Airport Capacity - Introduction

Dr. Antonio A. Trani
Professor of Civil and Environmental Engineering
Virginia Polytechnic Institute and State University

Blacksburg, Virginia
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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
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 solid and 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

\[
\text{Capacity} = \frac{1}{E(h)} \quad (1)
\]

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

δ_{ij} is the minimum separation matrix (nm)

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

δ is the minimum arrival-departure separation (nm)

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

σ_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\textsubscript{i} \hspace{1cm} TD\textsubscript{i} \hspace{1cm} ROT\textsubscript{j}

Time

\[\gamma\]

\[V\textsubscript{i}\]

\[V\textsubscript{j}\]

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:

- **Opening Case** - Instance when the approach speed of lead aircraft is higher than trailing aircraft \((V_i > V_j)\)

- **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 Diagram (Arrivals Only)

Space

Runway

ROT_i

ROT_j

Time

Entry Gate

V_i > V_j

δ_{ij}

γ

V_i

V_j

T_i

T_j
Opening Case (Equations)

*Error free headway,* $T_{ij} = T_j - T_i$, (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} (2)

*Position error buffer time* (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} (3)
Understanding Position Errors

Distribution of Aircraft Position

No Buffer

Real Aircraft Position

With Buffer

Distribution of Aircraft Position

\( \sigma_{qV}V_j \)

\( \delta_{ij} \)

50% 50%

5%
Closing Case Diagram (Arrivals Only)

Space

Runway

ROTᵢ

ROTⱼ

Time

Entry Gate

$V_i < V_j$

$T_i$

$T_j$

$\gamma$

$\delta_{ij}$

$V_i$

$V_j$
Closing Case (Equations)

Error free headway, $T_{ij} = T_j - T_i$ (no pilot and ATC controller error) with the minimum separation enforced when the lead aircraft passes the runway threshold,

$$T_{ij} = \frac{\delta_{ij}}{V_j} \quad (4)$$

Position error buffer time (with pilot and ATC controller error) is,

$$B_{ij} = \sigma_o q_v \quad (5)$$
Mixed Operations Diagram

\[ \mathbb{E}[T_{ij} + B_{ij}] = \mathbb{E}[\delta / V_j] + \mathbb{E}[\text{ROT}_i] + (n-1) \mathbb{E}(\text{TD}_k) + \mathbb{E}(\tau) \]

\( T_1 = T_i + \text{ROT}_i \)
\( T_2 = T_j - \delta / V_j \)

Gap (G) exist if \( T_2 - T_1 > 0 \)

\( \text{TD}_i \) is the departure runway occupancy time
Mixed Operations Notes

• The arriving aircraft leave natural gaps in the time space diagram

• When gaps \( (G) \) are sufficiently long, ATC controllers can schedule one or more departures in the gap

• The size of the gaps depends on:
  - Runway occupancy time (for lead aircraft)
  - Runway occupancy time for departing aircraft
  - Minimum departure-departure headway (seconds)
  - Minimum arrival-departure separation \((\delta)\)
Mixed Operations Notes

- In the U.S. the current minimum separation between arrivals and departures \((\delta)\) is 2 nautical miles

Define:

- \(T_1\) as the time when the lead aircraft completes the landing roll (i.e., exits the runway plane)

- \(T_2\) as the time when the following arriving aircraft is \((\delta)\) from the runway threshold

- The gap \((G)\) is the time difference between \(T_2\) and \(T_1\).

\[
G = T_2 - T_1
\]  

(6)
Mixed Operations (Gap Analysis)

Mathematically,

$$T_1 = T_i + ROT_i$$  \hspace{1cm} (7)

and

$$T_2 = T_j - \frac{\delta}{V_j}$$  \hspace{1cm} (8)

then

$$G = T_j - \frac{\delta}{V_j} - (T_i + ROT_i)$$  \hspace{1cm} (9)
Mixed Operations (Gap Analysis)

\[ G = (T_j - T_i) - \frac{\delta}{V_j} - ROT_i \]  \hspace{1cm} (10)

