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National Institute for Aerospace
Task: NIA/NNL13AA08B

Demand Forecast Model Development
Scenario Generation for Urban Air Mobility Concepts

UAM Aircraft and Landing Site Cost Models

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Objectives

- Present cost models to study UAM operations and demand
  - **UAM vehicle cost model**
    - UAM development cost model
    - UAM life-cycle operations cost model
  - **UAM landing site cost model**
  - UAM landing site operation model
    - Estimates UAM landing capacity

UAM Aircraft Cost Analysis Workflow

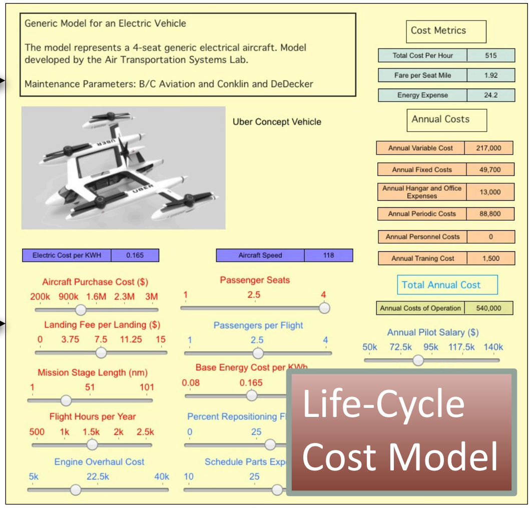
UAM Landing Site Cost Model

UAM design process considers:

- Aircraft range
- Payload
- Battery life
- Wing loading
- Maximum speed
- Aircraft size for vertiport compatibility

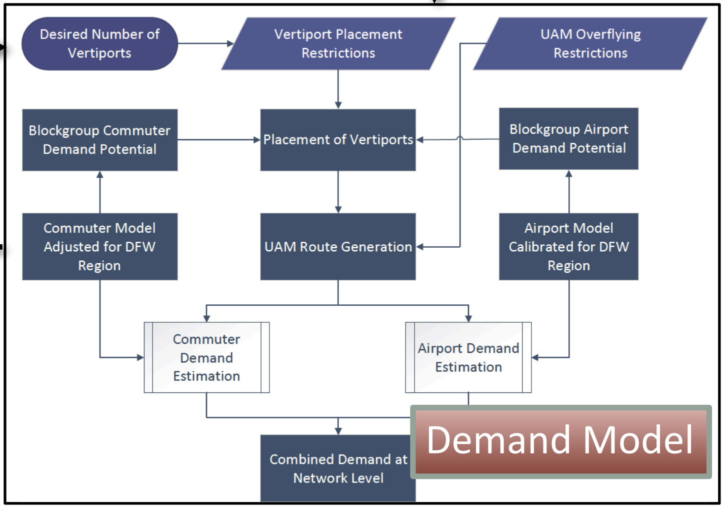
Aircraft cost development model (CER equations)

UAM Unit Cost



Cost per passenger-mile

Airspace Restrictions in Urban Areas



Output information from VT Model

- UAM commuter demand
- UAM airport demand
- UAM cargo demand
- UAM flight routes

Feedback

Aircraft Cost Development Model

- Nicolai and Raymer's cost categories
  - Airframe engineering
  - Development and support
  - Flight testing
  - Engines
  - Avionics
  - Manufacturing labor
  - Material and equipment
  - Tooling
  - Quality control
  - Test facilities

Example of cost-estimating equations

$$E = k_1 W^{c_1} S^{c_2} Q^{c_3}$$

E = Cumulative engineering hours (hrs)

W = aircraft empty weight in pounds

S = aircraft maximum speed (knots) at best altitude

k_1, c_1, c_2, c_3 are calibration constants

Q = UAM vehicles produced

- Model uses L. Nicolai's cost relationships adapted from the DAPCA IV model
- **Adaptations made to model battery, engine, and avionics costs for UAM application**
- Learning curves are different for different activities in the aircraft development cycle

Sources of model equations:

Nicolai, L. and Carichner, G., Fundamentals of Aircraft and Airship Design, American Institute of Aeronautics and Astronautics, 2010

Raymer, D.P., Aircraft Design: A Conceptual Approach, American Institute of Aeronautics and Astronautics, 2018

Functional Form of Cost-Estimating Relationships (CERs)

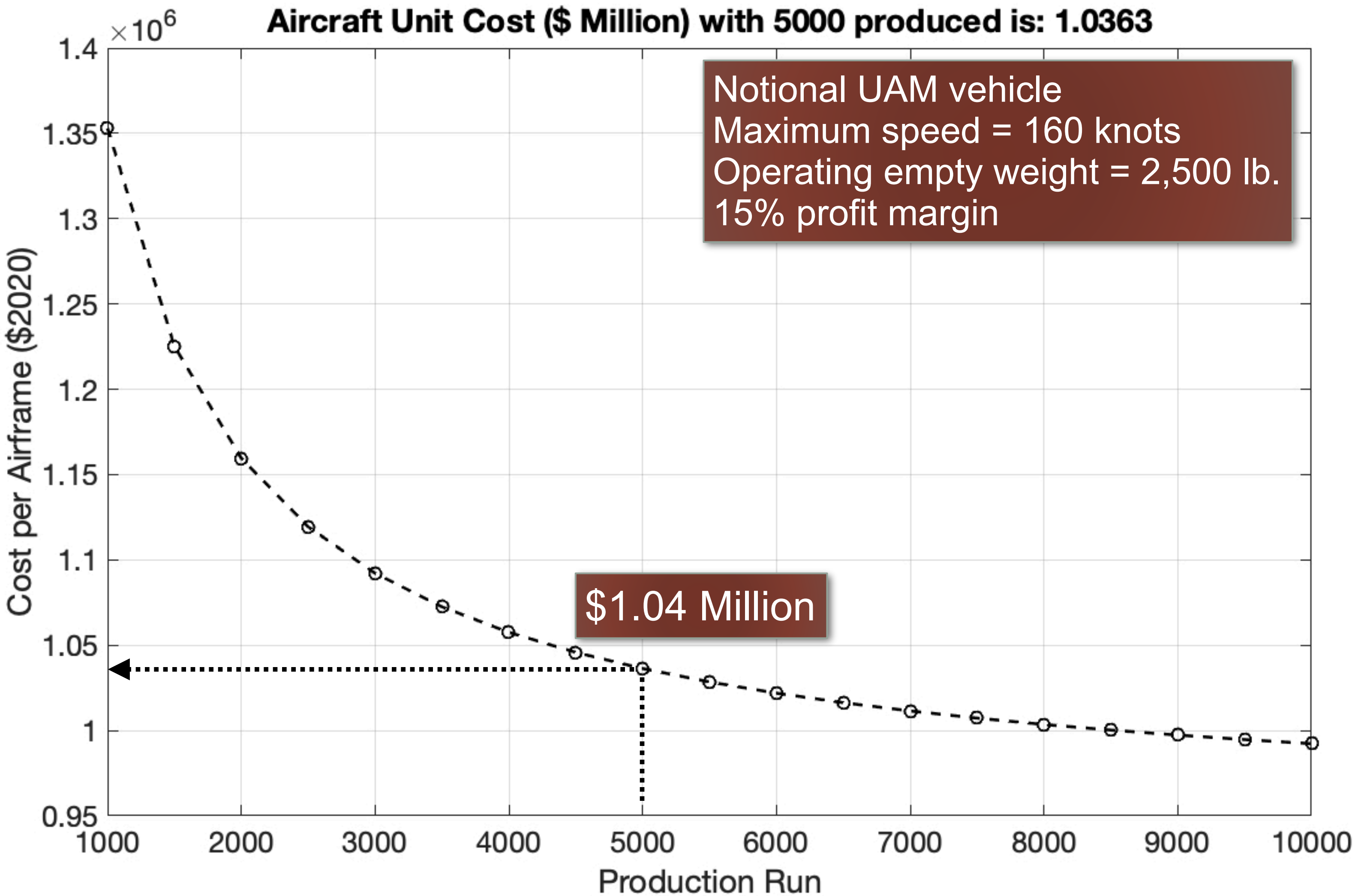
- **Empty weight** (equations in original RAND report use AMPR - American Manufacturer Planning Report) (W) in pounds
  - Nicolai adapted the equations to introduce W as the aircraft empty weight
- **Maximum speed** at best altitude (S) in knots
- **Aircraft quantity produced** (Q)

- Hourly rates are estimated using US Dept. of Labor data and includes:
  - direct labor
  - administrative cost
  - overhead
  - miscellaneous

Activity	Hourly Rate ($2020)	Hourly Rate ($1998)
Engineering	145.5	88.8
Tooling	157.7	94.2
Quality Control	140.0	82.8
Manufacturing	126.3	75.4

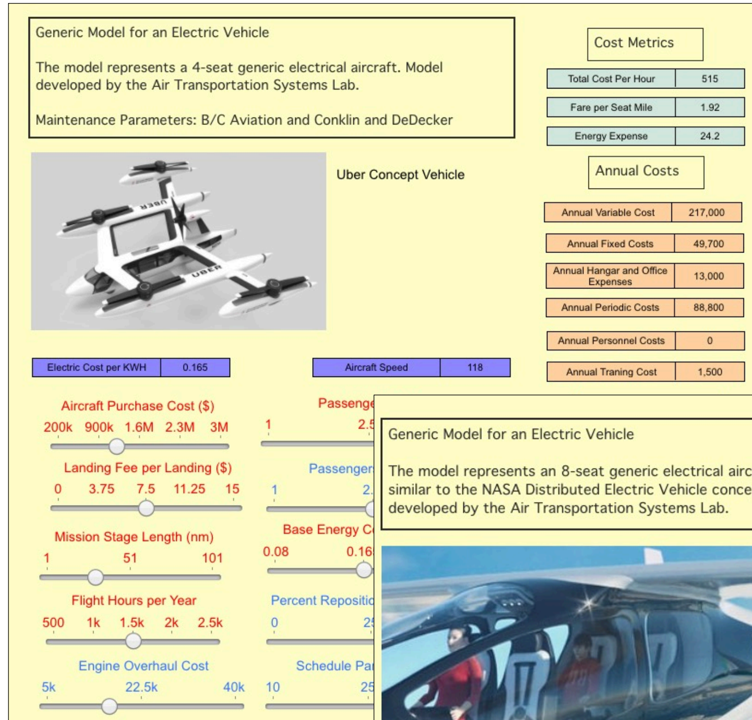
Source: Nicolai - Year 1998 is the baseline year of equations

Application to UAM Vehicle Development Cost

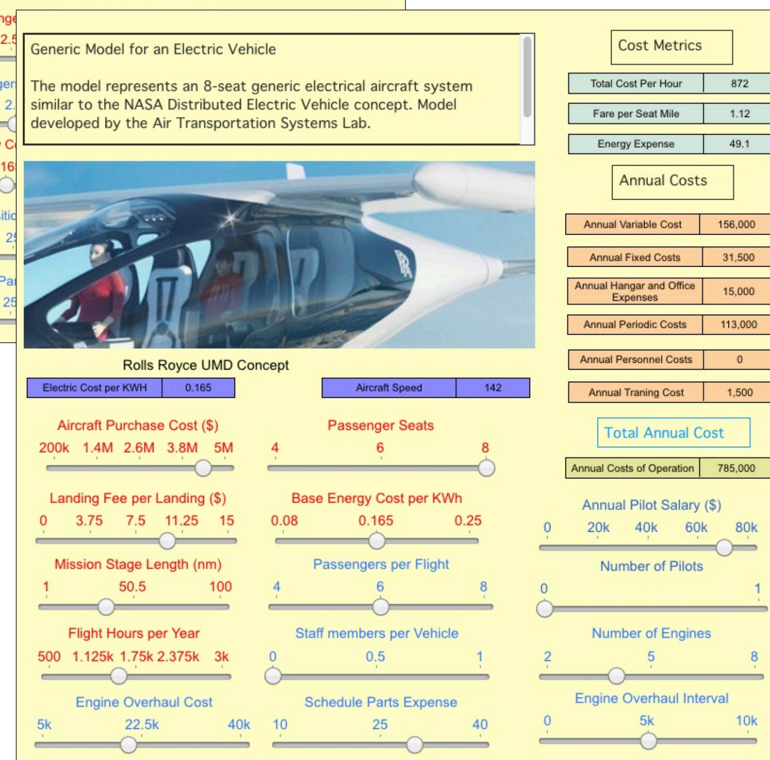


Developed Two UAM Vehicle Life Cycle Cost Models

- Models estimate average fares to be paid by commuter travelers considering eight costs groups
- Cost groups are consistent with cost estimates by Conklin and deDecker and ARGUS group
  - 4-Seat UAM transport
  - 8-Seat Air Metro aircraft concept
- Vehicle characteristics
  - Four electric engines
  - High time between maintenance actions (TBO)
  - Automated or piloted operation
- Models developed in STELLA (a framework software to develop Systems Dynamics models)



