MIT ICAT

MIT International Center for Air Transportation

A Multi Attribute Airport Capacity Model for Systematically Analyzing New Wake Vortex Separation Concepts

Tamas Kolos-Lakatos
tkolos@mit.edu
Professor R. John Hansman
rjhans@mit.edu

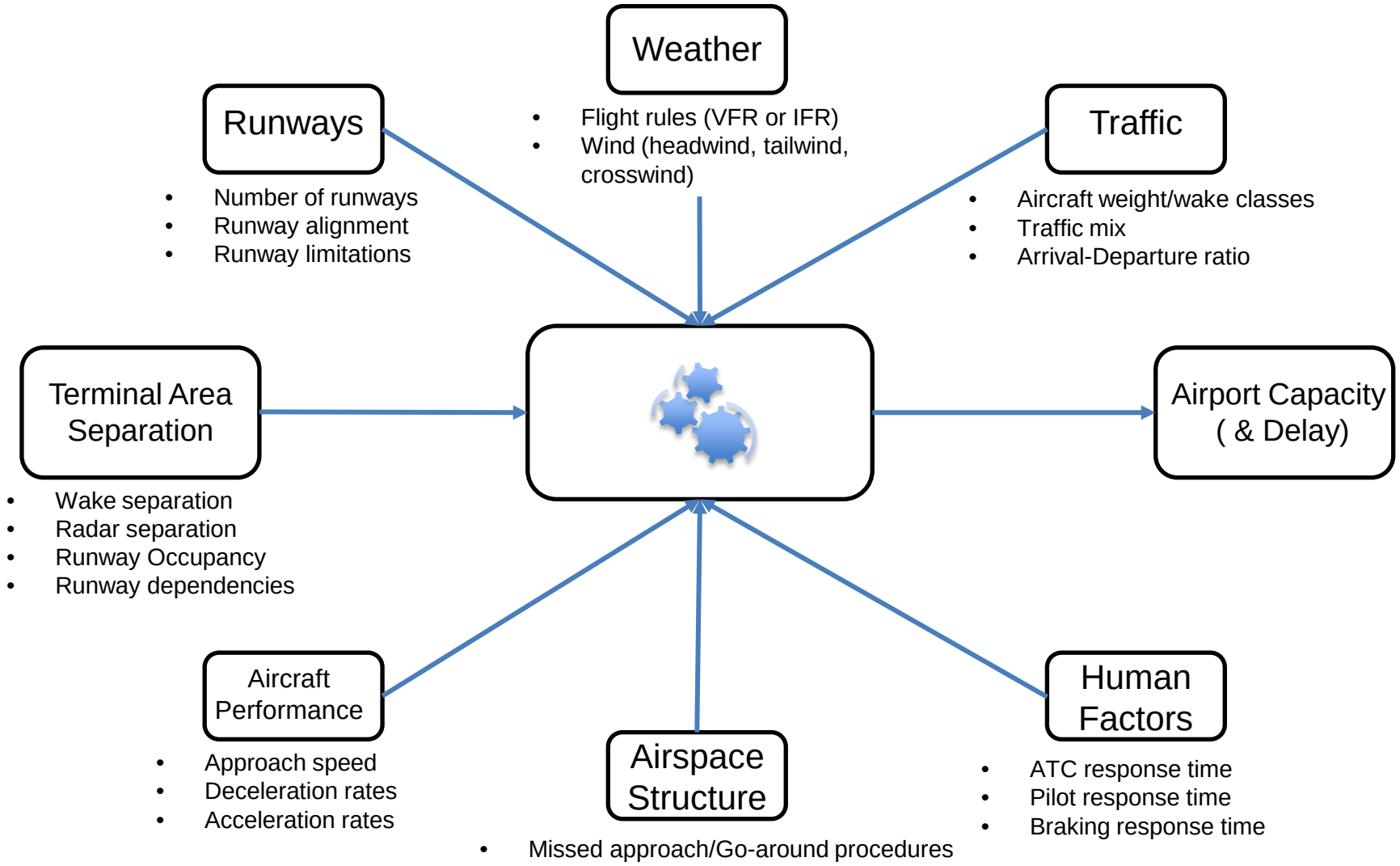
Autumn JUP Meeting

November 5, 2015

Increase in Demand for Air Travel – Limited Airport Capacity

- Demand for air travel is projected to keep growing over the next 20 years
- Current U.S. aviation network has limited capacity
  - *Capacity Needs in the National Airspace System* (FAA) states that 27 of the top 35 busiest airports have reached or are nearing their limit on capacity
- There are two ways to increase capacity:
  - Invest in new infrastructure
    - Construction of new runways require huge capital investments
    - Often limited by geographical or political constraints
  - Introduce new policies, procedures
    - Adjust capacity-demand imbalance by shifting schedules
    - Reduce separation between aircraft

Factors Influencing Airport Capacity



Wake Vortex Turbulence

- Wake vortex is byproduct of lift
- Wake strength is function of weight and wingspan[1]
- Aircraft are grouped into wake categories based on their maximum take off weight (MTOW)
- Wake separations limit runway capacity

NASA Langley Research Center

Current final approach separation standards applied (JO7110.65T[2]):

Current Final Approach Separation Standards (in NM)			
Leader\Follower	Heavy	Large	Small
Heavy	4	5	6
Boeing 757	4	4	5
Large	2.5	2.5	4
Small	2.5	2.5	2.5

Heavy: 300,000 lbs or more MTOW
Boeing 757: special category for the 757
Large: more than 41,000 lbs MTOW
Small: 41,000 lbs or less MTWO

[1] Y. A. Cengel, Fluid Mechanics, McGraw-Hill, 2010
[2] "Air Traffic Control, FAA Order 7110.65T" FAA -Federal Aviation Administration, 2010, Department of Transportation/Federal Aviation Administration, Washington, D.C.