Note that, \((T_j - T_i)\) is the actual headway between the lead and following aircraft \((T_{ij} + B_{ij})\). This actual headway includes the buffer times since air traffic control will apply those buffers to each successive arrival pair. Our analysis now concentrates in finding suitable gaps between successive aircraft arrivals leaving.
Gap Analysis

Assume that we would like to find instances such that the gap is zero. This is the limiting case to schedule one departure between successive arrivals.

\[ 0 = (T_j - T_i) - \frac{\delta}{V_j} - ROT_i \]  \hspace{1cm} (11)

knowing

\[ 0 = (T_{ij} + B_{ij}) - \frac{\delta}{V_j} - ROT_i \]  \hspace{1cm} (12)
Gap Analysis

\[(T_{ij} + B_{ij}) = \frac{\delta}{V_j} + ROT_i\]  \hspace{1cm} (13)

For \(n\) departures in gap \(k\) the expected value of \(T_{ij} + B_{ij}\) has to be longer than:

\[(T_{ij} + B_{ij}) = \frac{\delta}{V_j} + ROT_i + (n - 1)TD_k\]  \hspace{1cm} (14)

where \(TD_k\) is the runway occupancy time of departure \(k\). This expression typically applies under VFR conditions because controllers can dispatch aircraft as
soon as the previous departure clears the runway end (provided that the lead aircraft turns quickly away from runway heading).

Under IMC conditions, the runway occupancy time for a departing aircraft $TD_k$ is smaller than the minimum headway allowed between departures. This happens because under IMC conditions aircraft are expected to follow a prescribed climb procedure and usually navigate to a departure fix before changing heading.

Let $\epsilon_{ij}$ be the minimum departure-departure headway applied by air traffic control. Equation (14) can then be modified to estimate the availability of a gap to release $n$ departures.
Gap Analysis

\[ (T_{ij} + B_{ij}) = \frac{\delta}{V_j} + ROT_i + (n - 1)\varepsilon_{ij} \] (15)

One final term usually added to this equation is a pilot reaction time term to account for a possible delay time (departing aircraft) to initiate the takeoff roll. This time is justified because jet engines used in transport aircraft take a few seconds to “spool up” and generate full thrust. Let \( \tau \) be the time delay (in seconds) for the departing aircraft.
Gap Analysis

Adding the time delay term Equation (14) becomes,

\[
(T_{ij} + B_{ij}) = \frac{\delta}{V_j} + ROT_i + (n - 1)\varepsilon_{ij} + \tau
\] (16)

Since \((T_{ij} + B_{ij})\) is calculated as an expected value in the analysis for arrivals only,

\[
E(T_{ij} + B_{ij}) \geq E\left(\frac{\delta}{V_j}\right) + E(ROT_i) +
\]

\[
(n - 1)E(\varepsilon_{ij}) + E(\tau)
\] (17)
Gap Analysis

The use of Equation (17) allows us to estimate whether the natural gaps left by successive arrivals (expressed as the expected value of \((T_{ij} + B_{ij})\)) is large enough to schedule \(n\) departures.

The practical use of Equation (17) is to compare the actual headways between successive arrivals \((T_{ij} + B_{ij})\) against the sum of all four terms in the right hand side of Equation (17). We do this for various possible departure scenarios that include \(n\) departures (typically 1, 2, 3, ... 6 departures).
Aircraft Categories Used in Airport Runway Analysis

- Today, the FAA employs 5 aircraft groups to establish aircraft separations inside the terminal area:
  - Small, Large, B757, Heavy and Superheavy
  - The class Small + is seldom used for actual separations

- Today, ICAO (international body that regulates aviation activities outside the US) has 4 aircraft groups
  - Light, Medium, Heavy and Superheavy (A380)

- Many air navigation service providers may have deviations from these groups or classes (i.e., NAT UK recognizes 6 groups)
Aircraft Categories Used in Airport Runway Capacity Analyses

- FAA aircraft groups (at maximum takeoff weight)
  - Small (< 41,000 lb)
  - Large (< 255,000 lb)
  - B757
  - Heavy (> 255,000 lb)
  - Superheavy (Airbus A380 and Antonov 225)

