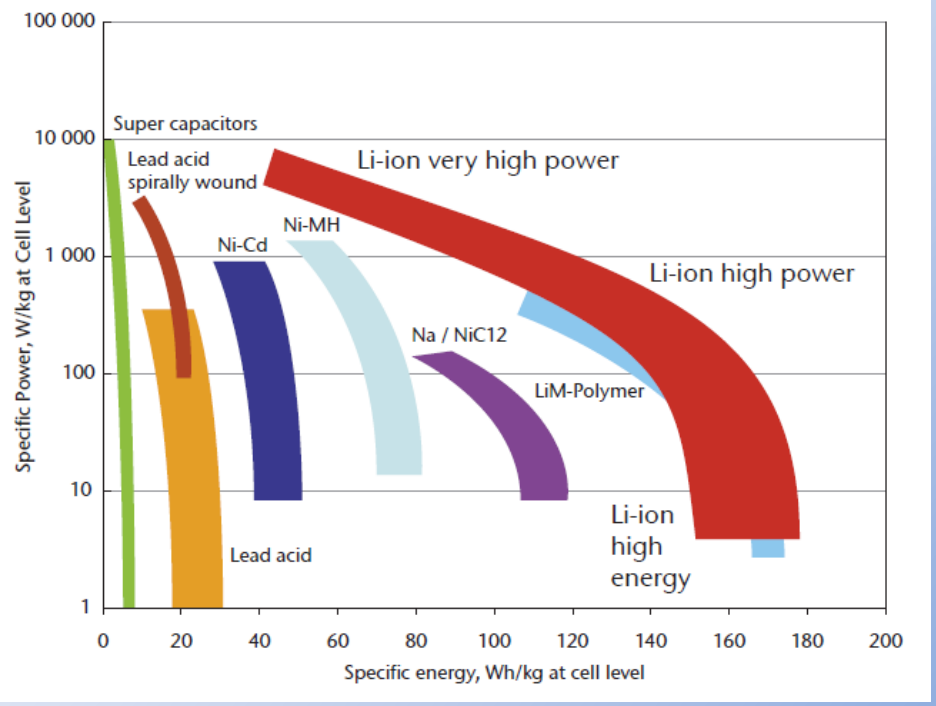
NARI



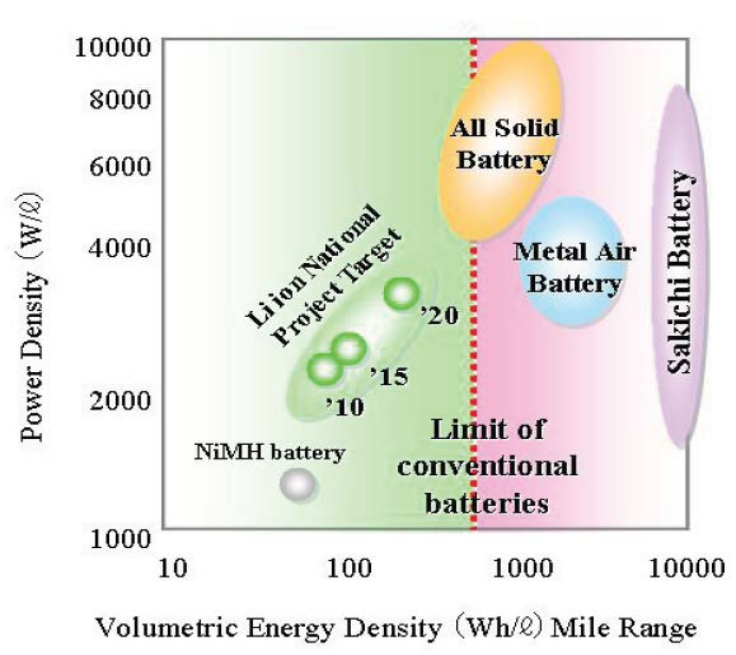
Energy Storage (EV/PHEV)

NARI

- Energy storage significant technical challenge
  - Need improvements in specific power, specific energy, and volumetric energy density
  - Automotive industry driving innovation for electric vehicles & plug-in hybrids
- Secondary considerations also impact battery chemistry viability
  - Cost - Volatility
  - Discharge characteristics - Charge/Recharge Cycle Life