Proposed Wake Mitigation Separation Concepts – Single Runway

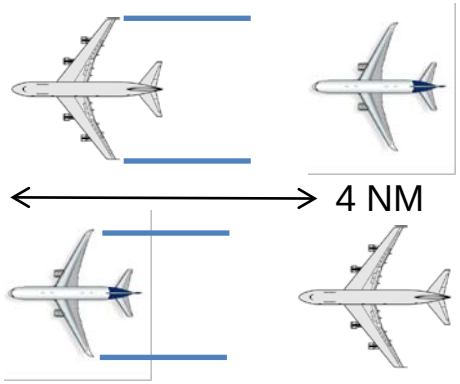
- Re-categorization of aircraft (RECAT) is a three phased project
- **RECAT I** is a static six-category based separation system
  - Operational at: MEM, ATL, CVG, ORD, MDW

RECAT Separation Matrix

Leader	Follower: A	B	C	D	E	F
A	MRS	5.0	6.0	7.0	7.0	8.0
B	MRS	3.0	4.0	5.0	5.0	7.0
C	MRS	MRS	MRS	3.5	3.5	6.0
D	MRS	MRS	MRS	MRS	MRS	5.0
E	MRS	MRS	MRS	MRS	MRS	4.0
F	MRS	MRS	MRS	MRS	MRS	MRS

- Separation was increased for some or all aircraft pairs
- Separation was decreased for some or all aircraft pairs
- Separation remained the same for some or all aircraft pairs
- MRS — Minimum Radar Separation (3NM, or 2.5 NM when existing requirements are met)

Example of a Heavy-Heavy pair (Boeing 747 - Boeing 767)



Current 4NM separation is safe

B767 followed by a B747 could be too conservative, because the lead aircraft generates weaker vortices than in the previous case

Proposed Wake Mitigation Separation Concepts – Single Runway

- **RECAT II** is also a static separation concepts with multiple implementation alternatives
  - Seven or more aircraft categories
  - Categories A-F optimized for local fleet mix, remainder aircraft make up seventh category
  - Based on 107 by 107 pair-wise separation matrix
  - Planned implementation: DEN. late 2015

RECAT Phase II 7-category separation matrix

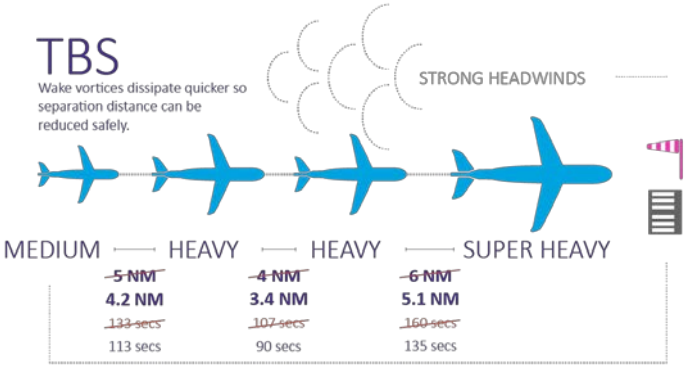
		Follower						
		A	B	C	D	E	F	G
Leader	A	MRS	5.0	6.0	7.0	7.0	8.0	8.0
	B	MRS	3.0	4.0	4.0	5.0	6.0	8.0
	C	MRS	MRS	MRS	MRS	3.5	5.0	8.0
	D	MRS	MRS	MRS	MRS	MRS	4.0	8.0
	E	MRS	MRS	MRS	MRS	MRS	MRS	8.0
	F	MRS	MRS	MRS	MRS	MRS	MRS	8.0
	G	8.0	8.0	8.0	8.0	8.0	8.0	8.0

*For concept illustration purposes only

- **RECAT III** is planned to be a dynamic pair-wise separation system
  - Required minimum separations are dynamically updated based on wind and aircraft data

Proposed Wake Mitigation Separation Concepts – Single Runway

- **Time Based Separation (TBS)**
  - Wake vortices dissipate more quickly in strong headwind conditions, but strong headwinds also reduce groundspeed
  - Applying constants TBS in all wind conditions can minimize impact on landing rates
  - Requires detailed forecast system from every aircraft on approach
  - Operational at: LHR

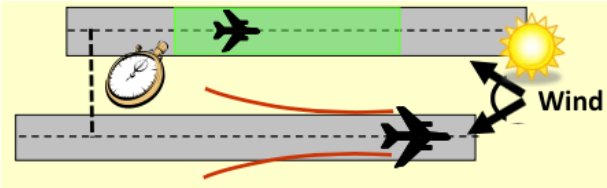


https://pbs.twimg.com/media/CBWR2VRWQAA0D6J.png:large

- **Large-Large 2NM separation**
  - Reduce minimum separation between Large-Large pairs to 2NM if average runway occupancy time is below 45 seconds
  - Assumes current separation buffer is big enough that the average separation in reality is close to ~3NM

Proposed Wake Mitigation Separation Concepts – Multiple Runways

- **Wake Turbulence Mitigation for Arrivals (WTMA)**
  - WTMA considers approaches on closely spaced parallel runways
  - Establishes a diagonal separation between lead and trailing aircraft
  - WTMA-System (WTMA-S) includes wind monitoring to enable reduced separations when strong crosswind is present
- **Wake Turbulence Mitigation for Departures (WTMD)**
  - WTMD considers departures on closely spaced parallel runways
  - Crosswind can enable reduced separations for aircraft departing on upwind runway behind a departure on the downwind runway
  - WTMD-Paired Departures (WTMD-PD) extends the concept by adding a time envelope for the upwind aircraft to depart



Objective I: Multi-Attribute Airport Capacity Analysis for Evaluating New Wake Separation Concepts

- There is a wide variety of wake mitigation concepts
- Most of these concepts are tailored to specific airports
- Need for a general characterization of the relationship between wake separation rules and their impact on airport capacity
- Systematically analyze arrival and departure capacities
  - How much additional airport capacity can be gained from new wake separation rules over existing rules?
  - How much additional benefit can be gained from dynamic separation rules over static separation rules?
  - What kind of changes in the fleet mix can a wake separation rules tolerate before having an inverse impact on capacity?
  - Do certain wake separation rules work better for certain runway configurations than others?
  - Does reducing wake separation requirements lead to higher go-around rates?