Four-passenger UAM cost model interface



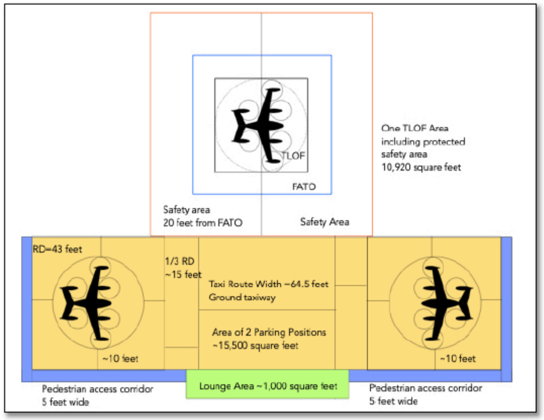
Eight-passenger UAM cost model interface

UAM Aircraft Life Cycle Cost Model Information

- UAM aircraft life-cycle cost model include the following:
  - Vehicle unit cost
  - Number of annual operations
  - Maintenance hours per flight hour
  - Engine overhaul costs
  - Time between overhauls
  - Landing fee per landing
  - Percent of repositioning flights
  - Energy consumption performance (vs. block speed)
  - Energy cost ($/kW-hr)
  - Hangar cost
  - Pilot vs no pilot switch
  - Avionics and interior refurbishing costs
  - Load factor per flight
  - Depreciation index
  - Life-cycle time

Urban Air Mobility (UAM) Landing Site Feasibility and Fare Model Analysis

Volume 2: Model Analysis with Prescribed UAM Demand Levels



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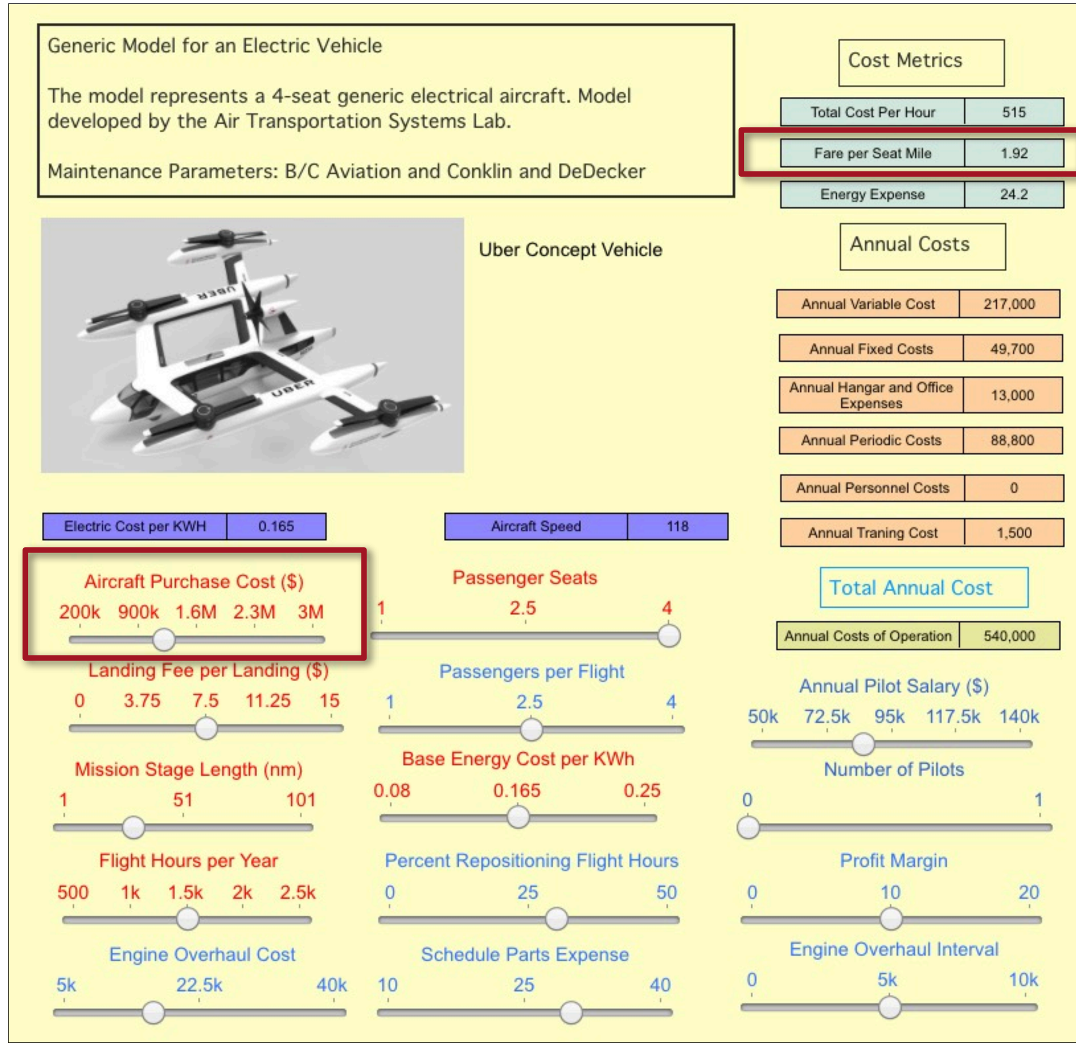
Air Transportation Systems Laboratory, Virginia Tech
May 1, 2020

More information in the report

4-Seat UAM Baseline Cost of $1.92 per Passenger Mile

- **Aircraft cost 1.04 million dollars per aircraft**
- Aircraft seats = 4
- No pilot (automation cost ~$160,000)
- Energy cost = 0.165 per kWh
- Aircraft utilization - 1,500 hours annually
- Average stage length 30 statute miles
- Number of engines = 4
- Overhaul engine cost = $16,500 per engine
- Overhaul interval = 5,000 hours
- Maintenance hours per flight hour = 0.9 (baseline)
- Landing fee = $7.5 per landing
- Maintenance cost per hour = $108
- **Load factor = 62.5%**
- **Percent repositioning flights = 30%**

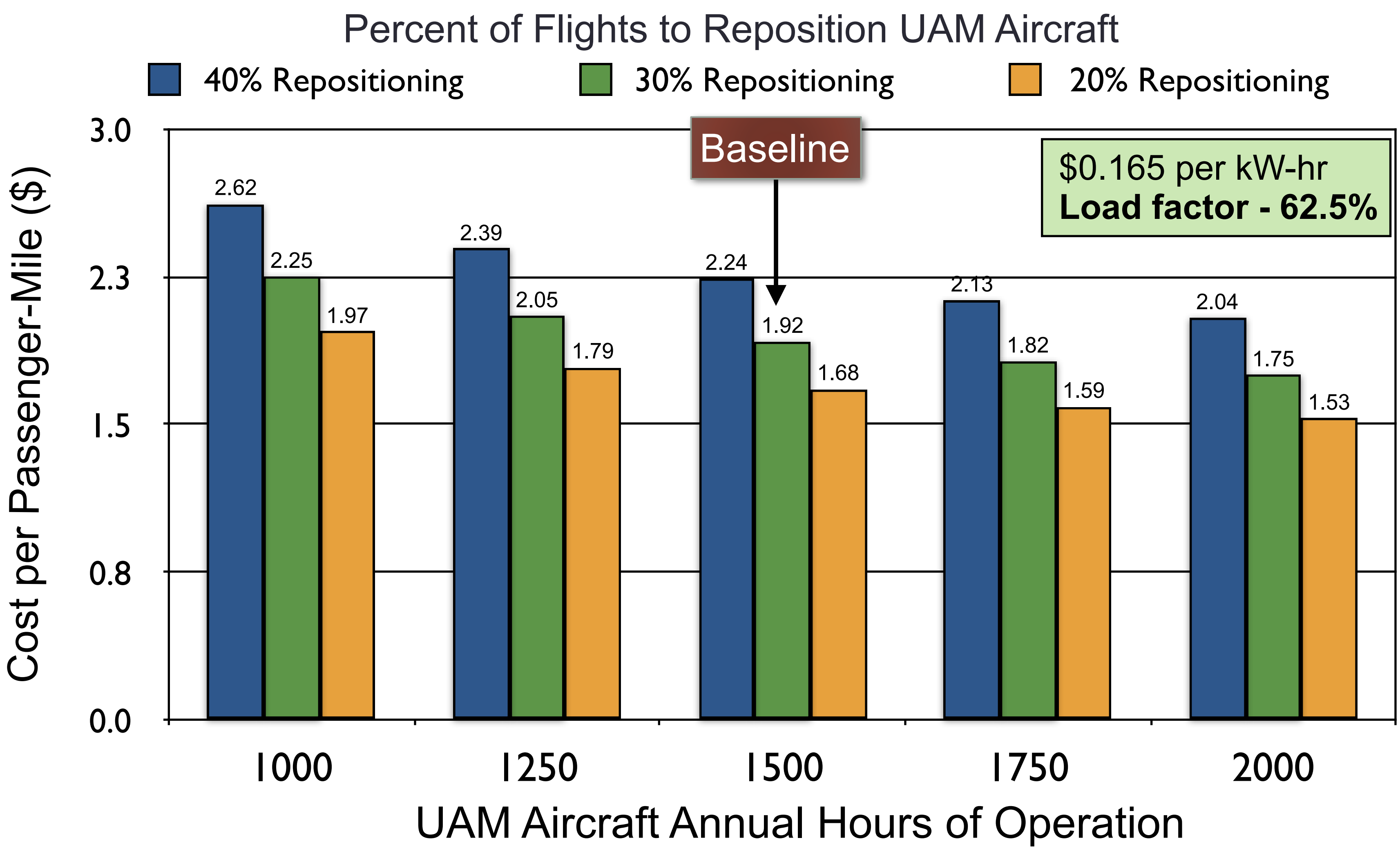
- **Example: $515 per hour of operation**