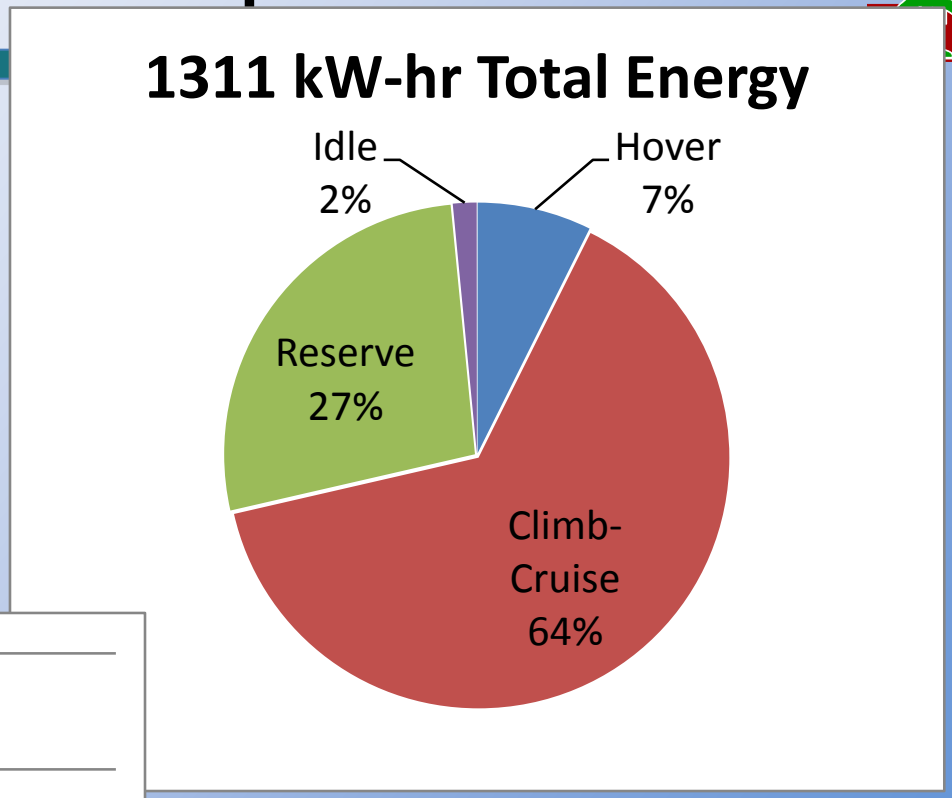
Source: International Energy Agency EV/PHEV Technology Roadmap June 2011