Objective I: Multi-Attribute Airport Capacity Analysis for Evaluating New Wake Separation Concepts

Set of Wake Separation Rules

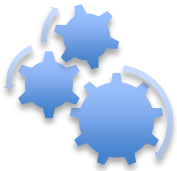
- Collect all currently proposed wake separation concepts
- Limit scope to non-cockpit based technology concepts
- Explore future options

Set of Representative Traffic Mixes

- Establish 5-7 representative traffic mixes
- Based on current fleets and future orders
- Use a few airport specific fleet mixes for model validation

Set of Runway Configurations

- Build a set of airport layouts based on most common runway configurations
- Superimpose basic runway geometries for more complex layouts



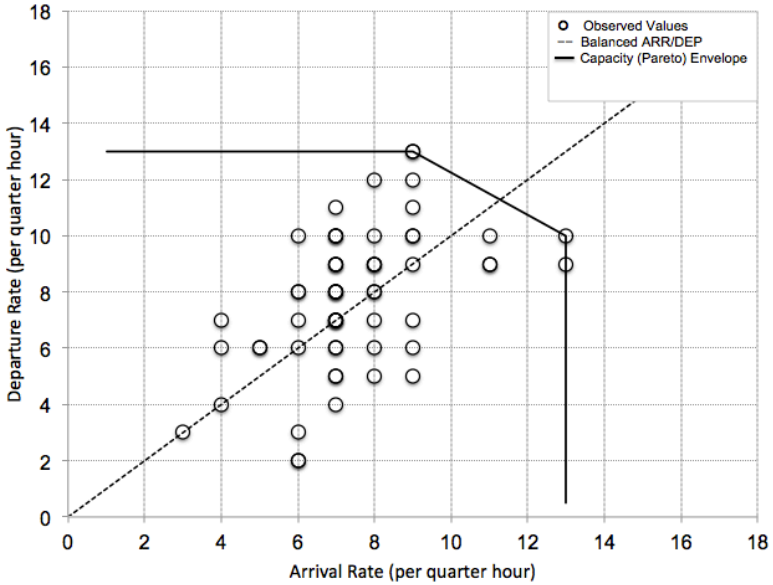
- Build or choose a tool that can evaluate all the input parameters (deterministic and stochastic) in sufficient details (wind, runway occupancy, aircraft deceleration, etc.)
- Capable of handling all currently known wake separation concepts

Airport Capacity (and Delays)

- Provide scenario based airport capacity estimates
- Possibly include metric for delays

Airport Capacity calculations

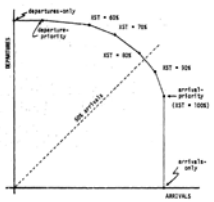
- Airport capacity studies are usually based on empirical observations



Example airport capacity envelope for BOS with a 15-minute departure/arrival window

- Results from one airport with similar characteristics can be extrapolated to other airports with some adjustments for fleet mix and runway configuration
- More detailed studies require airport simulation models
- From basic spreadsheet models to high-fidelity simulation tools

Objective II:
Build a Medium-Fidelity Airport Capacity Model



Increasing details and complexity

Airfield Capacity Model

TAAM, SIMMOD

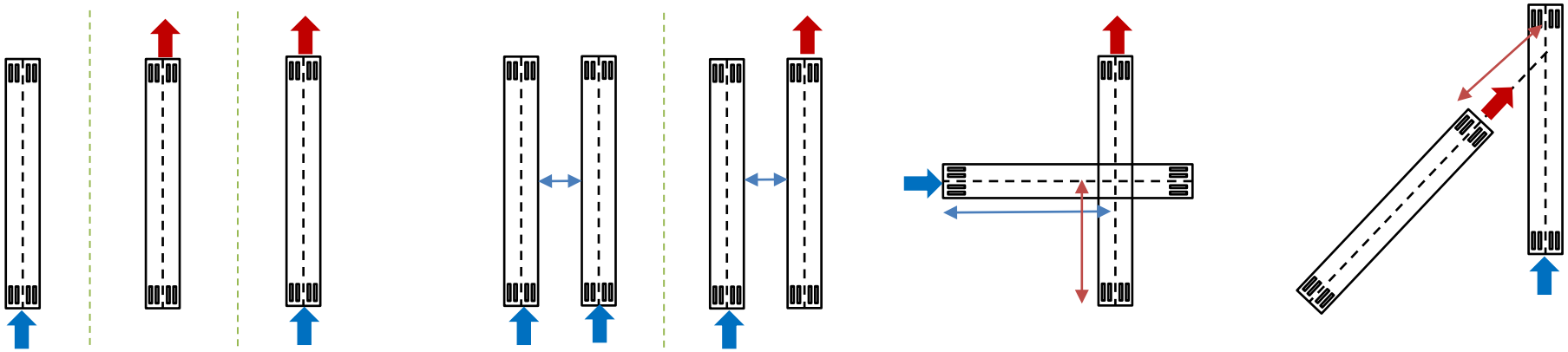
Analytical models
- Easy to setup for simulation
- Fast simulation runs
- *Limited runway configurations*
- *Limited stochastic variables*

High-fidelity 3D simulation tools
- Includes flight schedules
- Tracks aircraft individually to calculate delays
- Surface movements, taxiways, gates
- *Time-consuming scenario setup*
- *Expensive to acquire*
- *Results are influenced by airline schedule*

Medium-fidelity model
- Based on Monte-Carlo simulation
- Can accommodate a wide range of scenarios and wake separation rules
- No flight schedule needed