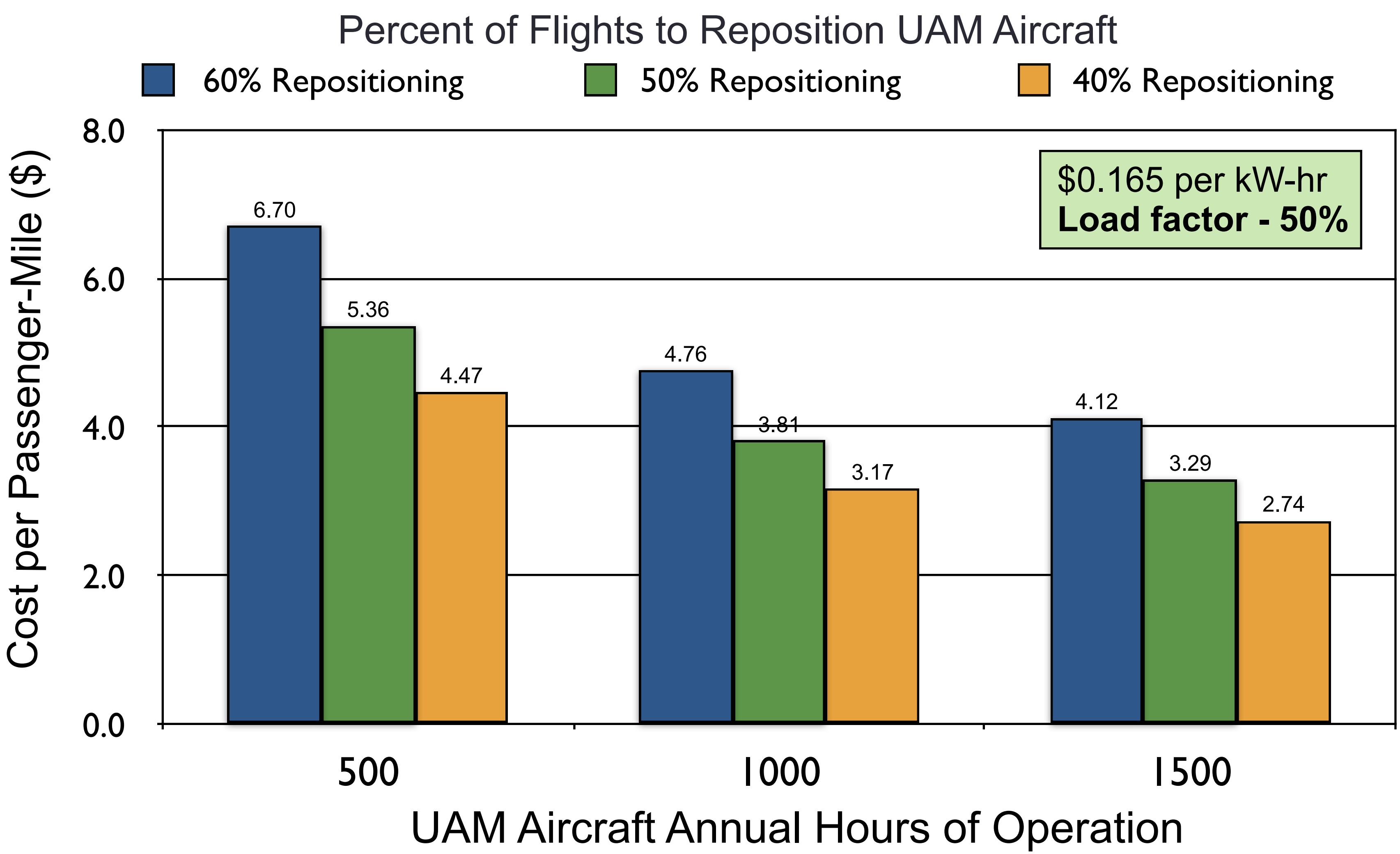
UAM Aircraft Life Cycle Cost Model Assumptions

Parameter	Value	Remarks
Aircraft Cost	$1.04 Million	Uses basic CER equations adapted from Nicolai and Carichner (2010)
Annual Operating Hours	1500	Typical operating hours of corporate jets is 450 hour/year Typical operating hours for commercial aircraft vary from 3,300 to 4,500 hrs./year
Number of Engines	4	Assumes a multi-rotor concept aircraft for added safety
Engine Overhaul Cost	$16,500	Overhaul costs for light turbine aircraft range from $100,000 to $175,000
Engine Overhaul Interval (TBO)	5,000 hrs.	Normal piston engine TBO is 2,000 hrs. Light turboprop engine TBO is 3,500 hrs.
Landing Fee per Landing	$7.5 per landing	$15 per landing typically needed for breakeven cost at the typical landing site
Schedule Parts Expense	$30/hr.	40% below allowance for light GA aircraft
Maintenance Hours per Flight Hour	0.9	45% lower than light helicopters
Maintenance Labor Expense	$108/hr.	Conklin and de Decker (2019)
Load Factor	62.5%	Assumed for commuter operations
Percent of Flights to Reposition Aircraft	30%	Initial estimate (a parameter in model)
Energy Cost	$0.165/kW-hr	Average commercial U.S. rates
Energy Used per Hour	Varies according to distance flown 180 to 85 kW-hr	Virginia Tech calculations based on reference vehicle provided by Georgia Tech
Pilot	None	Automated aircraft $75,000 automation cost
Typical Flight Distance	30 statute miles	Estimated from UAM demand model
Hull Insurance Rate /year	0.025	Percent of the aircraft cost
Liability Insurance /year	0.010	Percent of the aircraft cost
UAM Aircraft Block Speed	Varies according to distance (85 to 130 knots)	Assumes a 150-knot maximum operational cruise speed
Battery Replacement Cost	$30,000	Virginia Tech estimate
Battery Replacement Interval	1,500 hrs.	Virginia Tech estimate
Hangar and Storage Space Rental	$8,000/year	
Avionics and Interior Modernization	$15,000	Typical for small aircraft
Avionics and Interior Modernization Interval	3,000 hrs.	Typical for corporate jets
Profit Margin	10%	

Four-Seat UAM Vehicle Economics: High Utilization and Moderate Number of Repositioning of Flights

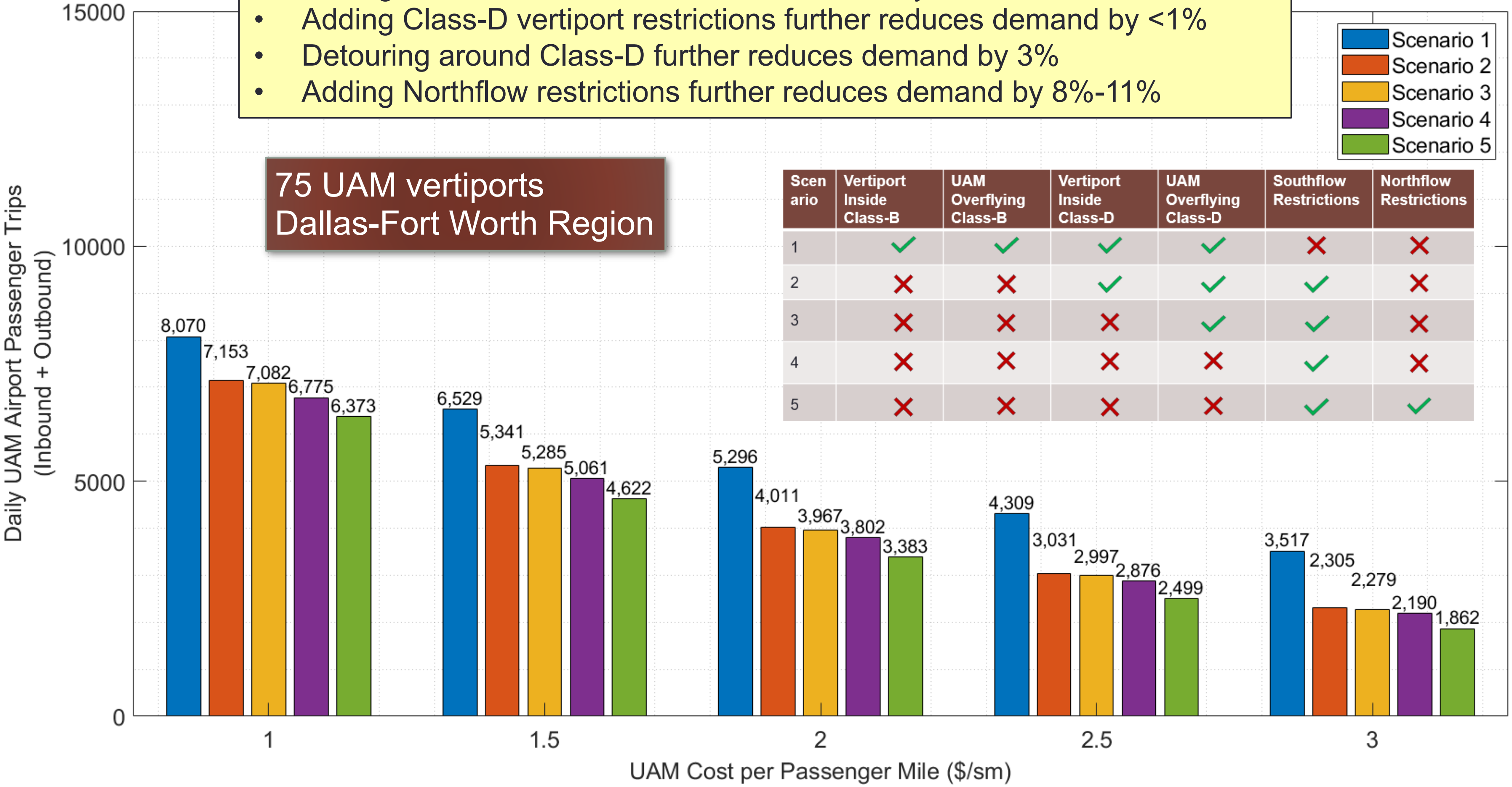


Four-Seat UAM Vehicle Economics: Low Utilization and High Number of Repositioning of Flights



UAM Vehicle Economics: Impact on UAM Airport Demand

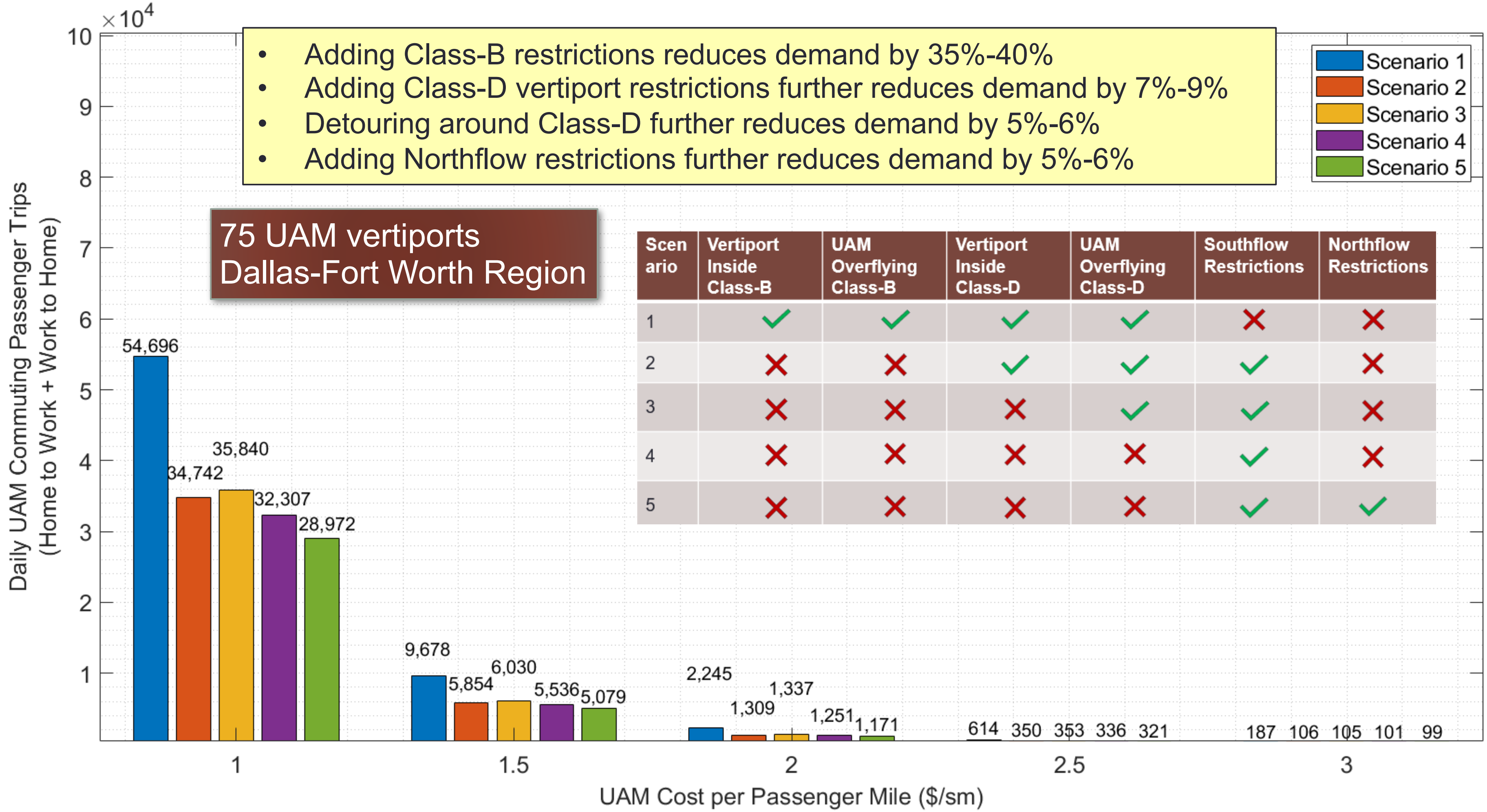
- Adding Class-B restrictions reduces demand by 10%-17%
- Adding Class-D vertiport restrictions further reduces demand by <1%
- Detouring around Class-D further reduces demand by 3%
- Adding Northflow restrictions further reduces demand by 8%-11%



