Review of Airport Runway Capacity

Airport Capacity

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Falls Church, Virginia
June 9-12, 2003
Methodologies to Assess Airport Capacity

The capacity of an airport is a complex issue. Several elements of the airport facility have to be examined. Namely: a) Airside and b) Landside components.
Airport and Airspace Components

The following components of NAS need to be examined:

a) Airside
   - Airspace
   - Runways
   - Taxiways

b) Landside
   - Gates
   - Terminal
   - Access road
Factors Affecting Runway Capacity

There are numerous factors that affect runway capacity. Here are some of the most relevant:

- Runway configuration (number of runways in use, location of runway exits, etc.)
- Aircraft mix (percent of aircraft in various wake vortex categories)
- Weather conditions (visibility, ceiling, wind direction and speed)
- Airport equippage (type of navaids, ATC equipment)
- Operating procedures (noise considerations, special approach and departure procedures)
Runway Separations at Airports Depend on Airport Surveillance Technology

The same technology used to establish the position of aircraft in the airspace is used to perform surveillance activities near airports

- Radar technology has inherent weaknesses for surveillance
- The farthest from the antenna, the larger the uncertainty to determine accurate positions
- Primary radar (skin paint)
- Secondary radar (transponder inside aircraft - Modes C and S)
Independent ILS or Precision Approaches

- IFR operational conditions
- 4,300 ft. between runway centerlines
- Standard radar systems (scan rate of 4.8 seconds or more)
- Radar surveillance is available

Airport Terminal

Runway 1

4,300 ft. or more

Independent arrival streams

Runway 2
Independent Parallel Approaches using the Precision Runway Monitor (PRM) in IFR

- The purpose of this standard is to use the Precision Runway Monitor (PRM) to allow independent ILS approaches to parallel runways separated down to 3,000 feet (FAA, 1998)
- This standard currently applies with PRM (fast-scan technology)
- Radar scan rate of 1 second or less
What is a PRM - Precision Runway Monitor?

Two pieces of software and hardware comprise the PRM system:

- Air Traffic Controller display (shows the aircraft blips plus the NTZ - No Transgression Zone (NTZ))
- Fast scanning radar (with $\tau \leq 1.0$ seconds)

This system reduces the uncertainty of knowing where aircraft are (i.e., thanks to its fast scan rate)
Independent Triple and Quadruple Approaches To Parallel Runways (IFR)

- The idea behind this concept is to allow triple and quadruple parallel approaches to runways separated by 5,000 feet using **standard radar systems** (scan update rate of 4.8 seconds) at airports having field elevations of less than 1,000 feet.

- Increase to 5,300 ft. spacing between runways for elevations above 5,000 ft.

---

Runway 1

Runway 2

Runway 3

5,000 ft. or more
Independent Departures in IFR Conditions and Standard Radar ($\tau \Rightarrow 4.8$ s.)

- Simultaneous departures can be conducted if two parallel runways are located 2,500 ft.

![Diagram of two parallel runways 2,500 ft apart with aircraft departing simultaneously]
Independent Departures and Arrivals in IFR Conditions and Standard Radar ($\tau \Rightarrow 4.8$ s.)

- Simultaneous departures and arrivals can be conducted if two parallel runways are located 2,500 ft.

**Departure Stream**

![Diagram of Departure Stream]

**Arrival Stream**

![Diagram of Arrival Stream]
Staggered Runways Rule (Decreasing Separation)

If two parallel runways are staggered (i.e., their runway thresholds are offset) use:

- Decrease runway centerline separation by 100 ft. for every 500 ft. of stagger

Runway 1

2,300 ft.

Runway 2

1,000 ft.
Staggered Runways Rule (Increasing Runway Centerline Separation)

If two parallel runways are staggered (i.e., their runway thresholds are offset) use:

- Increase runway centerline separation by 100 ft. for every 500 ft. of stagger
Independent Arrivals under VFR Conditions

Independent simultaneous arrivals can be conducted with at least 700ft between runway centerlines if:

- VFR conditions (visibility > 3 nm)
- No wake vortex effect is present

Runway 1

---

Runway 2

Independent arrival streams

No wake vortex effect (seldom the case)

700 ft. or more

Increase to 1,200 ft. if aircraft belong to Design groups V and VI
Independent Simultaneous Approaches to Converging Runways

Procedures governing independent converging approaches require that the distance between the missed approach points be 3 n.m. apart and that the Terminal Instrument Procedures (TERPS) surfaces not overlap. Because of these restrictions, minimums are high, thereby limiting the number of airports.
Dependent Approaches to Parallel Runways (IFR)

Procedures exist to conduct dependent arrivals when runway separation is below 4,300 ft. and above 2,500 ft. (standard radar).