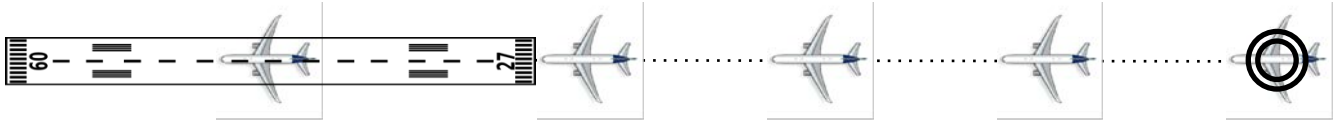
Setting up a Simulation Scenario – Runway Selection

- **Runway Configuration and Geometry Components**
  - User selects from four baseline runway geometries:
    - Single runway, closely spaced parallels, crossing runways, converging runways
  - Other runway configurations can be built from superimposing baseline geometries

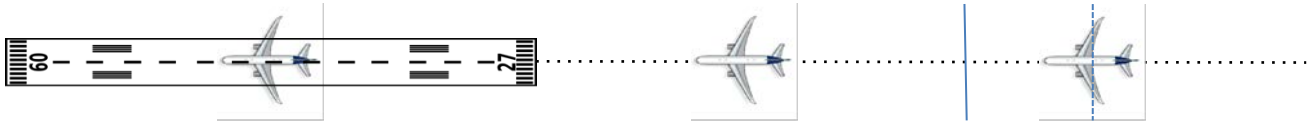


Setting up a Simulation Scenario – Airspace Components

- **Length of common final approach**
  - Shared by all arrivals flying at constant speeds in the model framework
  - User defines location of final approach fix (nautical miles)



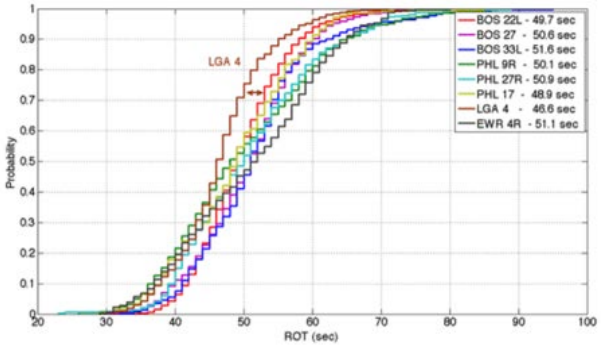
- **Separation buffer**
  - Excess separation of the required minimum separation
  - Can minimize risk of loss of separation, also reduces runway throughput
  - User can define time or distance based separation with a normal distribution mean and variance



Setting up a Simulation Scenario – Fleet Characteristics

- **Fleet mix**
  - User is provided 100+ aircraft types
  - Model uses ICAO aircraft type designators (DOC 8643)
  - Need to provide individual aircraft type count
- **Fleet wake class**
  - Wake classes need to be specified for each type
    - E.g. “U” for Super, “H” for Heavy, “7” for Boeing 757, “L” for Larges, “S” for Small
- **Fleet performance**
  - Average final approach speed per wake class group
    - Normal distribution with user specified mean and variance
  - Arrival runway occupancy time
    - Normal distribution with user specified mean and variance
  - Departure runway occupancy time
    - Default value 60 seconds for all departures

```
AcDistributionArray = {...
    'A306'  18  0    'C' 'H' 0 0; ...
    'A310'  0   361600  'C' 'H' 0 0; ...
    'A318'  0   130075  'D' 'L' 0 0; ...
    'A319'  296 141095  'D' 'L' 0 0; ...
    'A320'  598 145505  'D' 'L' 0 0; ...
    'A321'  224 206000  'D' 'L' 0 0; ...
    'A332'  58  533518  'B' 'H' 0 0; ...
    'A333'  2   533518  'B' 'H' 0 0; ...
    'A342'  0   0    'B' 'H' 0 0; ...
    'A343'  34  609578  'B' 'H' 0 0; ...
    'A346'  17  0    'B' 'H' 0 0; ...
    'A388'  70  1235000 'A' 'U' 0 0; ...
    'AT43'  0   0    'E' 'L' 0 0; ...
    'AT45'  0   0    'E' 'L' 0 0; ...
    'AT72'  0   0    'E' 'L' 0 0; ...
    'B190'  50  0    'F' 'S' 0 0; ...
    'B712'  0   0    'D' 'L' 0 0; ...
    'B722'  2   0    'D' 'L' 0 0; ...
    'B733'  200 139500  'D' 'L' 0 0; ...
    'B734'  45  0    'D' 'L' 0 0; ...
    'B735'  1   136000  'D' 'L' 0 0; ...
    'B736'  0   145500  'D' 'L' 0 0; ...
    'B737'  596 154500  'D' 'L' 0 0; ...
    'B738'  898 174200  'D' 'L' 0 0; ...
    'B739'  299 164000  'D' 'L' 0 0; ...
    'B742'  5   833000  'B' 'H' 0 0; ...
    'B744'  118 870000  'B' 'H' 0 0; ...
    'B748'  37  987670  'B' 'H' 0 0; ...
    'B74F'  0   0    'B' 'H' 0 0; ...
    'B752'  446 255000  'D' '7' 0 0; ...
    'B753'  102 0    'D' '7' 0 0; ...
    'B762'  16  350000  'C' 'H' 0 0; ...
    'B763'  210 0    'C' 'H' 0 0; ...
    'B764'  0 204120 'C' 'H' 0 0; ...
    'B772'  118 766000  'B' 'H' 0 0; ...
    'B773'  35  0    'B' 'H' 0 0; ...
    'B77L'  46  766106  'B' 'H' 0 0; ...
    'B77W'  97  774990  'B' 'H' 0 0; ...
    'B788'  22  502653  'B' 'H' 0 0; ...
    'BE40'  2   0    'F' 'S' 0 0; ...
    'BE9L'  1   0    'F' 'S' 0 0; ...
    'C172'  0   0    'F' 'S' 0 0; ...
    'C182'  0   0    'F' 'S' 0 0; ...
    'C206'  0   0    'F' 'S' 0 0; ...
```