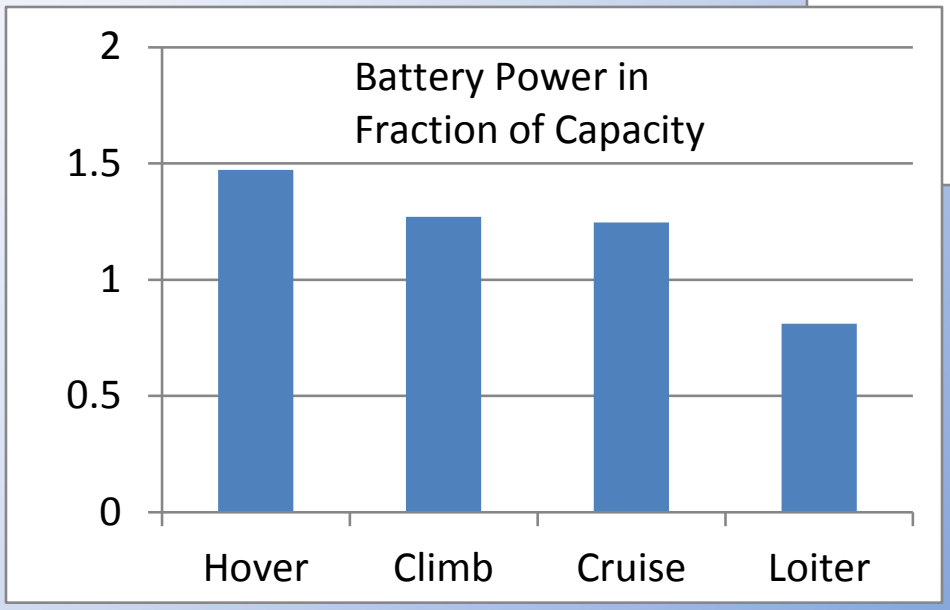


Source: SAE Paper 2011-39-7233

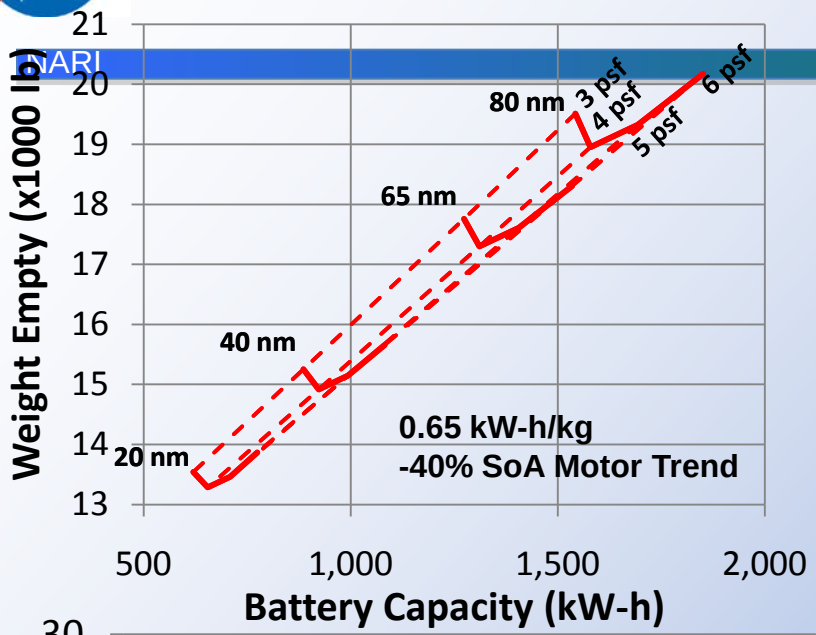
Power Consumption

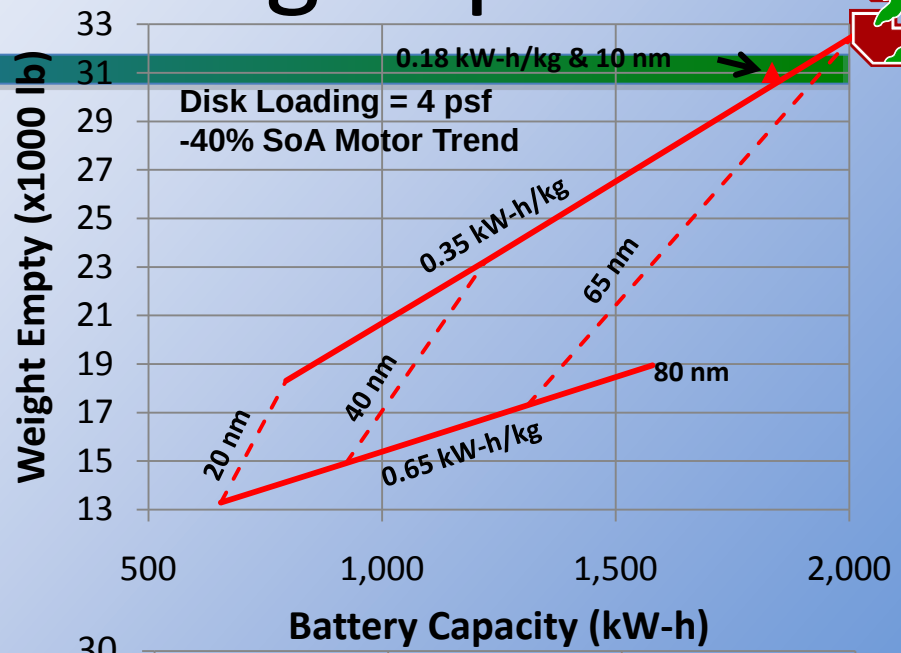
NARI

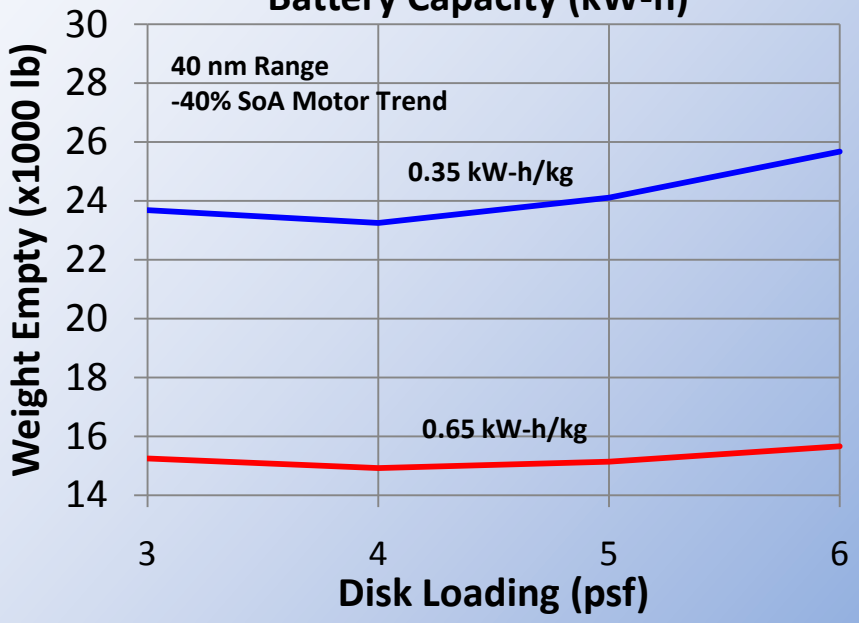


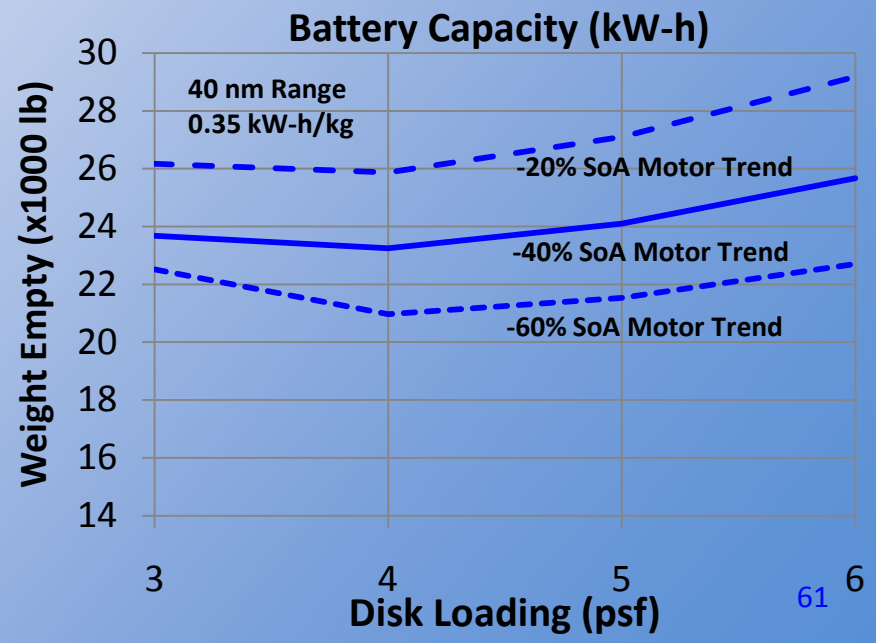


Electric Tandem Design Space









Electric Propulsion Model

NARI

- 0th order energy model
  - Size components for peak power event (Hover)
  - Integrate aircraft power required on profile
  - Determine required stored energy
    - Based on component efficiencies
    - Easily handles variety of propulsion topologies
    - Component efficiencies assumed constant

$$\bar{P}_i^{src} = \frac{\sum \bar{P}_{i,j}^{\text{rotor}} + \bar{P}_i^{\text{acc}}}{\sum_{\forall j} \eta_j}$$