- ICAO groups
  - Light (< 7 metric tons)
  - Medium (> 7 tons but < 136 tons)
  - Heavy (> 136 tons)
  - Superheavy (A380 and Antonov 225)
Issues in Separating Aircraft Near Runways

• Airspace criteria are intrinsically used for runway separations:
  – Minimum radar separations (driven by the ability to differentiate targets in a radar display)
  – Wake vortex separations - driven by the hazard created by flying behind the wake of a lead aircraft

• Runway occupancy time (ROT)
  – Can also be an important factor in separations on final approach
  – If ROT is small (i.e., due to high speed runway exits), the airspace separations may need to be increased to avoid simultaneous occupancy of the runway
Example of In-Trail Wake Airspace Separations
IMC Conditions (ICAO)

Lang, Eriksen and Tittsworth, WakeNet 3 Europe, 2010
Typical Minimum Values of Aircraft Separations ($\delta_{ij}$) in the United States under IMC Conditions Radar is Available (Table 2)

<table>
<thead>
<tr>
<th>Minimum Separation Matrix (nm)</th>
<th>Arrivals-Arrivals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Trailing Aircraft (Header Columns)</td>
</tr>
<tr>
<td>Lead (column 1)</td>
<td>Small</td>
</tr>
<tr>
<td>Small</td>
<td>3</td>
</tr>
<tr>
<td>Large</td>
<td>4</td>
</tr>
<tr>
<td>B757</td>
<td>5</td>
</tr>
<tr>
<td>Heavy</td>
<td>6</td>
</tr>
<tr>
<td>Superheavy</td>
<td>8</td>
</tr>
</tbody>
</table>

Highlighted values are minimum radar separations
Values behind Superheavy vary from 8-10 nm
VMC Separations

• Under visual meteorological conditions, pilots are expected to be responsible for separations

• Data collected at airfields in the United States indicates that VMC separations are 10% below those observed under IMC conditions

• Therefore:
  – Runways have more capacity under VMC conditions for the same fleet mix
  – Higher runway utilization is possible under VMC conditions
  – Runway occupancy times and VMC airspace separations are closer in magnitude
## Air Traffic Control (ATC) Departure-Departure In-Trail Separations

Typical In-trail Separations (in seconds) for Departing Aircraft on the same Runway. Includes Buffers Applied by ATC.

<table>
<thead>
<tr>
<th>Lead Aircraft</th>
<th>Trailing Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Superheavy</td>
</tr>
<tr>
<td>Superheavy</td>
<td>120</td>
</tr>
<tr>
<td>Heavy</td>
<td>120</td>
</tr>
<tr>
<td>B757</td>
<td>120</td>
</tr>
<tr>
<td>Large</td>
<td>60</td>
</tr>
<tr>
<td>Small</td>
<td>60</td>
</tr>
</tbody>
</table>

Separations are in seconds
## Aircraft Wake Groups: Who Is Who?

<table>
<thead>
<tr>
<th>Aircraft Group</th>
<th>Maximum Takeoff Weight (lb)</th>
<th>Sample Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Superheavy</strong></td>
<td>&gt;1,000,000</td>
<td>Airbus A380-800</td>
</tr>
<tr>
<td><strong>Heavy</strong></td>
<td>255,000 to 1e6</td>
<td>Boeing 747-8, Airbus A340-600, Airbus A330-300, Boeing 767-300</td>
</tr>
<tr>
<td><strong>B757</strong></td>
<td>255,000</td>
<td>Boeing 757-300 and Boeing 757-200</td>
</tr>
<tr>
<td><strong>Large</strong></td>
<td>&gt; 41,000 and &lt; 255,000</td>
<td>Boeing 737-700, Airbus A320-200, Embraer E175, Bombardier CRJ-900, etc.</td>
</tr>
<tr>
<td><strong>Small</strong></td>
<td>&lt;41,000</td>
<td>All single and multi-engine piston aircraft, single engine turboprops and small light business jets</td>
</tr>
</tbody>
</table>
Small Aircraft

Typically these aircraft can have one (single engine) or two engines (twin engine). Their maximum gross weight usually is always below 14,000 lb.