Setting up a Simulation Scenario – Weather Components

- **Weather component is restricted to wind only parameters**
  - Headwind
    - User specified deterministic value for headwind
    - Final approach speeds are adjusted accordingly
  - Tailwind
    - User specifies deterministic value for tailwind
    - Final approach speeds are adjust accordingly
  - Crosswind
    - Model calculates headwind component and adjusts final approach speeds
    - Strong crosswind can also be modeled for dynamic separations
      - User specifies probability of strong crosswind (model assumes crosswind is strong enough to enable reduced separations)
      - Model assigns binary value 0 (no wind) or 1 (wind) based on specified probability and chooses appropriate wake separation matrix to determine minimum separation

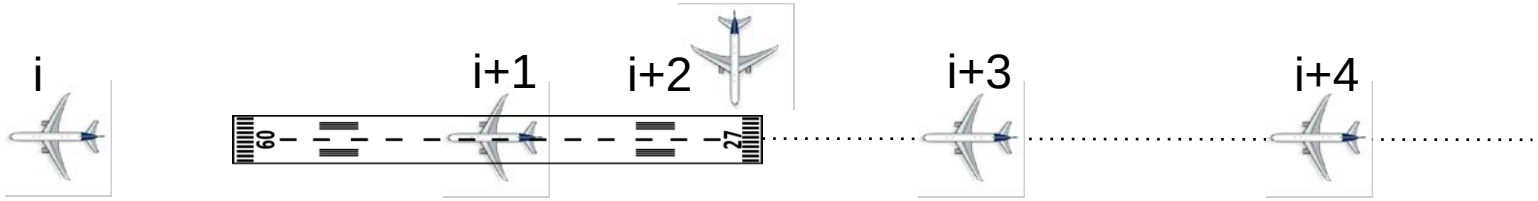
Running the Simulation Model

- **Traffic generation**
  - Model generates a sequence of 1000 aircraft based on user defined fleet mix (e.g. L, L, S, L, L, L , H, H, 7, S, L, L…)
  - Puts constant pressure on airport
  - The sequence is generated for all arrival-departure ratios
  - Model assigns a type of movement (DEP or ARR) for every aircraft in sequence
  - Total number of simulation runs per scenario: 101,000
- **Fleet performance assignment**
  - Final approach speed assigned to every arrival (user specified)
  - Runway occupancy time assigned to every arrival (user specified)
  - Touchdown distance assigned to every arrival (model specified)
    - Based on literature study
    - Normal distribution with mean of 1400ft and standard deviation of 150ft
  - Arrival deceleration assigned (model specified)
    - Normal distribution with mean of 10ft/s^2 and standard deviation of 2ft/s^2 (Boeing)
  - Departure acceleration assigned (model specified)
    - Normal distribution with mean of 8.4ft/s^2 and standard deviation of 0.4ft/s^2

Simulation Model – Airspace Logic
Single Runway Scenario

- Model goes from aircraft to aircraft in sequence and determines the inter-movement time based on required separations and airspace logic

  - Check departure separation: depMatrix(i,i+2)
  - Check if runway is clear: ROTa(i+1)
  - Check if next landing is far enough (i+2,i+3)

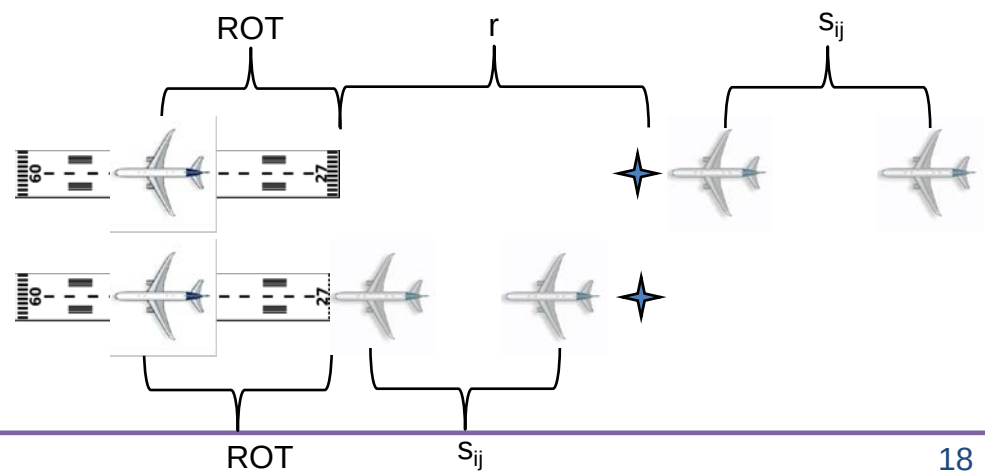


  - Check for previous arrival: arrMatrix(i+1,i+3)
  - Check if runway is clear: ROTa(i+1), ROTd(i+2)

  - Check if runway is clear: ROTa(i+3)
  - Check arrival separation: arrMatrix(i+3,i+4)
  - Compare approach speeds (i+3,i+4)

$$T_{ij} = max\left[\frac{r+s_{ij}}{v_j} - \frac{r}{v_i}, ROT_i\right] \text{ when } v_i > v_j \text{ “opening case”}$$

$$T_{ij} = max\left[\frac{s_{ij}}{v_j}, ROT_i\right] \text{ when } v_i \leq v_j \text{ “closing case”}$$