- Runway 1
- Runway 2

Dependent arrival streams:
- 2,500 ft. or more
- 1.5 nm
- 1.5 nm
Methodologies to Study Airport Capacity/Delay

- Analytic models
  - Easier and faster to execute
  - Good for preliminary airport/airspace planning (when demand function is uncertain)
  - Results are generally less accurate but appropriate

- Simulation-based models
  - Require more work to execute
  - Good for detailed assessment of existing facilities
  - Results are more accurate and microscopic in nature
Methodologies in Use to Study Capacity/Delay

• Analytic models
  - Time-space analysis
  - Queueing models (deterministic and stochastic)

• Simulation-based models
  - Monte Carlo Simulation
  - Continuous simulation models
  - Discrete-event simulation models
Time-Space Analysis

- A simple technique to assess runway and airspace capacity if the headway between aircraft is known.

- The basic idea is to estimate an expected headway, $E(h)$, and then estimate capacity as the inverse of the expected headway.

$$\text{Capacity} = \frac{1}{E(h)}$$

$E(h)$ is expressed in time units (e.g., seconds).
Time-Space Analysis Nomenclature

\( \delta_{ij} \) is the minimum separation matrix (nm)

\( T_{ij} \) is the headway between two successive aircraft (s)

\( \delta \) is the minimum arrival-departure separation (nm)

\( ROT_i \) is the runway occupancy time for aircraft \( i \) (s)

\( \sigma_0 \) is the standard deviation of the in-trail delivery error (s)

\( V_i \) is the speed of aircraft \( i \) (lead aircraft) in knots
Time-Space Analysis Nomenclature

\( V_j \) is the trailing aircraft speed (knots)

\( \gamma \) is the common approach length (nm)

\( B_{ij} \) is the buffer times matrix between successive aircraft (s)

\( q_v \) is the value of the cumulative standard normal at probability of violation \( p_v \)

\( p_v \) is the probability of violation of the minimum separation criteria between two aircraft
Final Approach and Landing Processes

Space

Runway

ROT$_i$

TD$_i$

ROT$_j$

Time

$\gamma$

$T_i$

$V_i$

$T_j$

$V_j$

Entry Gate
Possible Outcomes of a Single Runway Time-Space Diagram

Since aircraft approaching a runway arrive in a random pattern we distinguish between two possible scenarios:

- **Closing case** - Instance when the approach of the lead aircraft is less than that of the trailing aircraft ($V_i \leq V_j$)
- **Opening Case** - Instance when the approach speed of lead aircraft is higher than trailing aircraft ($V_i > V_j$)
**Closing Case (Equations)**

*Error Free Headway* (assume no pilot and ATC controller error) assuming control is exercised as the lead aircraft passes the entry gate

\[
T_{ij} = \frac{\delta_{ij}}{V_j}
\]  
(1)

*Position Error Consideration* (with pilot and ATC controller error)

\[
B_{ij} = \sigma_o q_v
\]  
(2)

\[
\text{(3)}
\]
Opening Case Diagram (Arrivals Only)

Space

Runway

ROT$_i$

ROT$_j$

Time

Entry Gate

$\gamma$

$\delta_{ij}$

$V_i > V_j$

$V_i$

$V_j$

$T_i$

$T_j$

$\delta_{ij}$

$\gamma$

$V_i$

$V_j$

$T_i$

$T_j$
Opening Case (Equations)

**Error Free Headway** (no pilot and ATC controller error) assuming control is exercised as the lead aircraft passes the entry gate

\[ T_{ij} = \frac{\delta_{ij}}{V_j} + \gamma \left( \frac{1}{V_j} - \frac{1}{V_i} \right) \]  \hspace{1cm} (4)