- **Single-Engine GA**
  - Cessna 172 (Skyhawk)

- **Twin-Engine GA**
  - Beechcraft 58TC (Baron)

- Beechcraft A36 (Bonanza)

- Cessna 421C (Golden Eagle)
Corporate Aircraft

Typically these aircraft can have one or two turboprop driven or jet engines (sometimes three). Maximum gross mass is up to 40,910 kg (90,000 lb)

Small
- Raytheon-Beechcraft King Air B300
- Cessna Citation II

Large (> 41,000 lb)
- Gulfstream G-V
Commuter Passenger Aircraft

Usually twin engine aircraft with a few exceptions such as the DeHavilland DHC-7 which has four engines. Their maximum gross mass is below 31,818 kg (70,000 lb)

Small
- Fairchild Swearinger Metro 23
- Bombardier DHC-8
- Saab 340B

Large (> 41,000 lb)
- Embraer 145
Commercial Aircraft (Single-Aisle)

Certified under FAR/JAR 25. Their maximum gross mass usually is below 68,182 kg (150,000 lb).

- Fokker F100
- Airbus A-320
- Boeing 737-300
- McDonnell-Douglas MD 82

All Large (> 41,000 lb)
Commercial Transport Aircraft (Wide-Body)

These are transport aircraft employed to fly routes of less than 3,000 nm (typical). Their maximum gross mass usually is above 159,090 kg (350,000 lb)

Airbus A340-200

Boeing 777-200

Boeing 747-400
Super-heavy Aircraft

- Airbus A380 was introduced into service in 2008

A380-800 at LAX Airport (A. Trani)
Example Problem (1)

Determine the saturation capacity of an airport serving two groups of aircraft: a) heavy (30% of the population) and b) Small (70% of the population). Assume the common approach length $\gamma$ to be 7 miles.

The aircraft performance characteristics are given in the following table.

Table 4. Aircraft Characteristics.

<table>
<thead>
<tr>
<th>Aircraft Group</th>
<th>Runway Occupancy Time (seconds)</th>
<th>Approach Speed (knots)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>60</td>
<td>150</td>
</tr>
<tr>
<td>Small</td>
<td>40</td>
<td>100</td>
</tr>
</tbody>
</table>
Example Problem (1)

Assume radar surveillance is available with 20 seconds for the standard deviation of in-trail delivery accuracy error and a probability of violation of 5%.

The airport is a medium hub airport. The arrival-arrival separation matrix is shown in page 27-E. The departure-departure separation matrix is shown in page 29.
Determine Aircraft Mix and Probabilities

The following is a probability matrix establishing the chance that an aircraft of type (i) follows aircraft of type (j). We assume random arrivals.

Table 4. Probability Matrix (P_{ij}). Aircraft (i) follows aircraft (j).

<table>
<thead>
<tr>
<th>Lead Aircraft</th>
<th>Trailing Aircraft</th>
<th>Heavy</th>
<th>Small</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>= (0.3) x (0.3) = 0.09</td>
<td>= (0.3) x (0.7) = 0.21</td>
<td></td>
</tr>
<tr>
<td>Small</td>
<td>= (0.7) x (0.3) = 0.21</td>
<td>= (0.7) x (0.7) = 0.49</td>
<td></td>
</tr>
</tbody>
</table>

NOTE: verify that \( \sum_{i,j} P_{ij} = 1.0 \)
Compute Headways Between Successive Arrivals

Closing case:

Lead = small, Following = heavy aircraft

\[ T_{S-H} = \frac{\delta_{S-H}}{V_H} = \frac{3}{150} = 0.02 \text{ hours} \]

Usually is convenient to express headway in seconds.

\[ T_{S-H} = \frac{\delta_{S-H}}{V_H} = \left( \frac{3}{150} \right) 3600 = 72 \text{ seconds} \]
Closing case (apply this case when speeds are equal):

Lead = small, Following = small aircraft

\[ T_{S-S} = \frac{\delta_{S-S}}{V_S} = \left( \frac{3}{100} \right) 3600 = 108 \text{ seconds} \]