Scenario	Vertiport Inside Class-B	UAM Overflying Class-B	Vertiport Inside Class-D	UAM Overflying Class-D	Southflow Restrictions	Northflow Restrictions
1	✓	✓	✓	✓	✗	✗
2	✗	✗	✓	✓	✓	✗
3	✗	✗	✗	✓	✓	✗
4	✗	✗	✗	✗	✓	✗
5	✗	✗	✗	✗	✓	✓

UAM Vehicle Economics: Impact on UAM Commuter Demand

- Adding Class-B restrictions reduces demand by 35%-40%
- Adding Class-D vertiport restrictions further reduces demand by 7%-9%
- Detouring around Class-D further reduces demand by 5%-6%
- Adding Northflow restrictions further reduces demand by 5%-6%

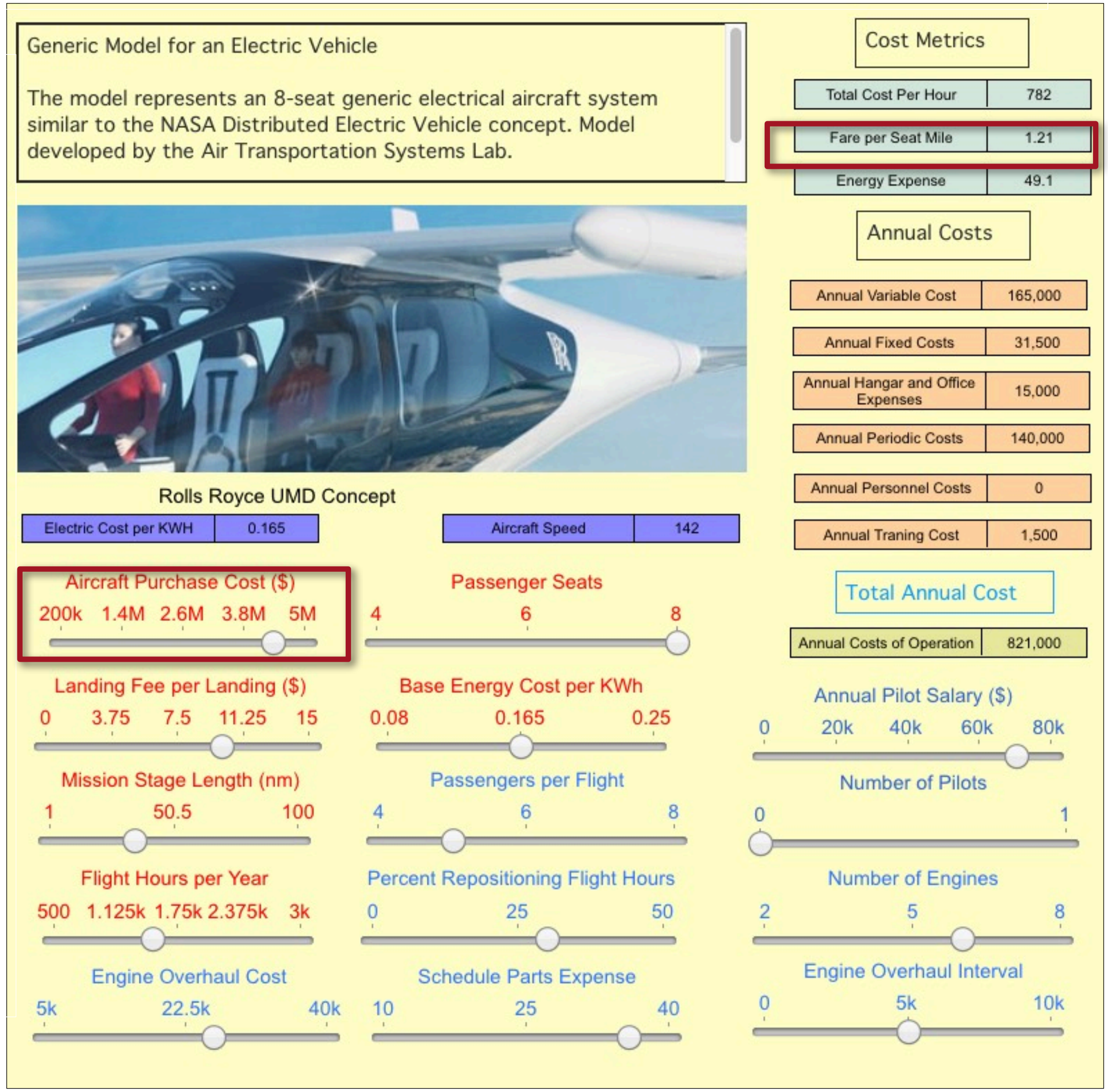


Scenario	Vertiport Inside Class-B	UAM Overflying Class-B	Vertiport Inside Class-D	UAM Overflying Class-D	Southflow Restrictions	Northflow Restrictions
1	✓	✓	✓	✓	✗	✗
2	✗	✗	✓	✓	✓	✗
3	✗	✗	✗	✓	✓	✗
4	✗	✗	✗	✗	✓	✗
5	✗	✗	✗	✗	✓	✓

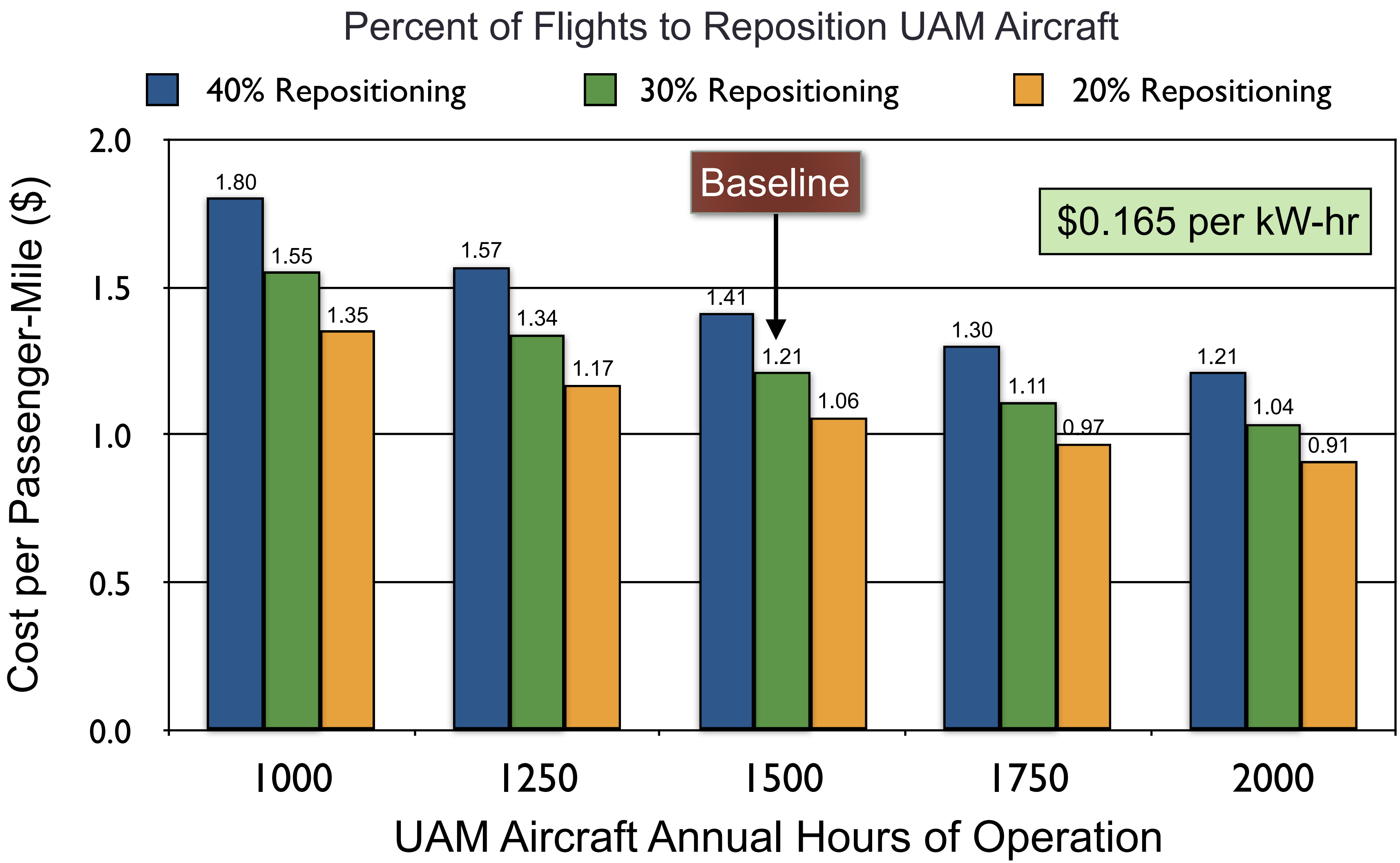
8-Seat UAM Baseline Cost of $1.21 per Passenger Mile

- **Aircraft cost 4.2 million dollars per aircraft**
- Aircraft seats = 8
- No pilot (automation cost ~$160,000)
- Energy cost = 0.165 per kWh
- Aircraft utilization - 1,500 hours annually
- Average stage length 37 statute miles
- Number of engines = 6
- Overhaul engine cost = $26,000 per engine
- Overhaul interval = 5,000 hours
- Maintenance hours per flight hour = 0.9 (baseline)
- Landing fee = $10.0 per landing
- Maintenance cost per hour = $108
- **Load factor = 62.5%**
- **Percent repositioning flights = 30%**

- **Example: $782 per hour of operation**



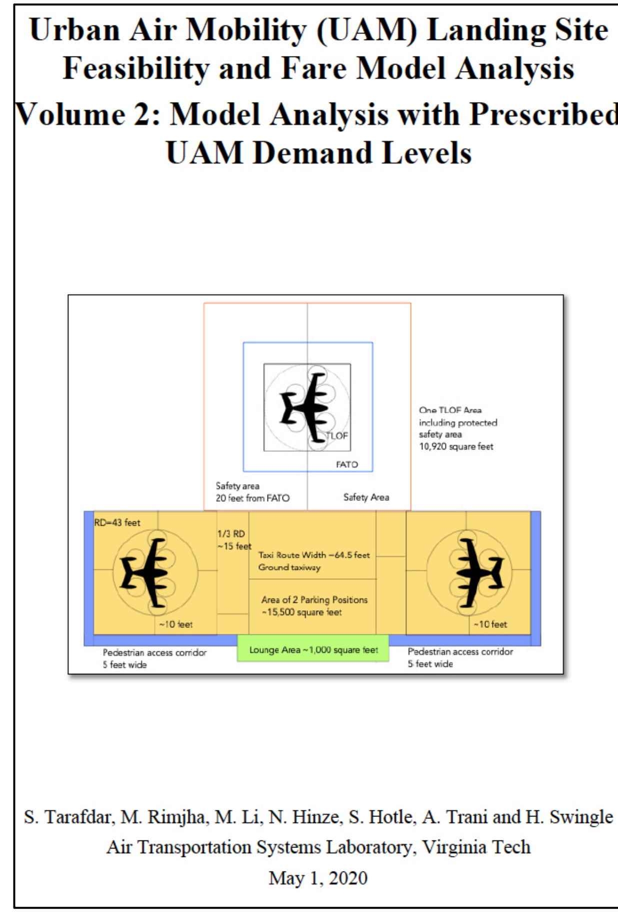
Sample Results of Life Cycle Cost Model: Eight-Seat Air Metro Vehicle