**Position Error Consideration** (with pilot and ATC controller error)

\[ B_{ij} = \sigma_o q_v - \delta_{ij} \left( \frac{1}{V_j} - \frac{1}{V_i} \right) \text{ or zero if } B_{ij} < 0. \]  \hspace{1cm} (5)
Notes on Buffer Times

- According to the model presented buffer times increase with larger values of

- For the opening case, the buffer time $B_{ij}$ could become negative under some circumstances (see equation 6).

$$B_{ij} = \sigma_o q_v - \delta_{ij} \left( \frac{1}{V_j} - \frac{1}{V_i} \right) \text{ or zero if } B_{ij} < 0.$$  \quad (6)

if $B_{ij} < 0$ then use zero for the buffer time.
Understanding Position Errors

Distribution of Aircraft Position

No Buffer

Runway

Real Aircraft Position

Distribution of Aircraft Position

With Buffer

Runway

\( \delta_{ij} \)

\( \sigma_o q_v V_j \)
Closing Case Diagram (Arrivals Only)

Space \hspace{1cm} \text{Runway} \hspace{1cm} \text{ROT}_i \hspace{1cm} \text{ROT}_j \hspace{1cm} \text{Time}

\[ V_i < V_j \]

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Closing Case (Equations)

*Error Free Headway* (no pilot and ATC controller error) assuming control is exercised as the lead aircraft passes the entry gate

\[ T_{ij} = \frac{\delta_{ij}}{V_j} \]  

(7)

*Position Error Consideration* (with pilot and ATC controller error)

\[ B_{ij} = \sigma_o q_v \]  

(8)

(9)
Mixed Operations Diagram

\[ T_1 = T_i - \text{ROT}_i \]
\[ T_2 = T_j - \delta / V_j \]
\[ G = T_2 - T_1 > 0 \]

\[ E[T_{ij} + B_{ij}] = E[\delta / V_j] + E[\text{ROT}_j] + (n-1) E(TD_i) + \sigma_g q_{vg} \]
### ATC Arrival-Arrival Wake Vortex Separations (I)

**IFR In-trail Separations Near Runways in nautical miles for Medium and Small Size Hub Airports**

<table>
<thead>
<tr>
<th>LEAD ACFT.</th>
<th>Trailing Aircraft</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heavy</td>
<td>Large</td>
<td>Small</td>
</tr>
<tr>
<td>Heavy</td>
<td>4.00</td>
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</tr>
<tr>
<td>Large</td>
<td>3.00</td>
<td>3.00</td>
<td>4.00</td>
</tr>
<tr>
<td>Small</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
</tr>
</tbody>
</table>

**NOTE:** for Boeing 757 when taken as a separate class use 4/4/5 nm respectively (add one more row to the table above)
## ATC Arrival-Arrival Wake Vortex Separations (II)

IFR In-trail Separations Near Runways in nautical miles for Large Size Hub Airports

<table>
<thead>
<tr>
<th>LEAD ACFT.</th>
<th>Trailing Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heavy</td>
</tr>
<tr>
<td>Heavy</td>
<td>4.00</td>
</tr>
<tr>
<td>Large</td>
<td>2.50</td>
</tr>
<tr>
<td>Small</td>
<td>2.50</td>
</tr>
</tbody>
</table>

NOTE: for Boeing 757 when taken as a separate class use 4/4/5 nm respectively (add one more row to the table above)
## Departure-Departure ATC Separations

**IFR In-trail Departure Separations Near Runways in seconds**

<table>
<thead>
<tr>
<th>LEAD ACFT.</th>
<th>Trailing Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>Heavy 90</td>
</tr>
<tr>
<td>Large</td>
<td>60</td>
</tr>
<tr>
<td>Small</td>
<td>60</td>
</tr>
</tbody>
</table>

**NOTE:** for Boeing 757 when taken as a separate class use 90/90/120 seconds respectively (add one more row to the table above)
Review of Runway Capacity Excel Program

- The Excel template provided in class attempts to illustrate how the time-space diagram technique can be “programmed” in a standard spreadsheet.

- You can extend the analysis provided in the basic template to more complex airport configurations.