Lead = heavy, Following = heavy aircraft

\[ T_{H-H} = \frac{\delta_{H-H}}{V_H} = \left( \frac{4}{150} \right) 3600 = 96 \text{ seconds} \]
Opening case:

Lead = heavy, Following = small aircraft

\[ T_{H-S} = \frac{\delta_{H-S}}{V_S} + \gamma \left( \frac{1}{V_S} - \frac{1}{V_H} \right) \] seconds

\[ T_{H-S} = \left( \frac{6}{100} \right) 3600 + 7 \left( \frac{1}{100} - \frac{1}{150} \right) 3600 = 300 \] seconds
Arrival Aircraft Headway Table

The following table summarizes the computed headways for all cases when an aircraft of type (i) follows aircraft of type (j). We assume random arrivals.

Table 5. Error-Free headways (in seconds) when aircraft (i) follows aircraft (j).

<table>
<thead>
<tr>
<th>Lead Aircraft</th>
<th>Trailing Aircraft</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heavy</td>
<td>Small</td>
</tr>
<tr>
<td>Heavy</td>
<td>96</td>
<td>300</td>
</tr>
<tr>
<td>Small</td>
<td>72</td>
<td>108</td>
</tr>
</tbody>
</table>
Compute Expected Value of Headway

The expected value of the headway is:

\[ E(T_{ij}) = \sum_{i,j} P_{ij} T_{ij} \text{ for all } i,j \text{ pairs} \]

\[ E(T_{ij}) = P_{HH} \times T_{HH} + P_{SH} \times T_{SH} + P_{HS} \times T_{HS} + P_{SS} \times T_{SS} \]

\[ E(T_{ij}) = 0.09(96) + 0.21(72) + 0.21(300) + 0.49(108) \]
\[ E(T_{ij}) = 0.09(96) + 0.21(72) + 0.21(300) + 0.49(108) \]

\[ E(T_{ij}) = 139.7 \text{ seconds} \]

Now compute the buffers between successive arrivals paying close attention to closing and opening equations.
Compute Arrivals-Only Buffers

Opening Case:

\[ B_{H-S} = \min\left(\sigma_v q_v - \delta_{H-S} \left(\frac{1}{V_S} - \frac{1}{V_H}\right), 0\right) \]

\[ B_{H-S} = 1.65(20) - 6\left(\frac{1}{100} - \frac{1}{150}\right)3600 \]

\[ B_{H-S} = \min(-39, 0) = 0 \text{ seconds} \]
Closing Case:

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

\[ B_{S-S} = B_{H-H} = B_{S-H} = \sigma_o q_v = 1.65(20) = 33 \text{ seconds} \]
Arrivals Only Analysis

The following table summarizes the computed headways (including the buffer times) for all cases when an aircraft of type (i) follows aircraft of type (j). We assume random arrivals.

Table 6. Actual headways (in seconds) when aircraft (i) follows aircraft (j).

<table>
<thead>
<tr>
<th>Lead Aircraft</th>
<th>Trailing Aircraft</th>
<th>Heavy</th>
<th>Small</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>96+33 = 129</td>
<td>300 + 0 = 300</td>
<td></td>
</tr>
<tr>
<td>Small</td>
<td>72+33 = 105</td>
<td>108+33 = 141</td>
<td></td>
</tr>
</tbody>
</table>
Expected Value of Headways (Including Buffer Times)

The expected value of the actual headways $E(T_{ij} + B_{ij})$ is **165.8 seconds**. The arrivals only capacity is,

$$C_{arrival} = \frac{1}{E(T_{ij} + B_{ij})} \text{ vehicles per second}$$

Using more standard units of capacity (aircraft per hour),

$$C_{arrival} = \frac{3600}{E(T_{ij} + B_{ij})} \text{ arrivals per hour}$$
Arrivals-Only Capacity

For the single runway example the arrivals-only capacity is,

\[ C_{\text{arrivals}} = \frac{3600}{165.8} = 21.8 \text{ aircraft arrivals per hour} \]

