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

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• 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
Wake Vortex Turbulence

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

Current final approach separation standards applied (JO 7110.65T):

<table>
<thead>
<tr>
<th>Leader\Follower</th>
<th>Heavy</th>
<th>Large</th>
<th>Small</th>
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<tr>
<td>Heavy</td>
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<td>5</td>
<td>6</td>
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<tr>
<td>Boeing 757</td>
<td>4</td>
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<td>Large</td>
<td>2.5</td>
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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 MTOW

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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.
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

<table>
<thead>
<tr>
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<th>C</th>
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Example of a Heavy-Heavy pair (Boeing 747 - Boeing 767)

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

Current 4NM separation is safe
• **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](image)

• **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

- **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.
• **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
• 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

Airport Capacity (and Delays)
- 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
- Provide scenario based airport capacity estimates
- Possibly include metric for delays
Airport Capacity calculations

• Airport capacity studies are usually based on empirical observations

• 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

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

Increasing details and complexity

Airfield Capacity Model
- TAAM, SIMMOD

Increasing details and complexity
• 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
• **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
• **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

• **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
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/s² and standard deviation of 2ft/s² (Boeing)
  - Departure acceleration assigned (model specified)
    - Normal distribution with mean of 8.4ft/s² and standard deviation of 0.4ft/s²
• 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)

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

\[
T_{ij} = \max \left[ \frac{s_{ij}}{v_j}, \text{ROT}_i \right] \text{ when } v_i \leq v_j \text{ “closing case”}
\]
• **CSPR Approaches**

  - Check for \( \text{ROT}_a(i) \)
  - Check arrival separation \( \text{arrMatrix}(i,i+1) \)
  - Check for \( \text{ROT}_a(i+1) \)
  - Check for separation \( \text{arrMatrix}(i+1,i+2) \) and \( \text{arrMatrix}(j+1,i+2) \)

• **Centerline distance < 2500ft**

  - Check for wake class \( (i+1,j+1) \)
  - Check arrival separation \( \text{arrMatrix}(j,j+1) \) and \( \text{diagMatrix}(i+1,j+1) \)
  - Check for \( \text{ROT}_a(j) \)

• **CSPR Different Arrival and Departure Runways**

  - Check for \( \text{ROT}_d(i) \)
  - Check departure separation \( \text{depMatrix}(i,i+1) \)
  - Check if \( j \) has crossed threshold

  - Check arrival separation \( \text{arrMatrix}(j,j+1) \)
  - Check for \( \text{ROT}_a(j) \)
• For two consecutive arrivals or two consecutive departures: single runway rules
• More complex rules when departure follows arrival or arrival follows departure

Simulation Model - Airspace Logic Crossing Runways Scenario

- 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)
- If NO, calculate time until intersection is clear
- If YES, check weight class and required separation: crossMatrix(i+1,i+2)

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