$$E_{\text{miss}} = \sum_i^N \bar{P}_i^{\text{src}} \Delta t_i$$

$\bar{P}_i^{\text{acc}}$: i^{th} segment average accessory power

$\bar{P}_{i,j}^{\text{rotor}}$: i^{th} segment average power jth rotor

$\bar{P}_i^{src}$: i^{th} segment average source power

η_j: j^{th} component efficiency

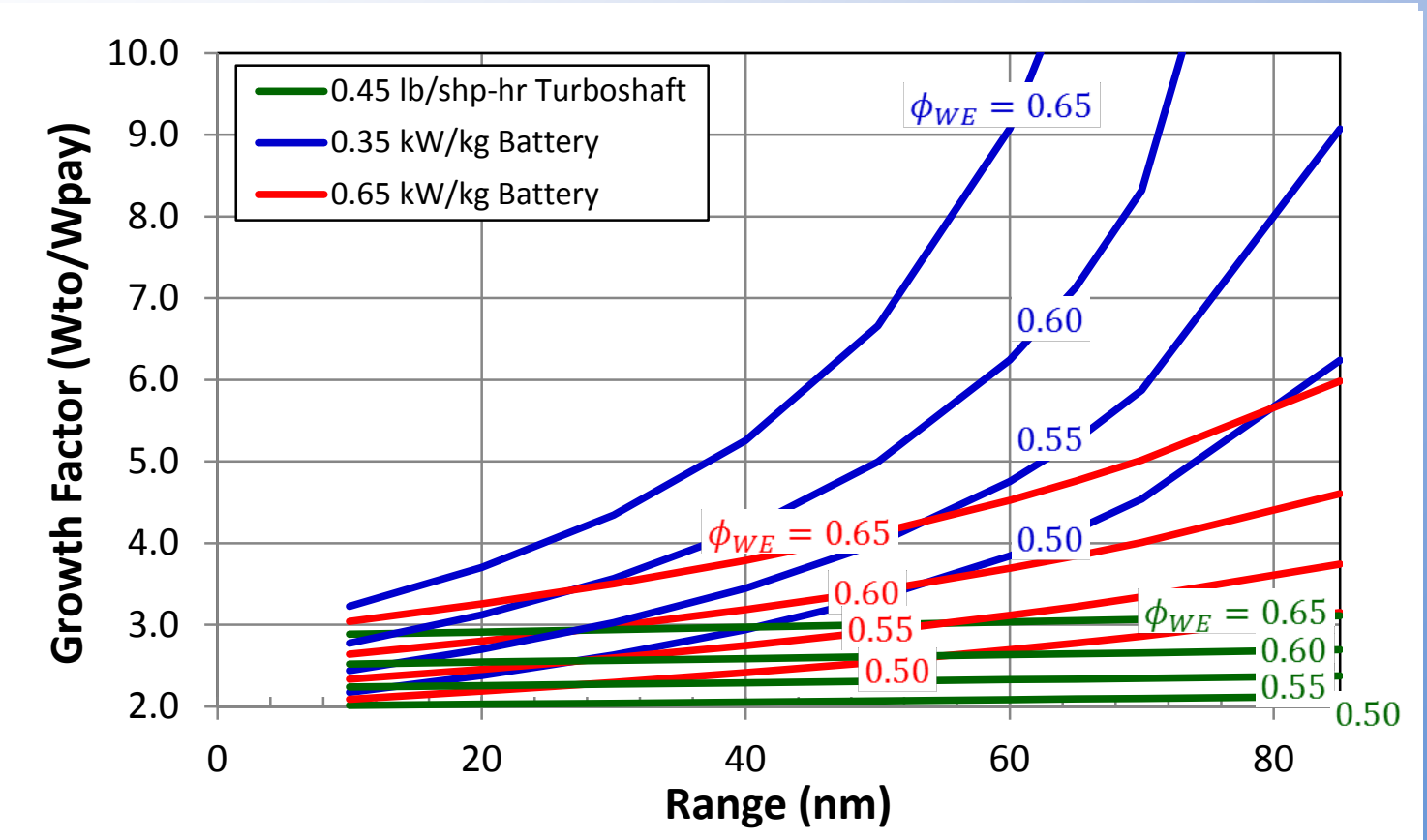
Δt_i: i^{th} segment time

$\eta_{batt} \sim 0.98$

$\eta_{motor} \sim 0.95$

$H_{pwr\text{-}dist} \sim 0.97$

Vehicle Size Driven by Growth Factor



$$\frac{W_{to}}{W_{pay}} = \frac{1}{1 - \phi_{WE} - \phi_{fuel/batt}}$$

$$\phi_{batt} \propto \frac{R}{L/De\eta_{pwr}\rho_{batt}}$$

$$\phi_{fuel} \propto 1 - \exp\left(\frac{-R * sfc}{L/De}\right)$$

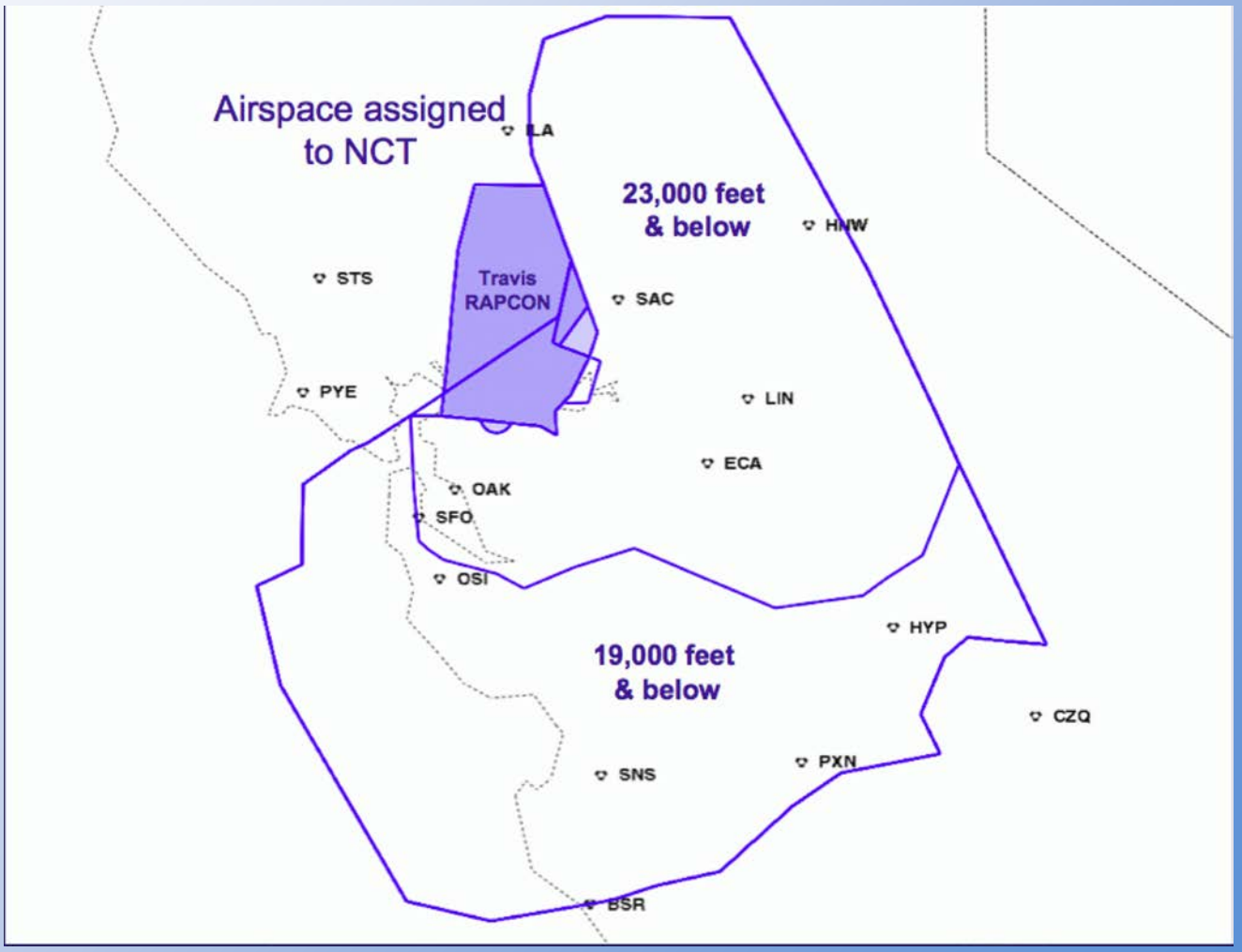
Way Forward

- Examine remaining power system topologies
- Complete sizing of 6 & 15 passenger electric rotorcraft
- Trade-offs in rotor RPM, gearing & motor sizing required higher fidelity rotor & motor models
  - Hover/cruise rotor optimization
    - Potential of variable speed for performance / acoustics