- The program, as it stands now, can only estimate the saturation capacity of a single runway. The program provides a simple graphical representation of the arrival-departure saturation diagram (sometimes called capacity Pareto frontier in the literature).
Excel Template Flowchart

Enter runway operation technical parameters
- Arrival minimum separation matrix ($\delta_{ij}$)
- Departure-departure separation matrix ($\epsilon_{ij}$)
- Arrival-departure minimum separation ($\delta$)
- Common approach length ($\gamma$)
- Runway occupancy times ($\text{ROT}_i$)
- Runway departure times ($t_d$)
- Aircraft mix ($P_i$)
- Standard deviation of intrail delivery error ($s_o$)
- Probability of separation violations ($P_v$)

1. Compute Expected value of ROT times ($E(\text{ROT})$)
   - $E(\text{ROT}_i)$

2. Estimate the “Error-Free” separation matrix
   - $T_{ij}$ values using opening and closing cases

3. Compute expected value of the error-free matrix
   - $E(T_{ij})$

4. Estimate the “Buffer” separation matrix
   - $B_{ij}$ values using opening and closing cases

5. Compute expected value of the buffer matrix
   - $E(B_{ij})$
**Excel Template Flowchart (continuation)**

5. Compute augmented separation matrix
   - $A_{ij} = T_{ij} + B_{ij}$ (error-free + buffer)

6. Compute the probability matrix (i follows j)
   - $P_{ij}$

7. Compute expected value of $A_{ij}$ matrix
   - $E(A_{ij}) = E(T_{ij} + B_{ij})$

8. Compute expected value of departure-departure matrix
   - $E(\epsilon_{ij})$

9. Compute gaps for n departures (n=1,2,...,5)
   - $E(G_n)$

10. Compute feasible departures per arrival gap (implemented as an Excel Macro)

Compute arrivals-only runway saturation capacity $C_{arr}$

Compute departures-only runway saturation capacity $C_{dep}$
Excel Template Flowchart (continuation)

11. Compute number of departures per gap if arrivals have priority

12. Draw the arrival-departure diagram using points:
   - $C_{arr}$
   - $C_{dep}$
   - $C_{dep-arr-priority}$

End

Departure capacity with arrival priority $C_{dep-arr-priority}$
Computer Program Screen 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>δ</td>
<td>2</td>
</tr>
<tr>
<td>γ</td>
<td>7</td>
</tr>
<tr>
<td>σ</td>
<td>18</td>
</tr>
<tr>
<td>P_y</td>
<td>5</td>
</tr>
<tr>
<td>q_ν</td>
<td>1.65</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Technical Parameters (inputs)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Runway Saturation Capacity Estimation</td>
<td></td>
</tr>
<tr>
<td>Using the Analytical Model of Harris</td>
<td></td>
</tr>
<tr>
<td>Programmer: A. Trani (September 22, 2000)</td>
<td></td>
</tr>
<tr>
<td>Amendments: 13-Mar-01 Added some comments and</td>
<td></td>
</tr>
<tr>
<td>VFR separation multiple</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Small</th>
<th>Large</th>
<th>Heavy</th>
<th>Total %</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROT (s)</td>
<td>47</td>
<td>52</td>
<td>59</td>
<td>53.6 E(ROT)</td>
</tr>
<tr>
<td>Percent Mix Percent Mix</td>
<td>10</td>
<td>60</td>
<td>30</td>
<td>100 Total %</td>
</tr>
<tr>
<td>V_{approach} (ks)</td>
<td>110</td>
<td>130</td>
<td>145</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Minimum Separation Matrix (nm)</th>
<th>Arrivals-Arrivals</th>
<th>Hub Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>Trailing</td>
<td>Small</td>
</tr>
<tr>
<td>Small</td>
<td>Large</td>
<td>Weather Conditions</td>
</tr>
<tr>
<td>Small</td>
<td>Heavy</td>
<td>IFR</td>
</tr>
<tr>
<td>Large</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Computer Program (Screen 2)

### Table 1: Error Free Separation Matrix

<table>
<thead>
<tr>
<th></th>
<th>Small</th>
<th>Large</th>
<th>Heavy</th>
<th>Expected Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>98.18</td>
<td>83.08</td>
<td>74.48</td>
<td>E(Tij)</td>
</tr>
<tr>
<td>Large</td>
<td>198.88</td>
<td>83.08</td>
<td>74.48</td>
<td></td>
</tr>
<tr>
<td>Heavy</td>
<td>284.39</td>
<td>158.51</td>
<td>99.31</td>
<td>96.08</td>
</tr>
</tbody>
</table>