NOTE: this value is a little low for a busy airport. At busy airports small aircraft are generally handled at a different runway if possible to improve the capacity of a runway operated by heavy aircraft.
Analysis of Runway Gaps

Gaps can be studied for all four possible instances studied so far. For example, if a heavy aircraft is followed by a small one, there is a headway of 300 seconds between two successive arrivals. This leaves a large gap that can be exploited by air traffic controllers to handle a few departures on the same runway.

\[ E(T_{ij} + B_{ij}) \geq E\left(\frac{\delta}{V_j}\right) + E(ROT_i) + \\
(n - 1)E(\epsilon_{ij}) + E(\tau) \]
Computation of Minimum Gaps

\[ E(T_{ij} + B_{ij}) \geq 64.8 + 46 + (n - 1)78 + 10 \text{ seconds} \]
\[ E(T_{ij} + B_{ij}) \geq 64.8 + 46 + 10 + 78n - 78 \text{ seconds} \]
\[ E(T_{ij} + B_{ij}) \geq 42.8 + 78n \text{ seconds} \]

For \( n = 1 \) (one departure between arrivals) we need,
\[ E(T_{ij} + B_{ij})_{n=1} \geq 120.8 \text{ seconds} \]

For \( n = 2 \) (two departures between arrivals) we need,
\[ E(T_{ij} + B_{ij})_{n=2} \geq 198.8 \text{ seconds} \]
Computation of Minimum Gaps

For $n = 3$ (three departures between arrivals) we need,

$$E(T_{ij} + B_{ij})_{n=3} \geq 276.8 \text{ seconds}$$

For $n = 4$ (four departures between arrivals) we need,

$$E(T_{ij} + B_{ij})_{n=4} \geq 354.8 \text{ seconds}$$

and so.

We need to compare the values stated in Table 6 $(T_{ij} + B_{ij})$ against the gaps needed to schedule $n$ departures per arrival gap instance.
Gap Analysis

The following table summarizes the number of departures possible when an aircraft of type (i) follows aircraft of type (j). We assume random arrivals.

Table 7. Number of departures per arrival gap when aircraft (i) follows aircraft (j).

<table>
<thead>
<tr>
<th>Lead Aircraft</th>
<th>Trailing Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heavy</td>
</tr>
<tr>
<td>Heavy</td>
<td>1</td>
</tr>
<tr>
<td>Small</td>
<td>0</td>
</tr>
</tbody>
</table>
Interpretation of Table 7

One departure (on the average) can be scheduled between a heavy aircraft followed by another heavy aircraft. Note that a heavy - heavy arrival sequence implies an average of 129 seconds between successive arrivals.

Since 121 seconds are needed to schedule a departure (expected value for all types of operations), we conclude that one departure can occur anytime two heavy aircraft follow each other.

Other cells are computed in a similar fashion.
Analysis of Arrival Gaps

The final question that needs to be answered is: how many times each gap happens during the period of interest?

From our analysis of arrivals only, we determined that on the average hour 21.8 arrivals could be processed at the runway. Since two successive arrivals are needed to form a gap, we can infer that an average of 20.8 gaps are present in one hour.

The probability of each one of the four arrival instances is known and has been calculated in Table 4. Thus using
these two pieces of information we estimate the number of times gaps will occur during one hour.

Consider the instance of a heavy aircraft leading another heavy aircraft. Nine percent of the time this instance occurs at the airport. Thus for 20.8 gaps per hour this represents an equivalent number of hourly departures per arrival instance ($ED_{H-H}$),

$$ED_{H-H} = TG(P_{H-H})(DG_{H-H})$$

where: $TG$ is the total number of gaps per hour, $P_{H-H}$ is the probability that a heavy aircraft follows another heavy, and $DG_{H-H}$ is the number of departures per gap for each instance (numbers in Table 7).
\[ ED_{H-H} = 20.8(0.09)(1) = 1.87 \]

equivalent departures per hour

Similarly,

\[ ED_{H-S} = 20.8(0.21)(3) = 13.10 \]
\[ ED_{S-H} = 20.8(0.21)(0) = 0 \]
\[ ED_{S-S} = 20.8(0.49)(1) = 10.19 \]

equivalent departures per hour per instance
**Departures with Arrival Priority**

Table 8 summarizes the number of departures per hour per instance.