    - Direct drive vs. gearbox
  - Electric motor torque & efficiency behavior
- Quantify community noise
- Consideration of economic factors
  - Propulsion $/lb
  - Reliability, maintainability, repairability

Airspace: Northern California TRACON (NCT)

NARI

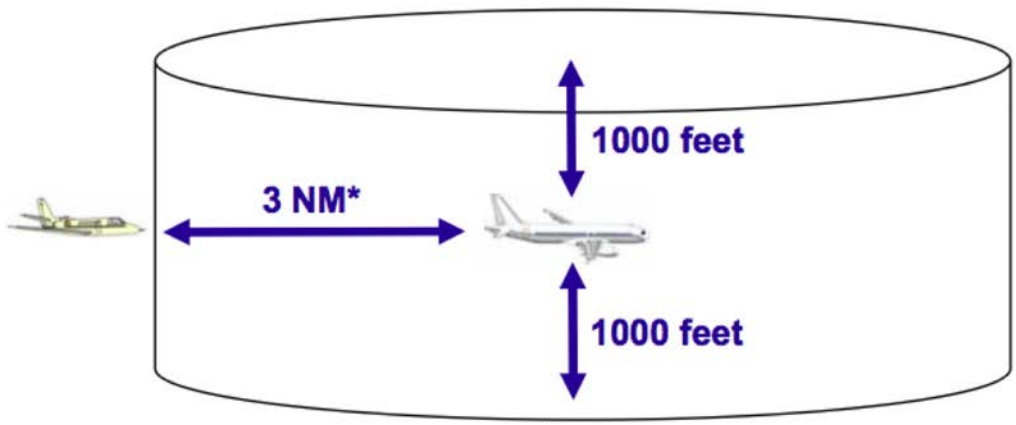
- Hopper vehicles initially designed to operate within the Northern California TRACON (NCT)
- NCT handles major arrival and departure flows to San Francisco, Oakland, San Jose and Sacramento



Airspace: Separation Standards

NARI

- TRACON Instrument Flight Rules (IFR) separation standards initially used to detect potential losses of separation between historical NCT traffic and simulated hopper traffic
- Standards are likely too restrictive but are useful for examining the worst-case-scenario



* 5NM when operating behind a "heavy jet" (B747, B767, B777, MD11, A380 for examples), 40NM or more from the radar antenna, or when using multiple (mosaic) radar data sources.