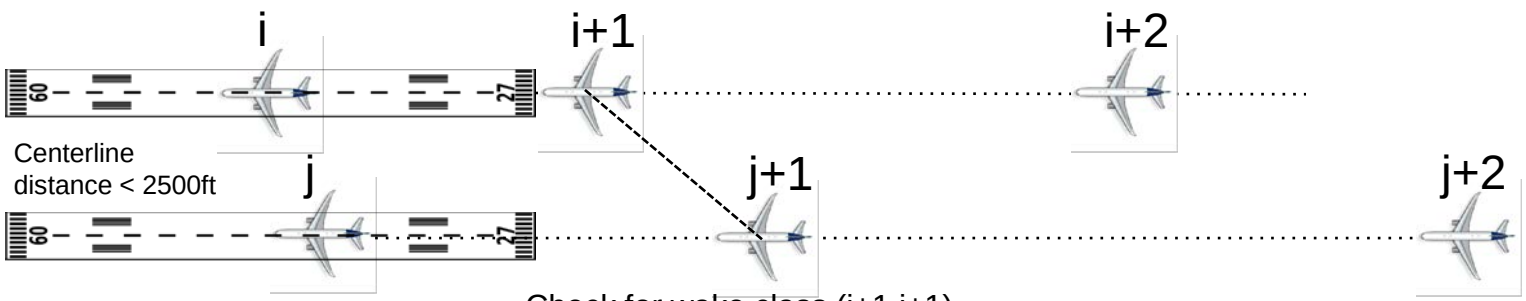


Simulation Model – Airspace Logic
CSPR Scenario

- **CSPR Approaches**

  - Check for ROTa(i)
  - Check arrival separation arrMatrix(i,i+1)

  - Check for ROTa(i+1)
  - Check for separation arrMatrix(i+1,i+2) and arrMatrix(j+1,i+2)

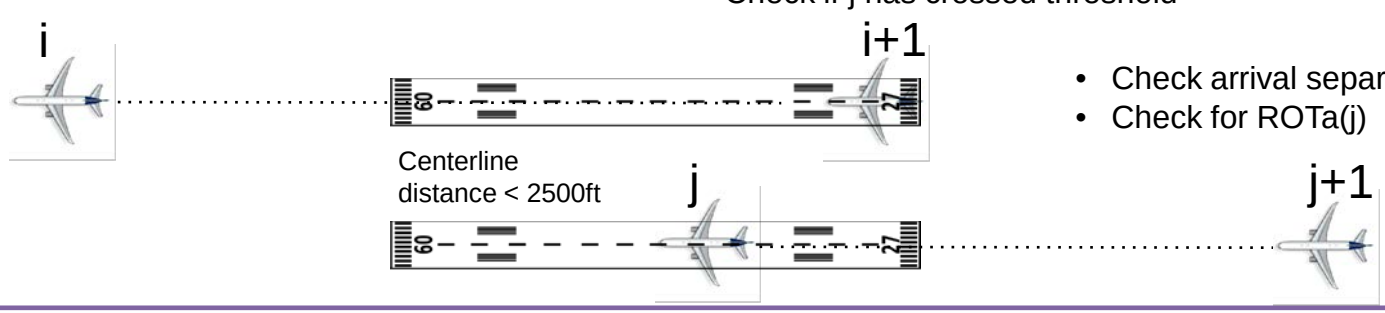


  - Check for wake class (i+1,j+1)
  - Check arrival separation arrMatrix(j,j+1) and diagMatrix(i+1,j+1)
  - Check for ROTa(j)

- **CSPR Different Arrival and Departure Runways**

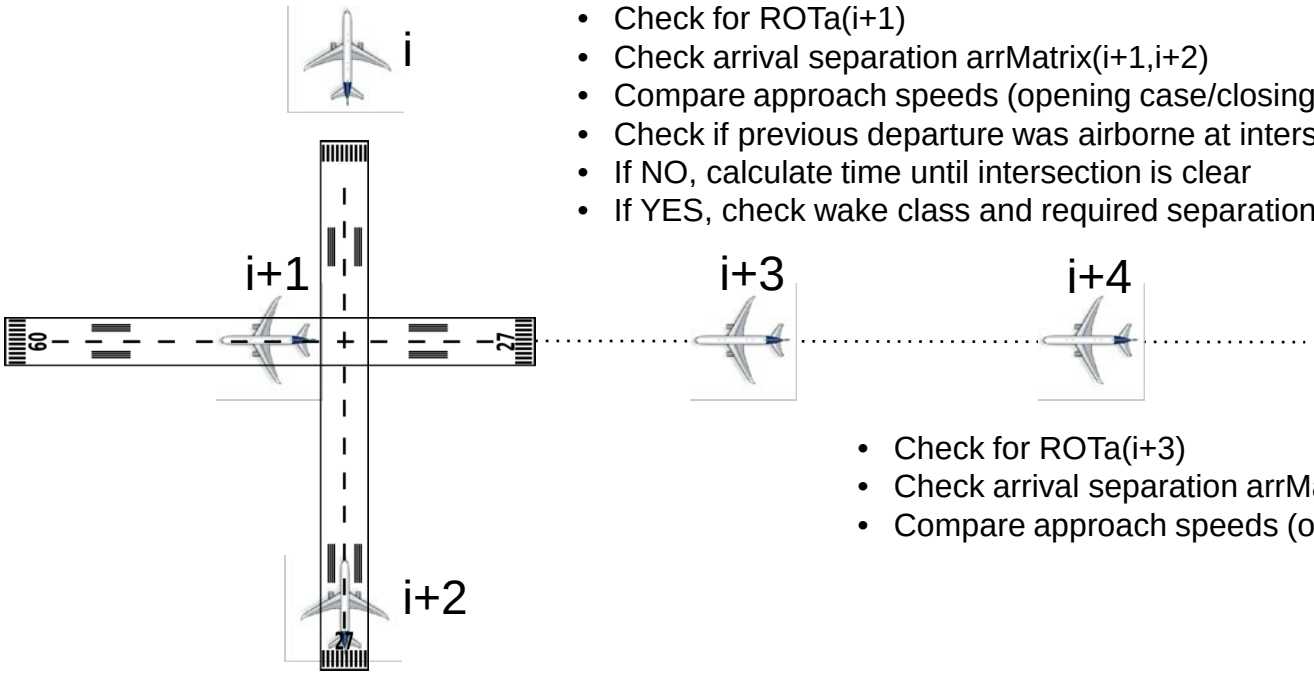
  - Check for ROTd(i)
  - Check departure separation depMatrix(i,i+1)
  - Check if j has crossed threshold