### Table 2: Fij Matrix

<table>
<thead>
<tr>
<th></th>
<th>Small</th>
<th>Large</th>
<th>Heavy</th>
<th>Sum of Fij</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>0.010</td>
<td>0.060</td>
<td>0.030</td>
<td>0.10</td>
</tr>
<tr>
<td>Large</td>
<td>0.060</td>
<td>0.360</td>
<td>0.180</td>
<td>0.60</td>
</tr>
<tr>
<td>Heavy</td>
<td>0.030</td>
<td>0.180</td>
<td>0.090</td>
<td>0.30</td>
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</tbody>
</table>

### Table 3: Buffer Matrix

<table>
<thead>
<tr>
<th></th>
<th>Small</th>
<th>Large</th>
<th>Heavy</th>
<th>Expected Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>29.70</td>
<td>29.70</td>
<td>29.70</td>
<td>B(Tij)</td>
</tr>
<tr>
<td>Large</td>
<td>4.53</td>
<td>29.70</td>
<td>29.70</td>
<td></td>
</tr>
<tr>
<td>Heavy</td>
<td>0.00</td>
<td>15.38</td>
<td>29.70</td>
<td>24.72</td>
</tr>
</tbody>
</table>
### Computer Program (Screen 3)

#### Augmented Matrix

<table>
<thead>
<tr>
<th>Small</th>
<th>Large</th>
<th>Heavy</th>
<th>Expected Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>127.88</td>
<td>112.78</td>
<td>104.18</td>
<td>E(Tij) + B(Tij)</td>
</tr>
<tr>
<td>203.41</td>
<td>112.78</td>
<td>104.18</td>
<td>134.17</td>
</tr>
<tr>
<td>284.39</td>
<td>173.89</td>
<td>129.01</td>
<td></td>
</tr>
</tbody>
</table>

#### Arrivals Only Capacity (per hour)

- 26.83

#### Departure-Departure Separation Matrix (km)

<table>
<thead>
<tr>
<th>Small</th>
<th>Large</th>
<th>Heavy</th>
<th>Expected Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>60</td>
<td>60</td>
<td>E(Tij)</td>
</tr>
<tr>
<td>90</td>
<td>90</td>
<td>90</td>
<td>82.5</td>
</tr>
<tr>
<td>120</td>
<td>90</td>
<td>90</td>
<td></td>
</tr>
</tbody>
</table>

#### Departures Only Capacity (per hour)

- 43.64

#### Estimation of Critical Departure Gaps

<table>
<thead>
<tr>
<th>Departures</th>
<th>Gap (EΔTij)</th>
<th>E(ROT)</th>
<th>E(ΔVij)</th>
<th>E(g*qv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>126.21</td>
<td>53.60</td>
<td>59.41</td>
<td>13.20</td>
</tr>
<tr>
<td>2</td>
<td>208.71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>291.21</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>373.71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>456.21</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Computer Program (Screen 4)

<table>
<thead>
<tr>
<th>Departures per Gap</th>
<th>Trailing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>1.00</td>
</tr>
<tr>
<td>Large</td>
<td>1.00</td>
</tr>
<tr>
<td>Heavy</td>
<td>2.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Departures per hour with 100% Arrival Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
</tr>
<tr>
<td>0.26</td>
</tr>
<tr>
<td>1.55</td>
</tr>
<tr>
<td>1.55</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Expected Value</th>
<th>0.26</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.55</td>
</tr>
<tr>
<td></td>
<td>8.52</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Summary for Arrival - Departure Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrivals</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>26.83</td>
</tr>
<tr>
<td>26.83</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

Total Departures with 100% arrival priority: 10.33
Computer Program (Screen 5)

Arrival - Departure Diagram

Arrivals (per hour)

Departures (per hour)
Estimating Runway Saturation Capacity for Complex Airport Configurations

• The methodology explained in the previous handout addresses a simple Time-Space diagram technique to estimate the runway saturation capacity.

• The time-space approach can also be used to estimate the saturation capacity of more complex runway configurations where interactions occur between runways.