Schedule Summary

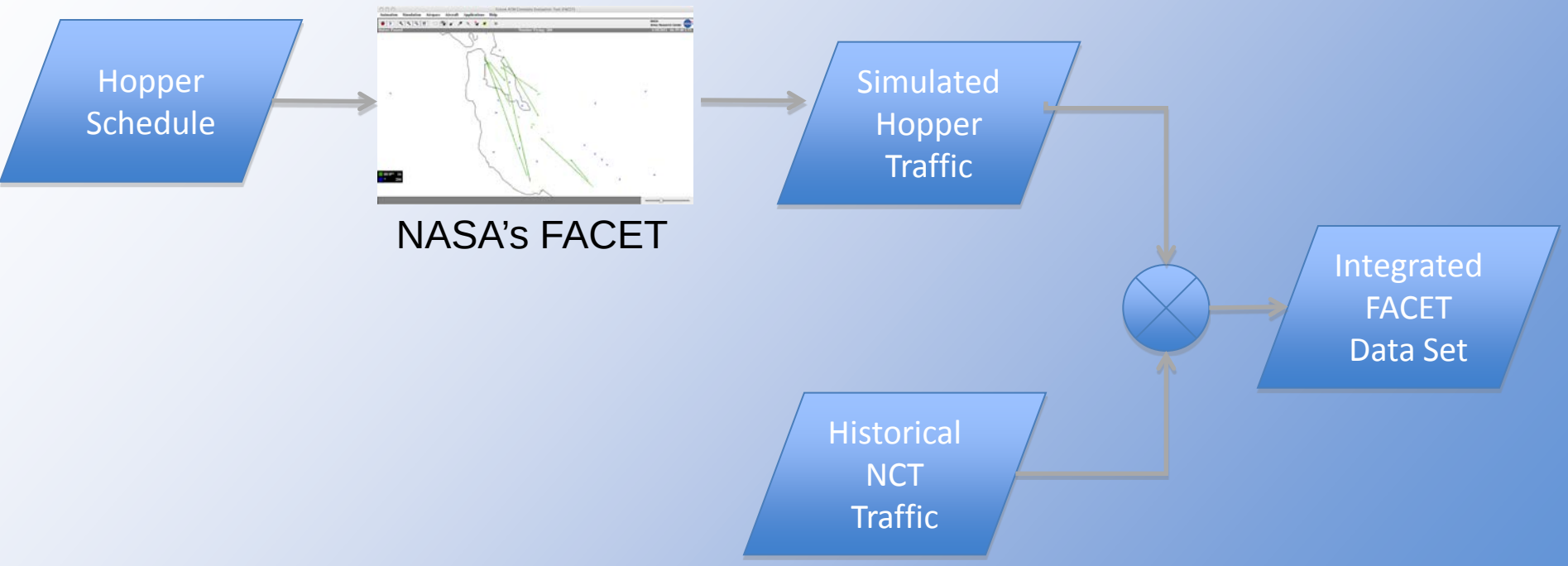
- Preliminary results show emerging trends
  - Vehicle size distribution
  - A small number of repositioning flights can drastically reduce fleet size
  - As ridership increases, station footprint must be managed effectively
- Additional fidelity in scheduling model will be needed to assess business case scenarios

Future Work

- Schedule modifications to improve system efficiency
  - Changes in the structure and scheduling
  - Combine flights,
  - Remove low capacity flights
- Tail assignment in addition to fleet assignment to formulate actual schedules
- Explicit inclusion of space and noise requirements
- Further economic analysis will inform many outstanding issues