  - Check arrival separation arrMatrix(j,j+1)
  - Check for ROTa(j)



Simulation Model – Airspace Logic Crossing Runways Scenario

- For two consecutive arrivals or two consecutive departures: single runway rules
- More complex rules when departure follows arrival or arrival follows departure

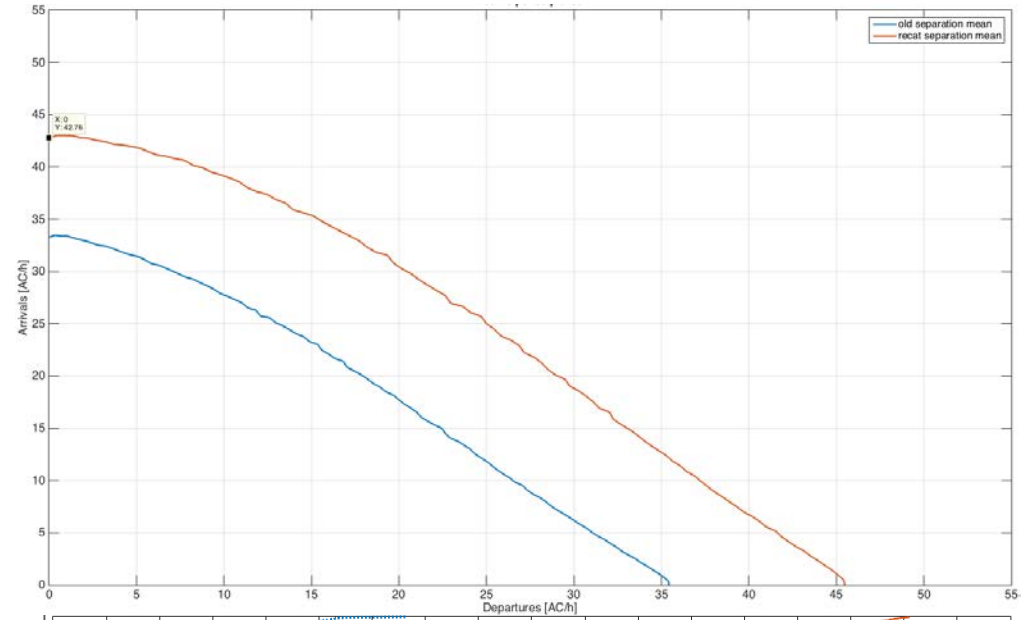


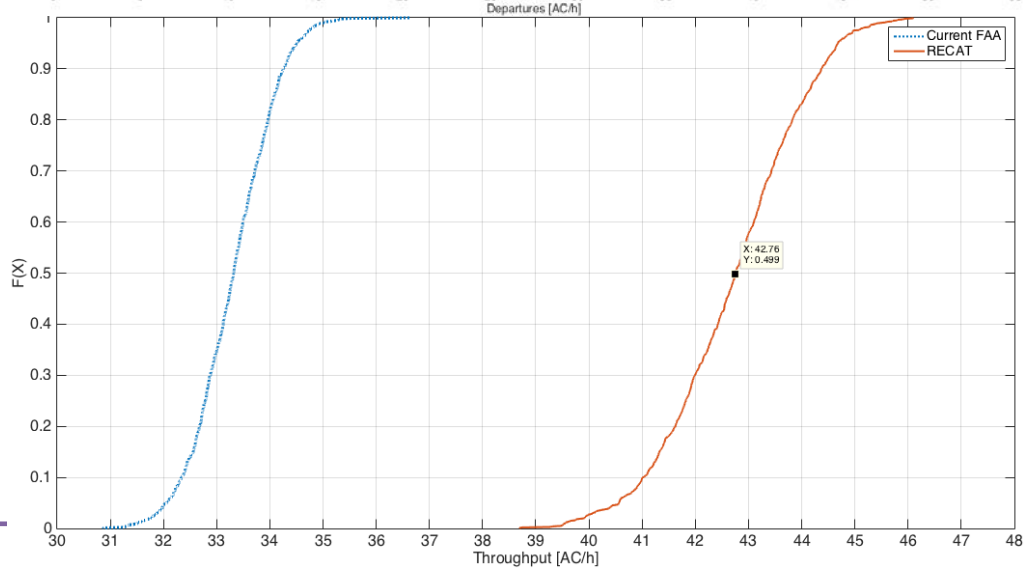
- Check for ROTa(i+1)
- Check arrival separation arrMatrix(i+1,i+2)
- Compare approach speeds (opening case/closing case)
- Check if previous departure was airborne at intersection (i+2,i+3)
- If NO, calculate time until intersection is clear
- If YES, check wake class and required separation: crossMatrix(i+2,i+3)

- Check for ROTa(i+3)
- Check arrival separation arrMatrix(i+3,i+4)
- Compare approach speeds (opening case/closing case)

- Check for ROTd(i)
- Check departure separation: depMatrix(i,i+2)
- Check next arrival is far enough (i+2,i+3)
- Check if intersection is clear (i+1,i+2)
- Check if previous arrival was airborne at intersection (i+1,i+2)
- If NO, calculate time until intersection is clear
- If YES, check weight class and required separation: crossMatrix(i+1,i+2)