• Example problems taken from the FAA Airport Capacity benchmark document will be used to illustrate the points made.
Methodology

- Understand the runway use according to ATC operations
- Select a primary runway as the basis for your analysis
- Estimate the saturation capacity characteristics of the primary runway using the known time-space method
- Examine gaps in the runway operations at the primary runway. These gaps might exist naturally (i.e., large arrival-arrival separations) or might be forced by ATC controllers by imposing large in-trail separations allowing operations at other runways
• If runway operations are independent you can estimate arrival and departure saturation capacities for each runway independently

• If the operations on runways are dependent estimate the runway occupancy times (both for arrivals and departures) very carefully and establish a logical order of operations on the runways.
Example 1 - Charlotte-Douglas Intl. Airport

Operational Conditions

1) Runways 18R/36L and 18L/36R are used in mixed operations mode
2) Runway 5/23 is inactive
3) Parallel runway separation > 4,300 ft.
4) ASR-9 airport surveillance radar (scan time 4.8 seconds)
5) Aircraft mix
   a) Heavy - 20%
   b) Large - 30%
   c) Small - 50%
6) Approach speeds
   a) Heavy - 150 knots
   b) Large - 140 knots
   c) Small - 110 knots
7) Runway occupancy times
   a) Heavy - 57 s.
   b) Large - 52 s.
   c) Small - 49 s.
8) Common approach length - 7 nm
9) In-trail delivery error standard deviation -18 s.
10) Large hub separation criteria (2.5/4/5/6 nm)
11) IMC weather conditions
Some Intermediate Results

Augmented Matrix

<table>
<thead>
<tr>
<th></th>
<th>Small</th>
<th>Large</th>
<th>Heavy</th>
<th>Expected Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>111.52</td>
<td>93.99</td>
<td>89.70</td>
<td>E(Tij) + B(Tij)</td>
</tr>
<tr>
<td>Large</td>
<td>181.65</td>
<td>93.99</td>
<td>89.70</td>
<td>132.51</td>
</tr>
<tr>
<td>Heavy</td>
<td>257.45</td>
<td>161.70</td>
<td>125.70</td>
<td></td>
</tr>
</tbody>
</table>

Arrivals Only Capacity (per hour) 27.17

Departure-Departure Separation Matrix (seconds)

<table>
<thead>
<tr>
<th></th>
<th>Small</th>
<th>Large</th>
<th>Heavy</th>
<th>Expected Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>E(Td)</td>
</tr>
<tr>
<td>Large</td>
<td>90</td>
<td>60</td>
<td>60</td>
<td>76.5</td>
</tr>
<tr>
<td>Heavy</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td></td>
</tr>
</tbody>
</table>

Departures Only Capacity (per hour) 47.06
Results of CLT Analysis

Single runway analysis - mixed operations
Results of CLT Analysis

Two-parallel runway analysis - mixed operations

Arrivals per Hour

54

0

Departures per Hour

23

95

50% arrivals
50% departures
The FAA capacity benchmarks offer an assessment of the estimated capacity by the FAA.

### Table 1
Capacity Benchmarks for Today’s Operations at 31 Airports

<table>
<thead>
<tr>
<th>Airport</th>
<th>Optimum</th>
<th>Reduced</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATL (Atlanta Hartsfield International)</td>
<td>185–200</td>
<td>167–174</td>
</tr>
<tr>
<td>BOS (Boston Logan International)</td>
<td>118–126</td>
<td>78–88</td>
</tr>
<tr>
<td>BWI (Baltimore-Washington International)</td>
<td>111–120</td>
<td>72–75</td>
</tr>
<tr>
<td>CLT (Charlotte/Douglas International)</td>
<td>130–140</td>
<td><strong>108–116</strong></td>
</tr>
<tr>
<td>CVG (Cincinnati-Northern Kentucky)</td>
<td>123–125</td>
<td>121–125</td>
</tr>
</tbody>
</table>

Reduced capacity = IMC conditions
Variations occur because the assumptions made in our example are not necessarily the same as those made by FAA.
Example 2 - Charlotte-Douglas Intl. Airport