Airspace: Integrating Hopper Traffic with Historical Traffic Flows

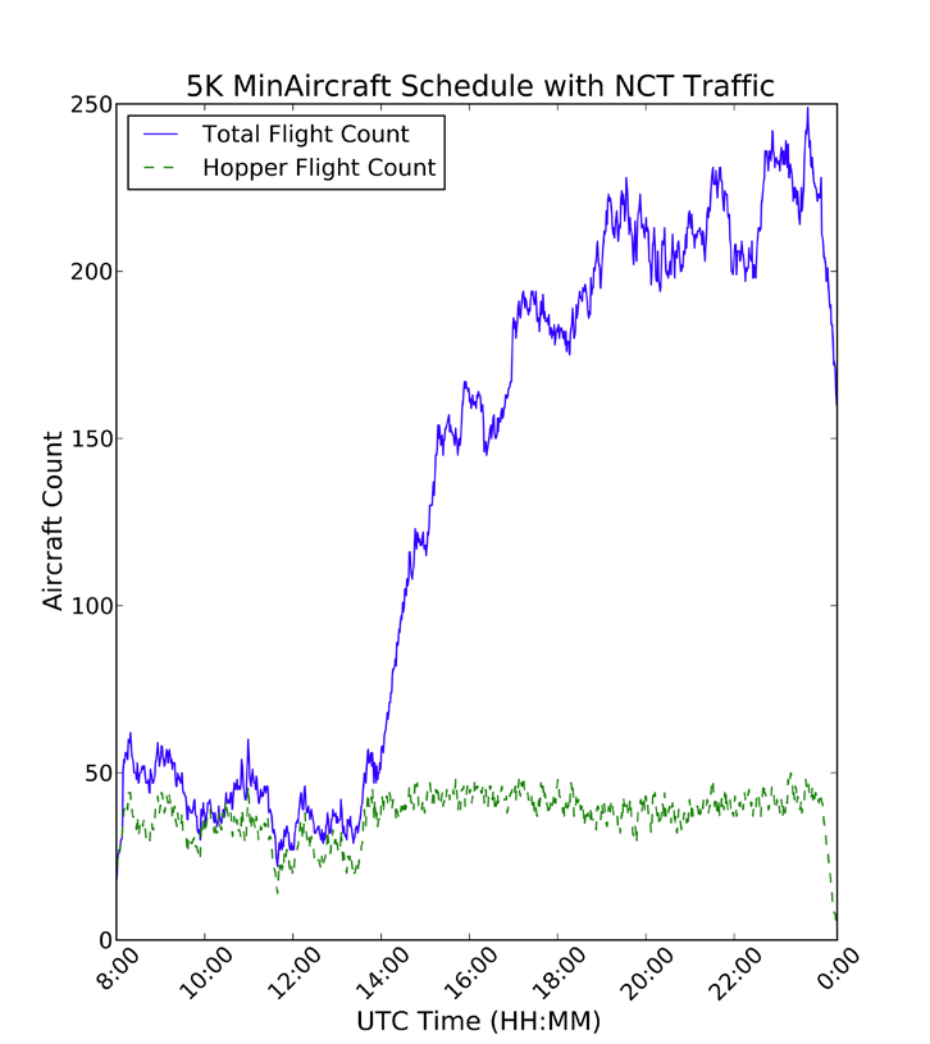
NARI



Airspace Results: Aircraft Counts

NARI

5K Minimum Aircraft Schedule integrated with Northern California TRACON traffic from Jan. 18, 2011



June 2011 DOE Transportation Energy Data Book

http://cta.ornl.gov/data/index.shtml

Great care should be taken when comparing modal energy intensity data among modes. Because of the inherent differences among the transportation modes in the nature of services, routes available, and many additional factors, it is not possible to obtain truly comparable national energy intensities among modes. These values are averages, and there is a great deal of variability even within a mode.

Table 2.12
Passenger Travel and Energy Use, 2009

	Number of vehicles (thousands)	Vehicle-miles (millions)	Passenger-miles (millions)	Load factor (persons/vehicle)	Energy intensities (Btu per vehicle-mile)	Energy intensities (Btu per passenger-mile)	Energy use (trillion Btu)
Cars	**134,880.0**	**1,606,815**	**2,490,564**	**1.55**	**5,484**	**3,538**	**8,811.0**
Personal trucks	**88,683.4**	**934,631**	**1,719,722**	**1.84**	**6,740**	**3,663**	**6,299.4**
Motorcycles	**7,929.7**	**20,800**	**24,128**	**1.16**	**2,854**	**2,460**	**59.4**
Demand response[a]	**68.9**	**1,529**	**1,477**	**1.0**	**15,111**	**15,645**	**23.1**
Buses	[b]	[b]	[b]	[b]	[b]	[b]	**200.0**
Transit	65.4	2,345	21,645	9.2	39,160	4,242	91.8
Intercity[c]	[b]	[b]	[b]	[b]	[b]	[b]	31.4
School[c]	683.7	[b]	[b]	[b]	[b]	[b]	76.9
Air	[b]	[b]	[b]	[b]	[b]	[b]	**1,751.4**
Certificated route[d]	[b]	5,453	541,646	99.3	280,734	2,826	1,530.8
General aviation	223.9	[b]	[b]	[b]	[b]	[b]	220.6
Recreational boats	**13,290.7**	[b]	[b]	[b]	[b]	[b]	**245.7**
Rail	**20.7**	**1,402**	**36,150**	**25.8**	**66,916**	**2,594**	**93.8**
Intercity (Amtrak)	0.3	283	5,914	20.9	50,924	2,435	14.4
Transit	13.5	775	19,004	24.5	61,663	2,516	47.8
Commuter	6.9	344	11,232	32.7	91,936	2,812	31.6

5K: 15,900 BTU/PX-mile 15K: 10,700 BTU/PX-mile 45K: 6,110 BTU/PX-mile

5.1 PX/vehicle 7.5 PX/vehicle 13.2 PX/vehicle