UAM Landing Site Cost Model

UAM Landing Site Life Cycle Cost Model Information

- The building blocks of the life-cycle cost model include the following:
  - Landing area type (vacant land, rooftop, parking lot)
  - Critical vehicle dimensions
  - Number of landing pads
  - Number of parking stalls
  - Number of charging stations
  - Staffing of landing site
  - Lounge areas for waiting passengers
  - Lighting requirements
  - Number of hours of operation per day for the landing site)
  - Landing fees
  - Percent subsidy to build the landing site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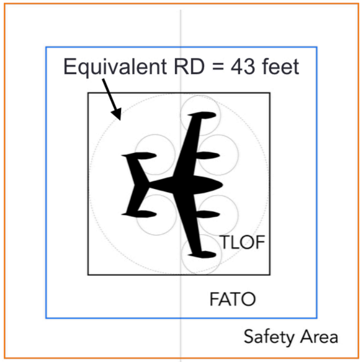
UAM Landing Site Space Requirements



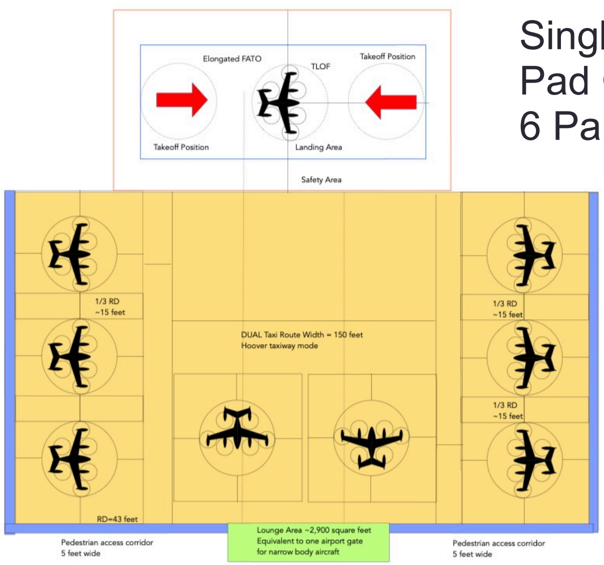
TLOF area = 1,849 ft²
FATO area = 4,160 ft²
Safety area = 10,920 ft²

Dimension	Rule	Dimension (feet)
A- TLOF Length	1 RD	43
B- TLOF Widt	1 RD	43
C - Min. FATO Length	1.5 D	64.5
E - Min. FATO Width	1.5 D	64.5
F - Min. Distance TLOF and FATO	3/4D - 1/2RD	10.75
G - Min Safety Area Width	Table	20

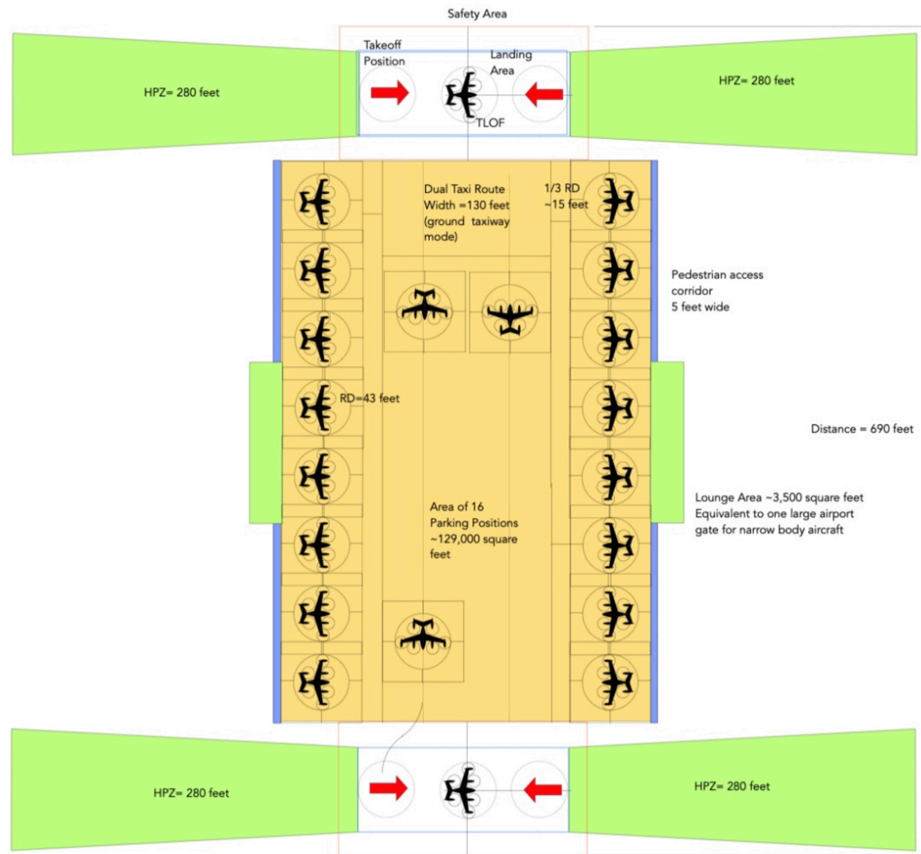
D = Total length of aircraft
RD = rotor diameter of aircraft
MHR = minimum rotor height

Source: FAA 150/5390-2c (2012)

Single Landing Pad Configuration 6 Parking Stalls



Dual Landing Pad Configuration 16 Parking Stalls



UAM Landing Site Space Requirements

- Estimated UAM landing site requirements for various configurations (1-6 landing pads)
  - Number of landing pads
  - Number of parking positions

Single Pad UAM landing Site Requirements

Landing Pads	Parking Stalls	Landing Pad Safety Area (acres)	Hover Taxi Operation	Ground Taxi Operation		
			Parking Stall Area (acres)	Total Area (acres)	Parking Stall Area (acres)	Total Area (acres)
1	0	0.25	0.00	0.25	0.00	0.25
1	1	0.25	0.12	0.38	0.09	0.34
1	2	0.25	0.43	0.68	0.36	0.61
1	3	0.25	0.71	0.96	0.53	0.78
1	4	0.25	0.86	1.11	0.64	0.89
1	5	0.25	1.07	1.32	0.81	1.06
1	6*	0.46	1.50	1.95	1.18	1.63
1	7*	0.46	1.73	2.18	1.35	1.80
1	8*	0.46	1.96	2.41	1.52	1.97

* Configurations with six or more parking stalls use dual taxi lanes and elongated FATO areas for added flexibility.
The calculations assume an equivalent rotor diameter (RD) of 43 feet.

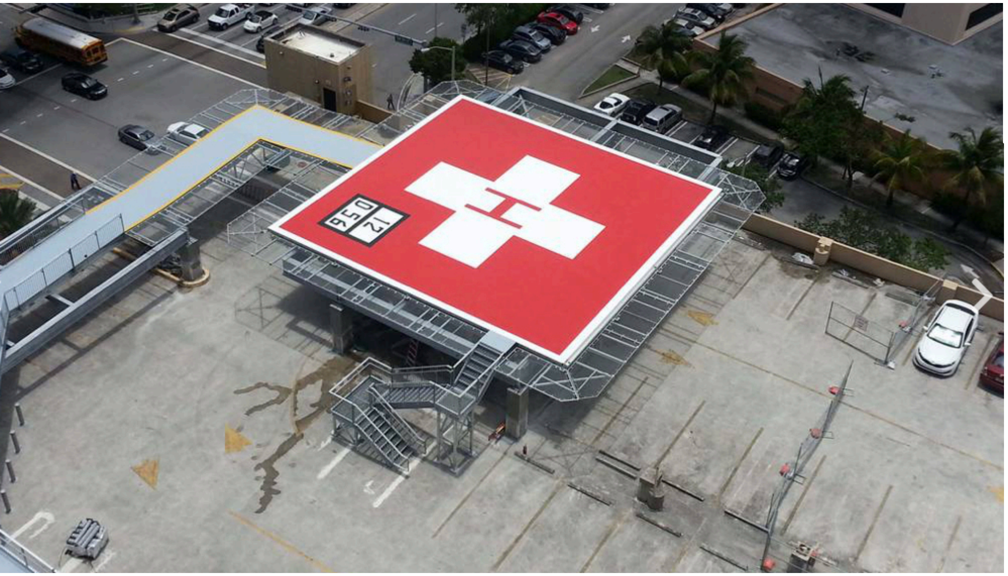
UAM Landing Site Vertical Distribution Concepts

Rooftop solution
Elevated landing pad solution
No land cost

Table top solution
Elevated landing pad solution
Land cost is possible

Source: FEC Heliports
https://fecheliports.com

UAM Landing Site Vertical Distribution Concepts



Parking garage solution
Elevated landing pad solution
No land cost
Opportunity cost considered

Ground level solution
Land cost is a factor

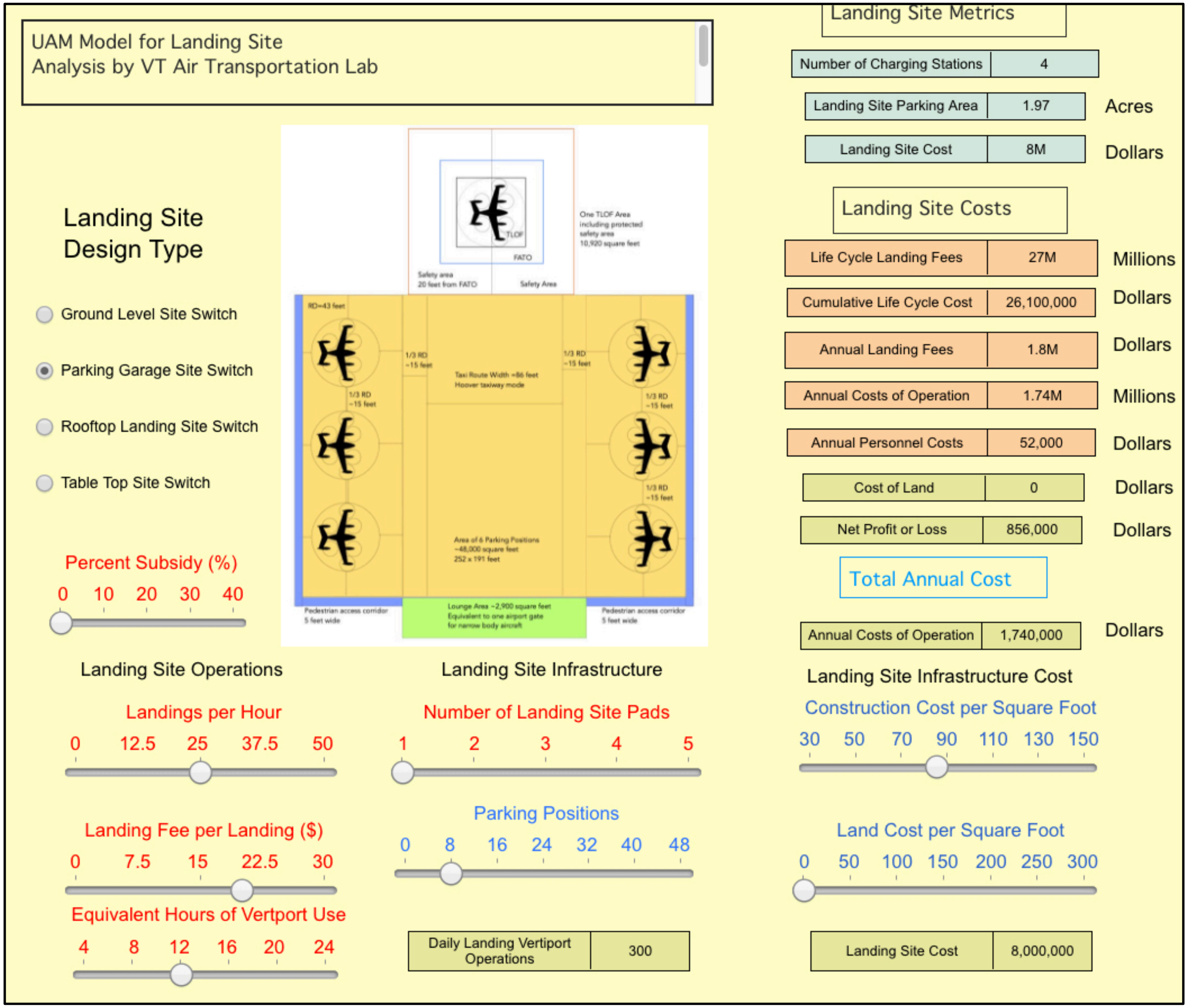
Source: FEC Heliports
https://fecheliports.com