Preliminary Simulation Results – Memphis (MEM) Traffic Mix





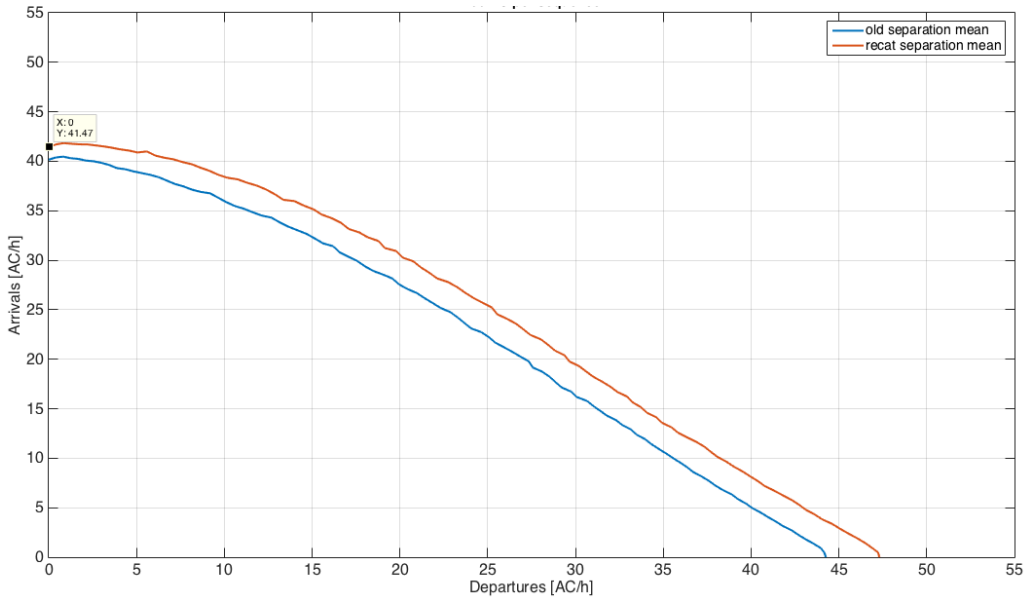
Runway capacity envelope scenario:

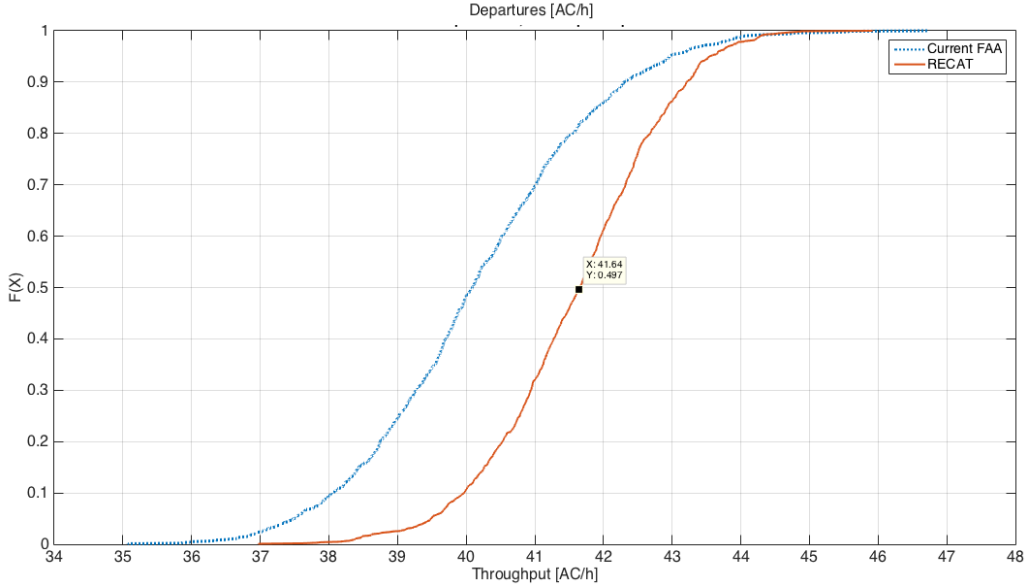
- Single runway mixed mode operations
- Old FAA wake separation rules and RECAT 1.5 rules
- MEM traffic mix (FlightAware – 1 week of data)
- 101,000 simulation runs
- 0.1 NM separation buffer
- No wind
- Recat mean ARR throughput: 42.76 Ac/hr

Empirical CDF:

- Single runway ARRIVALS only
- Old FAA wake separation rules and RECAT 1.5 rules
- MEM traffic mix (FlightAware – 1 week of data)
- 100,000 simulation runs
- 0.1 NM separation buffer
- No wind
- Recat mean ARR throughput: 42.76 Ac/hr

Preliminary Simulation Results – Los Angeles (LAX) Traffic Mix





Runway capacity envelope scenario:

- Single runway mixed mode operations
- Old FAA wake separation rules and RECAT 1.5 rules
- LAX traffic mix (FlightAware – 1 week of data)
- 101,000 simulation runs
- 0.1 NM separation buffer
- No wind
- Recat mean ARR throughput: 41.47 Ac/hr

Empirical CDF:

- Single runway ARRIVALS only
- Old FAA wake separation rules and RECAT 1.5 rules
- LAX traffic mix (FlightAware – 1 week of data)
- 100,000 simulation runs
- 0.1 NM separation buffer
- No wind
- Recat mean ARR throughput: 41.64 Ac/hr

Ongoing work and Next Steps

- **Finish converging runway configuration model**
- **Superimpose baseline configurations for more complex airport layouts:**
  - Relatively simple when runways have minimum or no dependencies
  - Requires basic adjustments when runways are dependent
    - E.g. SFO has two pairs of crossing CSPR
- **Model verification and fine tuning:**
  - Take fleet mix from a few airports with corresponding separation rules and compare airport capacity results with ASPM throughput and called rates
- **Integrate go-around re-sequencing into model**

Ongoing work and Next Steps

- **Simulation of dynamic separations**
  - Assumed best case scenario: highest airport capacity with existing infrastructure and given fleet mix can be achieved when wake separation is completely eliminated and only ROT dictates separations
  - Apply cross wind binary classification to look at airport capacity benefits of eliminated wake separations
- **Calculating delays due to wake separation requirements**
  - Delays can occur for many reason, but delays due to wake separation can be quantified relative to each other
  - Delays occurs when an airplane is ready to take off/land but the previous aircraft prohibits this
  - Calculate nominal time, measure any additional time due to wake separation as delay

Questions?