Operational Conditions

1) Runway 18R/36L for departures
   Runway 18L/36R for arrivals
2) Runway 5/23 is inactive
3) Parallel runway separation > 4,300 ft.
4) ASR-9 airport surveillance radar
   (scan time 4.8 seconds)
5) Aircraft mix
   a) Heavy - 20% 
   b) Large - 30% 
   c) Small - 50%
6) Approach speeds 
   a) Heavy - 150 knots 
   b) Large - 140 knots 
   c) Small - 110 knots 
7) Runway occupancy times 
   a) Heavy - 57 s. 
   b) Large - 52 s. 
   c) Small - 49 s. 
8) Common approach length - 7 nm 
9) In-trail delivery error standard deviation -18 s. 
10) Large hub separation criteria (2.5/4/5/6 nm) 
11) IMC weather conditions
Results of CLT Analysis

Two-parallel runway analysis - segregated operations

Original Runway Configuration

New Runway Configuration

Arrivals per Hour

Departures per Hour
Example 3 - Charlotte-Douglas Intl. Airport

Operational Conditions

1) Runways 18R/36L and 18L/36R are used in mixed operations mode
2) Runway 5/23 is inactive
3) Parallel runway separation > 4,3000 ft.
4) ASR-9 airport surveillance radar (scan time 4.8 seconds)
5) Aircraft mix
   a) Heavy - 20%
   b) Large - 30%
   c) Small - 50%
6) Approach speeds
   a) Heavy - 150 knots
   b) Large - 140 knots
   c) Small - 110 knots
7) Runway occupancy times
   a) Heavy - 57 s.
   b) Large - 52 s.
   c) Small - 49 s.
8) Common approach length - 7 nm
9) In-trail delivery error standard deviation -18 s.
10) Large hub separation criteria (2/3/4/5 nm)
11) VMC weather conditions
Results for CLT VMC Scenario

Single runway analysis - mixed operations

![Graph showing the relationship between departures and arrivals per hour]
Results of CLT VMC Analysis
Two-parallel runway analysis - mixed operations

Arrivals per Hour

Departures per Hour

 VM C
 IM C

Virginia Tech
Airport Capacity Model (ACM)

- Model developed by FAA to expedite computations of runway saturation capacity
- Later modified by John Barrer (at MITRE) to be more user friendly (using a Visual Basic Interface)
- Inputs and output of the model are similar to those included in the spreadsheet shown in class
- Provides 7-9 data points to plot the arrival-capacity saturation capacity envelope (Pareto frontier)
Sample Enhanced ACM Results

![Sample Enhanced ACM Results Diagram]

Classes: SMALL MEDIUM LARGE HEAVY
Class Mix [%]: RWY 1: 10 20 50 20
       RWY 2: 10 20 50 20
ARVL ROT [s]: RWY 1: 45 50 50 65
       RWY 2: 45 50 50 65
SPEEDS (kn): 110 120 130 140
DEP ROT's [s]: 34 34 45 49
Wake Vortex Separations [nm]
3 3 3 3
4 3 3 3
4 3 3 3
8 6 5 4
Minimum Time Between Departures [s]
60 60 60 60
100 60 60 60
100 60 60 60
120 120 120 90
Length of Common Path: 7 nm
ARR-DEP SEPARATION: 2 nm
ARRIVAL R.O.T. Std. Dev.: 4 s
INTER-ARRIVAL TIME Std. Dev.: 18 s
DEPARTURE R.O.T. Std. Dev.: 6 s
CLEARED-TO-ROLL Std. Dev.: 0 s

5: TWO PARALLEL RUNWAYS - MIXED MODE ON BOTH
ARR  DEP  TOTAL  ARR%
1  52  6  58  90
2  52  18  70  75
3  52  47  99  53
4  50  50 100  50
5  48  54 102  47
6  25  75 100  25
7  98  98 100  0

ARRIVAL PRIORITY
50-50 CAPACITY
MAXIMUM DEPARTURES
Summary of Results

- The saturation capacity of an airport depends on the runway configuration used.
- The saturation capacity during VMC conditions is higher than during IMC conditions (due to shorter separation minima).
- The variation in technical parameters such as $\gamma$ and $\delta$ affects the results of saturation capacity.
- The estimation of departures with 100% arrival priority in our analysis seems very conservative.
- The time-space analysis does not provide delay results (use deterministic queueing theory or FAA AC 150/5060 to estimate delay).