Summary for Landing Site Cost Model Choices

Landing Site Configuration	Cost Contribution Assumptions	Remarks
Ground level	Land cost required Elevated or non elevated pad (assume non-elevated for now)	Ground location (basic land use cost) Pier location (50% additional cost if pier needs to be extended)
Rooftop	No land cost required Elevated platform needed Elevator and access required	Cost could increase substantially, if elevated pad is offset or cantilevered
Table top	Land cost may be required Elevated platform needed with significant additional cost (taller and stronger beams and girders)	Most configurations will use the land owned by organization that owns building.
Parking garage	Elevated landing pad solution Land cost not a factor Opportunity cost is a factor	Revenue lost depends on location. Central business district parking garage locations. 1 landing pad ~ 100 car positions

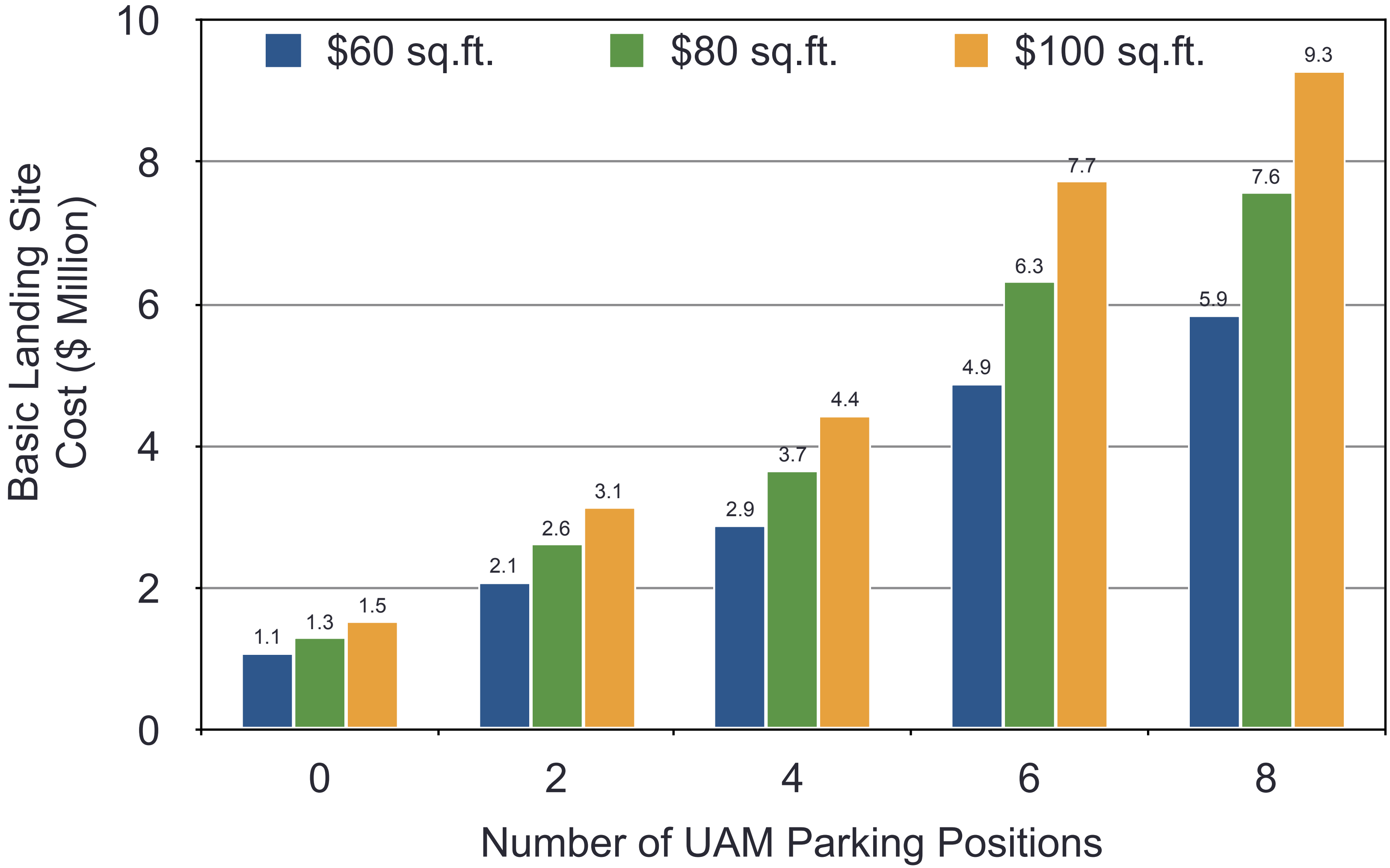
UAM Landing Site Life-Cycle Cost Model

- Example: $8 Million for one landing pad and 8 parking stalls
- $20 landing fee per landing
- $87/sq. foot construction cost
- 25 landings/hr
- Parking garage configuration



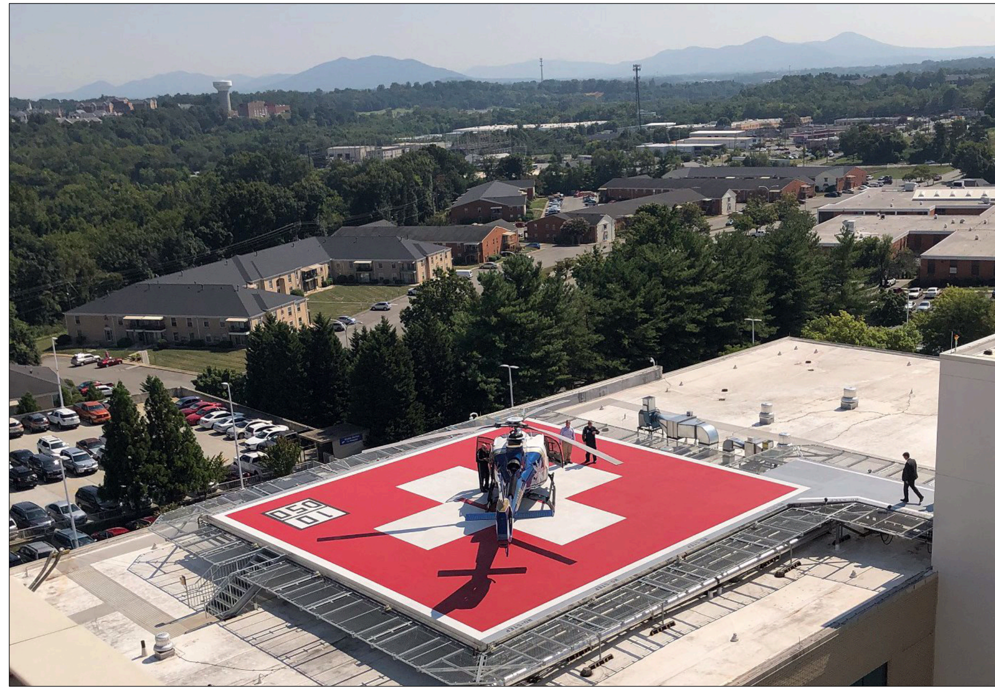
Model developed in STELLA Author

Sample Landing Site Costs (Rooftop Configuration - One Landing Pad)



Real Cost of a Rooftop Heliport Project

- Lewis Gale Hospital - Salem VA
  - 42x42 feet landing area
  - Aluminum deck
  - Steel beams and girders to support metal deck
  - 12,000 lb. design load (Helicopter load + 50% load factor)
  - Three-story elevator to have access to emergency room
  - $3 million (total cost)



Real Cost of a Rooftop Heliport Project

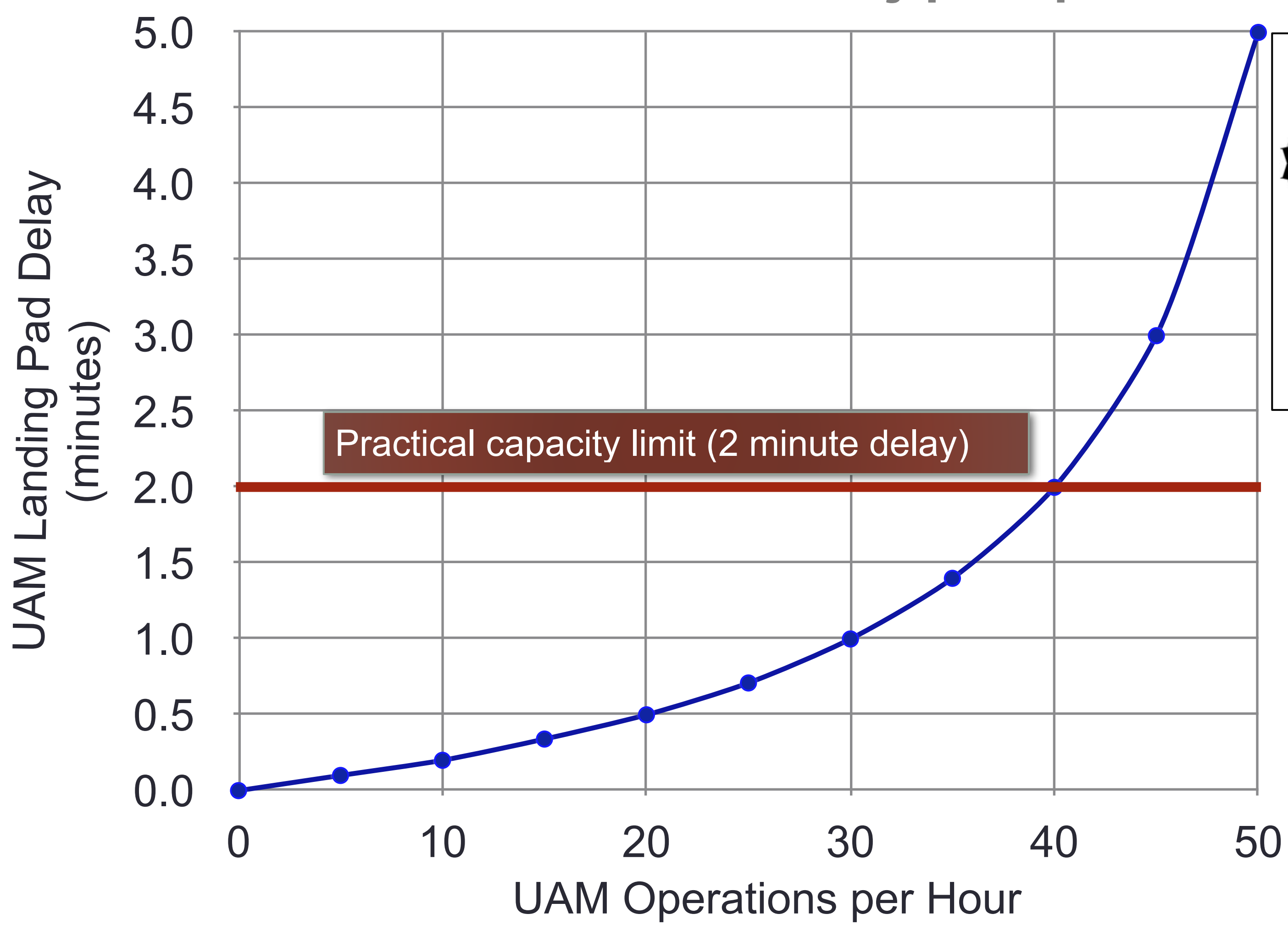
- Roanoke Memorial Hospital-Roanoke VA
  - Octagonal 65x65 feet landing area
  - Aluminum deck
  - Steel beams and girders to support metal deck
  - 20,000 lb. design load (Helicopter load + 50% load factor)
  - Elevator to have access to emergency room
  - $3.7 million (total cost)

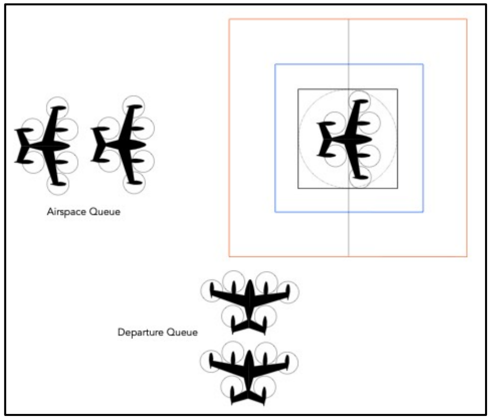
UAM Landing Site Requirements Operational Analysis

Landing Site Operations/Delay Model

- Estimates UAM throughput capacity considering delays associated with UAM operations at a landing site
- Delays at a landing site affect the disutility of UAM mode and ultimately affect potential UAM demand
- A landings site operational analysis uses two independent queueing models to quantify delays for various configurations
  - Landing pad
  - Parking positions (includes the ability to recharge UAMs)
- In a well-designed landing site, parking position capacity and landing pad capacity should be in balance
- It is expected that in most UAM landing site operations parking capacity may be the limiting factor depending upon recharging times

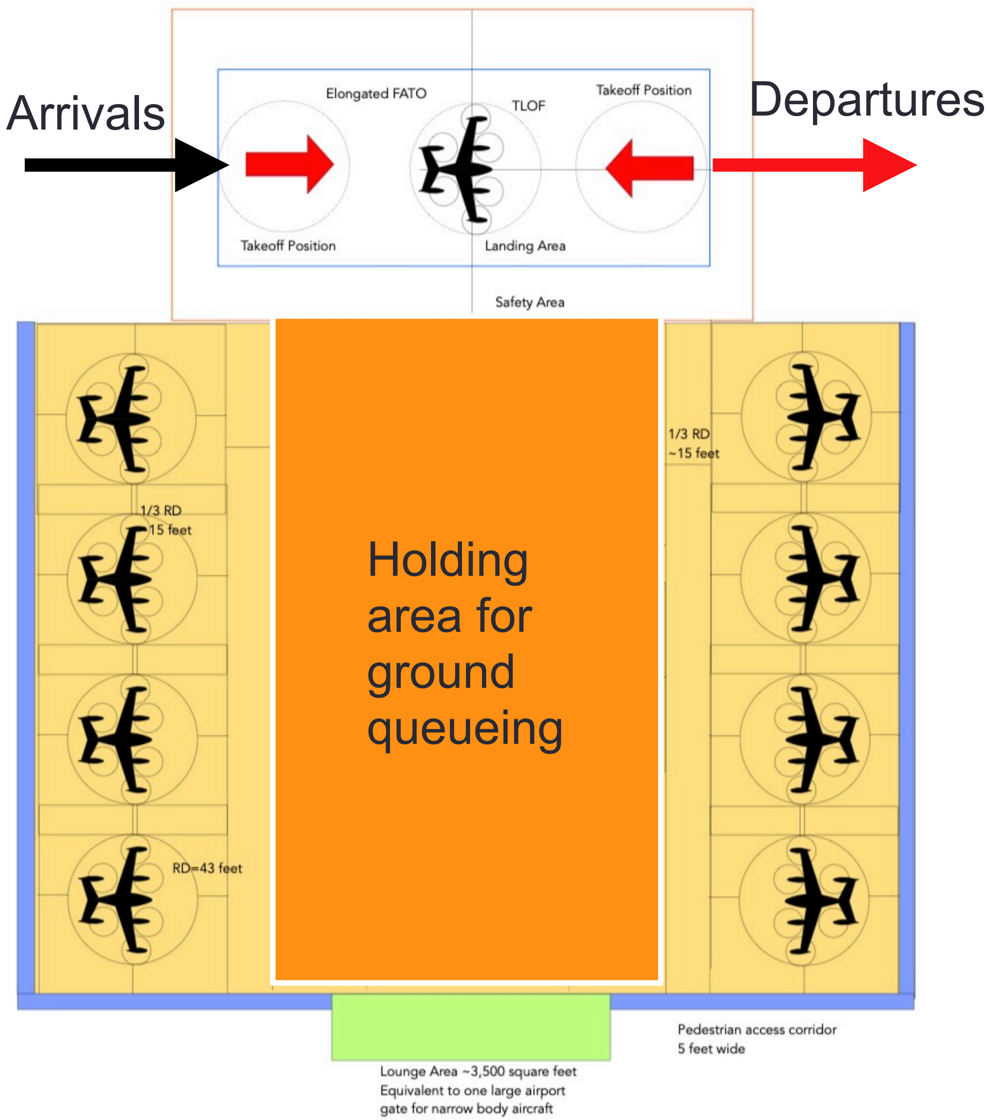
Landing Pad Queueing Model (M/M/1 Model)
40 Operations per Hour is the Practical Capacity of the Vertiport
(2 Minutes of Delay per Operation)





Stochastic Queueing Model with:
1 Landing Pad
60 seconds between UAM operations (arrivals or departures)
Variable demand rate
Random arrivals (Poisson)
Exponential service times

Parking Area Queueing Model (M/M/S)



- Parking positions are servers (S)
- Taxiway system is used for UAM queueing
- Random arrivals and departures
- Fraction of UAMs charging
- Push-Back and push-in times
- Arrival function is the combined effect of arrivals and departures using the landing pad
- Service times are estimated as the composite of regular passenger turnaround and charging UAM times

Model outputs:

Expected number of UAMs at vertiport

Average delays in holding area (taxiways)

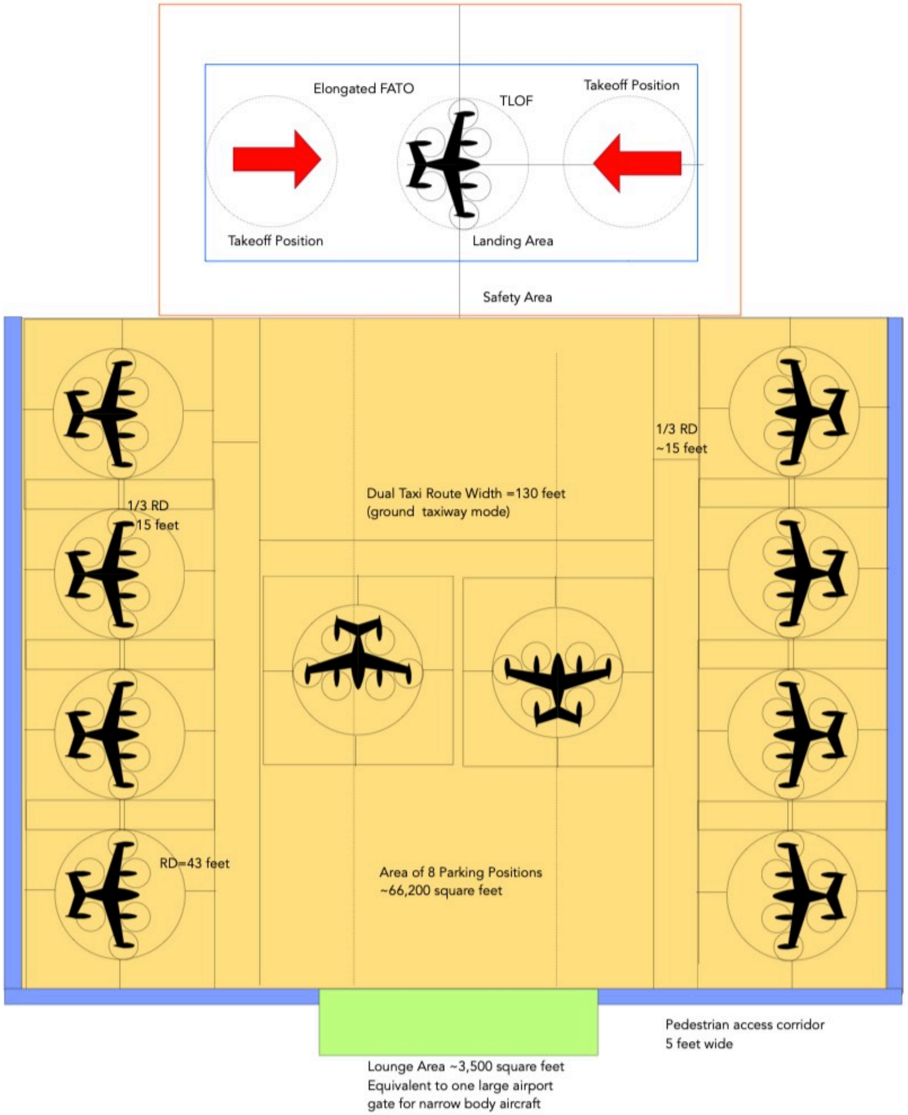
Utilization of parking areas

Example: Application of Queuing Models to a Single Landing Pad Site with 8 Parking Positions

UAM Landing Site Configuration (8 Parking Positions)

Operational analysis shows that a single taxi lane configuration **will not work well** for a vertiport with 6-8 parking positions

- For a vertiport with 8 parking positions, the dual taxilane configuration requires 29% more space compared to a single taxi lane configuration
-
- More flexibility allowing simultaneous taxiing operations
- More holding capacity in queue



Ground Taxiway Configuration

40-43 Operations per Hour is the Practical Capacity of a Single Pad with 8 Parking Positions with Acceptable Delays

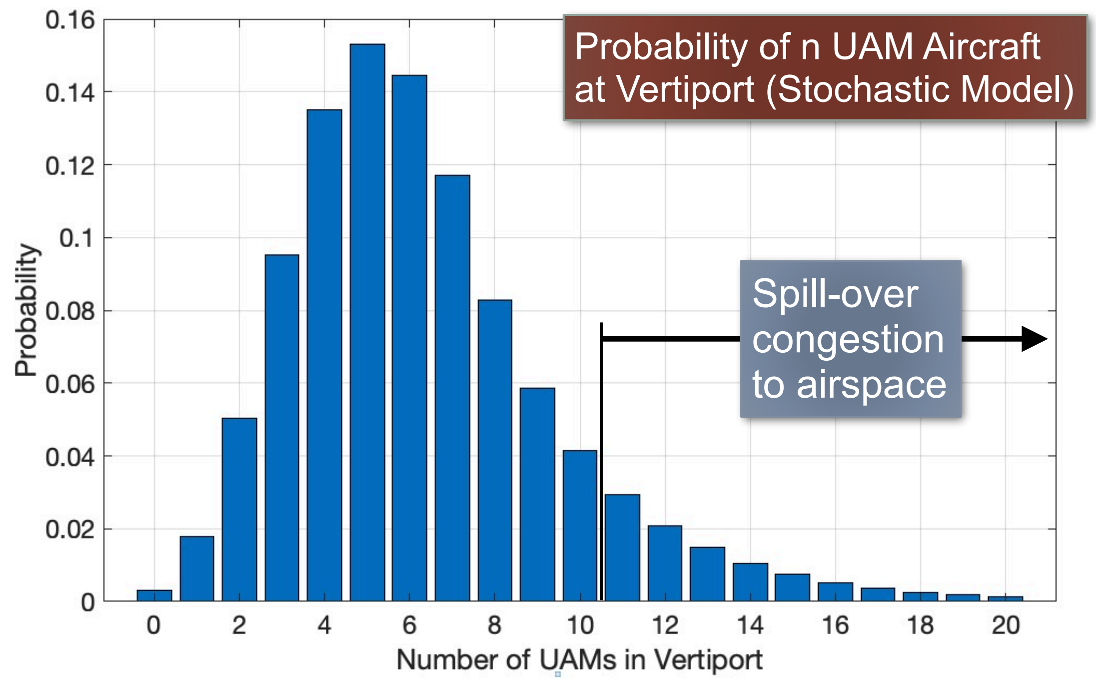
Normal UAM service time = 5 minutes
UAM Charging time = 15 minutes
Push-back and push-in allowance = 2 minutes
UAM demand = 40/hr
Number of parking positions = 8
Fraction of UAMs recharging = 0.3

```
Queueing Parameters
UAM Demand /hr =   40
Equivalent Service Rate per Server (UAMs/hr) =   7.0588
System utilization (%) =   70.8333
Idle Probability for Servers (dim) =   0.0031414
Expected No. of UAMs in taxiway system (Lq)  =   0.68975
Expected No. of UAMs in Vertiport System (L)  =   6.3564
Average Waiting Time in Queue (Minutes) =   1.0346
Average UAM Aircraft Time in Vertiport System (includes service time) (Minutes)  =   9.5346
```

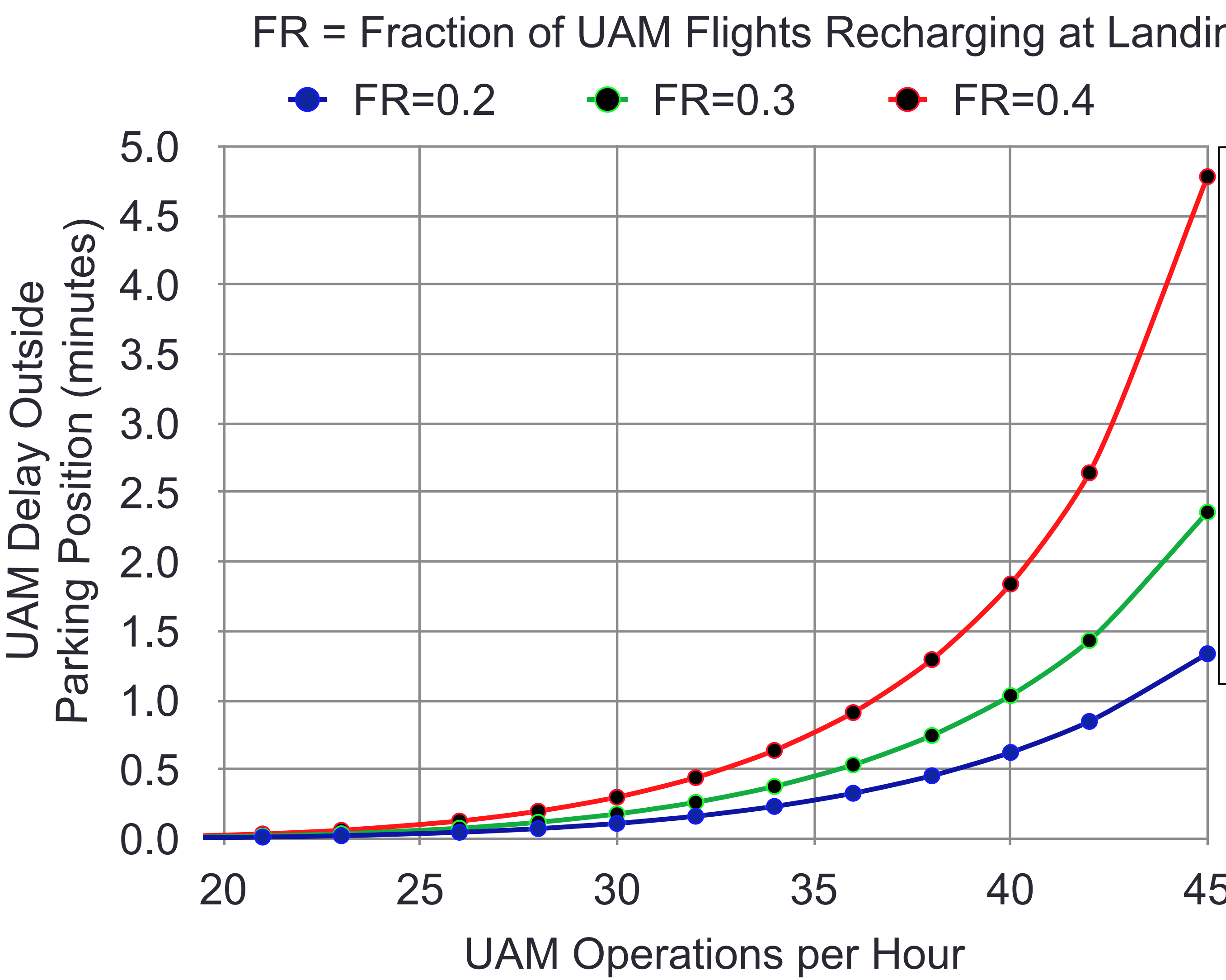
Queueing Model Equations

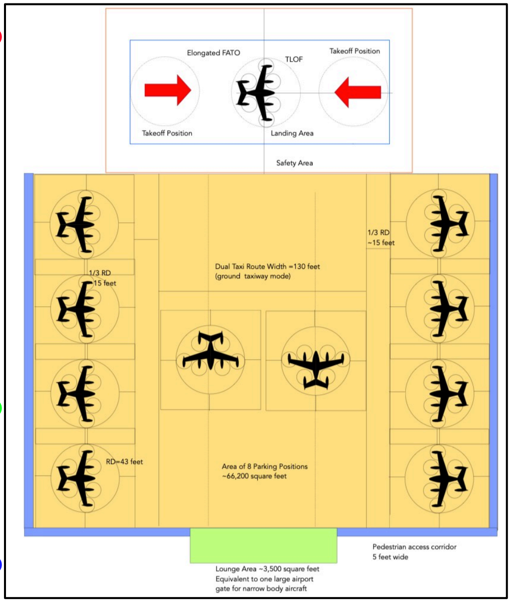
```
% Find Po
  Po_inverse=0;
  sum_den=0;

for i=0:S-1          % for the first term in the denominator (den_
  den_1=(Lambda/Mu)^i/factorial(i);
  sum_den=sum_den+den_1;
end

  den_2=(Lambda/Mu)^S/(factorial(S)*(1-Rho)); % for the secon
  Po_inverse=sum_den+den_2;
  Po=1/Po_inverse;

% Find probabilities (Pn)

  Pn(1) = Po;    % Initializes the first element of Pn column vect
  n(1) = 0;      % Vector to keep track of number of entities in s

% loop to compute probabilities of n entities in the system

  for j=1:1:nlast
    n(j+1) = j;
    if (j) <= S
      Pn(j+1) = (Lambda/Mu)^j/factorial(j) * Po;
    else
      Pn(j+1) = (Lambda/Mu)^j/(factorial(S) * S^(j-S)) * Po;
    end
  end
```

Taxiway delays ~ 1.04 minutes per UAM operation



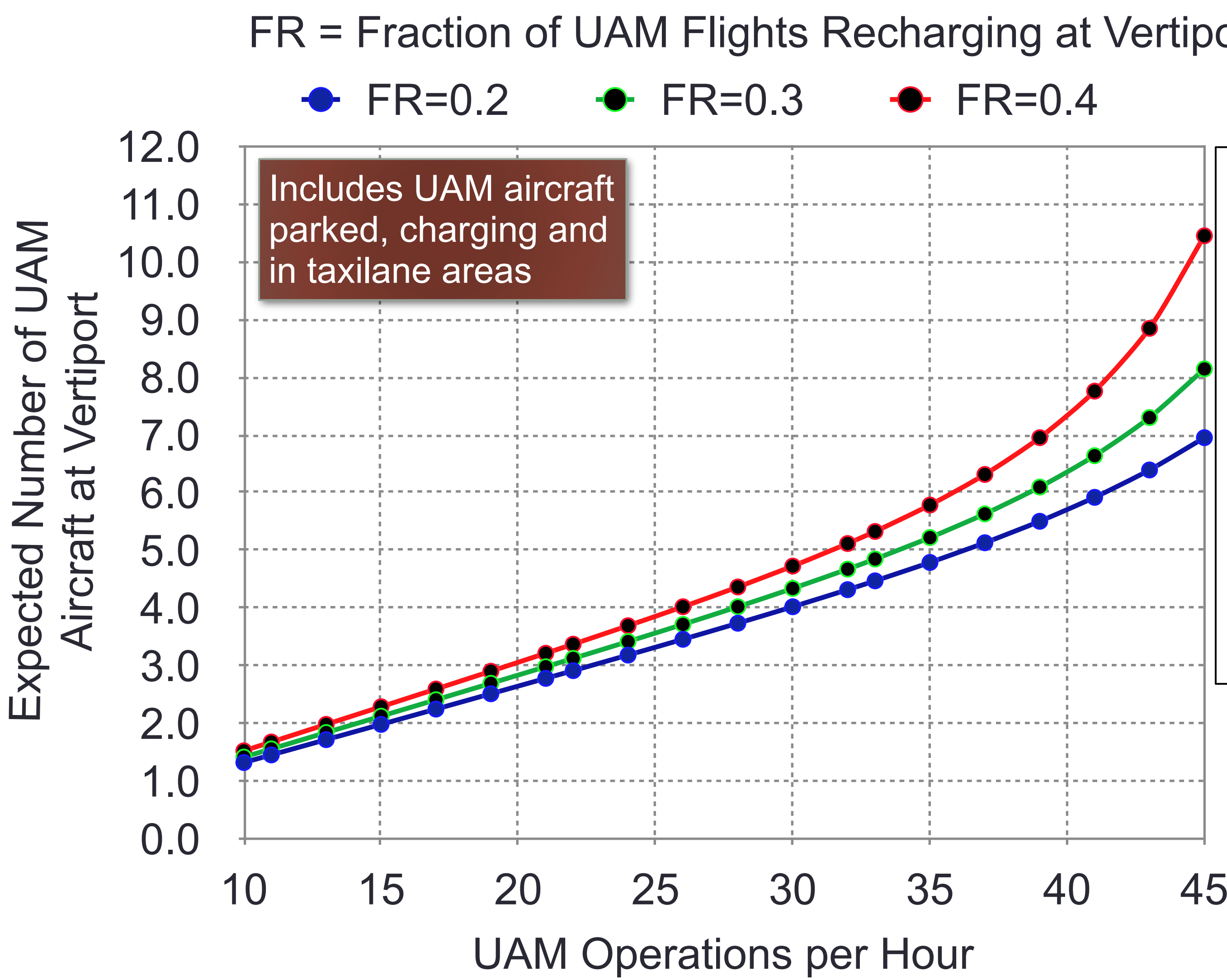
Example Analysis: 8 Parking Stations and One Landing Pad

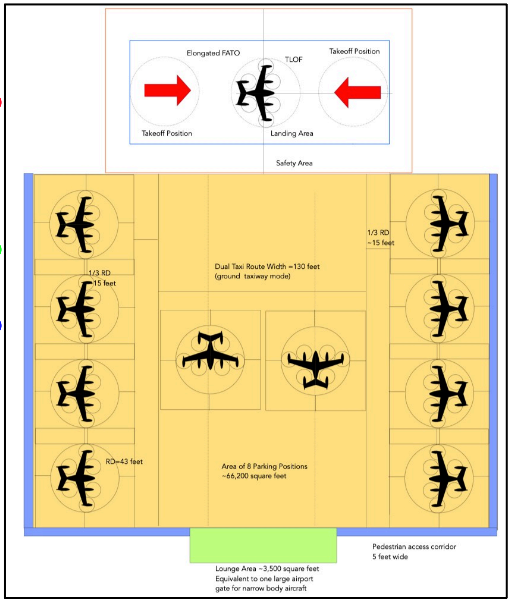




Stochastic Queueing Model with:
1 Landing Pad
8 Parking Positions
5 Minute Service Time
15 Minute Recharging Time
1 minute taxi-in time
1 minute taxi-out time

Example Analysis: 8 Parking Stations and One Landing Pad





Vertiport Stochastic Queueing Model with:
1 Landing Pad
8 Parking Positions
5 Minute Service Time
15 Minute Recharging Time
1 minute taxi-in time
1 minute taxi-out time

Observations

- 40-43 UAM operations per hour is the practical capacity of a single pad UAM vertiport with dual lane taxi lanes and 8 parking positions (i.e., 2 minutes of delay in holding area)
- One landing pad and 8 parking stations with a single taxi lane makes the operation of this vertiport limiting on the airside (i.e., cannot operate UAM arrivals and departures to and from the landing pad simultaneously)
- To improve the efficiency of the vertiport provided dual taxi lanes on the airside movement areas
- At 42 UAM operations per hour, the single landing pad delay is 2.5 minutes per operation
- 42 UAM operations for a 1 pad + 8 parking position configuration will involve a total of 4.5 minutes of additional delay in UAM operations
- Longer UAM recharging times will decrease the practical capacity of the vertiport