Table 8. Equivalent departures per hour per arrival instance when aircraft (i) follows aircraft (j).

<table>
<thead>
<tr>
<th>Trailing Aircraft</th>
<th>Heavy</th>
<th>Small</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead Aircraft</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy</td>
<td>1.87</td>
<td>13.10</td>
</tr>
<tr>
<td>Small</td>
<td>0.00</td>
<td>10.19</td>
</tr>
</tbody>
</table>

Total departures per hour = **25.2 departures per hour**
Recapitulation of Results so Far

\[ C_{\text{arrivals}} = \frac{3600}{165.8} = 21.8 \text{ arrivals per hour} \]

\[ C_{\text{departures}} = 25.2 \text{ departures per hour} \]

These results indicate that a single runway can process 21.8 arrivals per hour and during the same period process 25.2 departures per hour using the gaps formed by the arrivals.

Total operations = 47 aircraft per hour
If only departures are processed at this runway (no arrivals), the departures only capacity is the reciprocal of the departure headway (78 seconds),

\[ C_{dep-NA} = \frac{3600}{78} = 46.2 \text{ departures per hour} \]

Airport engineers use a capacity diagram illustrated in the figure to display all three hourly capacity results in a single diagram. These diagrams represent a Pareto frontier of arrivals and departures. The airport can be operated inside the Pareto boundary.
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).

- The following pages illustrate the use of the program using the values of the previous runway example.
Enter runway operation technical parameters
- Arrival minimum separation matrix ($\delta_{ij}$)
- Departure-departure separation matrix ($\varepsilon_{ij}$)
- 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. Estimate the “Buffer” separation matrix
   - $B_{ij}$ values using opening and closing cases

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

5. Compute expected value of the buffer matrix
   - $E(B_{ij})$
Compute augmented separation matrix
   \[ A_{ij} = T_{ij} + B_{ij} \] (error-free + buffer)

Compute the probability matrix (i follows j)
   \[ P_{ij} \]

Compute expected value of \( A_{ij} \) matrix
   \[ E(A_{ij}) = E(T_{ij} + B_{ij}) \]

Compute expected value of departure-departure matrix
   \[ E(\epsilon_{ij}) \]

Compute gaps for \( n \) departures (\( n=1,2,\ldots,5 \))
   \[ E(G_n) \]

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:
   - $C_{arr}$
   - $C_{dep}$
   - $C_{dep-arr-priority}$

Departure capacity with arrival priority $C_{dep-arr-priority}$

End
# Computer Program Screen 1

## Technical Parameters (inputs)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta$</td>
<td>2</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>7</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>20</td>
</tr>
<tr>
<td>$P_v$</td>
<td>5</td>
</tr>
<tr>
<td>$q_v$</td>
<td>1.65</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Small</th>
<th>Large</th>
<th>Heavy</th>
<th>E(ROT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>48</td>
<td>60</td>
<td>46</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Small</th>
<th>Large</th>
<th>Heavy</th>
<th>Total %</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>0</td>
<td>30</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Small</th>
<th>Large</th>
<th>Heavy</th>
<th>Vapproach (kr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>140</td>
<td>150</td>
<td></td>
</tr>
</tbody>
</table>

## Minimum Separation Matrix (nm)

<table>
<thead>
<tr>
<th>Small</th>
<th>Large</th>
<th>Heavy</th>
<th>Arrivals-Arrivals</th>
<th>Airport Type</th>
<th>Weather Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>Small</td>
<td>IFR</td>
</tr>
<tr>
<td>Large</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Computer Program (Screen 2)

### 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>108.00</td>
<td>77.14</td>
<td>72.00</td>
<td>E(Tij) 139.68</td>
</tr>
<tr>
<td>Large</td>
<td>252.00</td>
<td>77.14</td>
<td>72.00</td>
<td></td>
</tr>
<tr>
<td>Heavy</td>
<td>300.00</td>
<td>140.57</td>
<td>96.00</td>
<td></td>
</tr>
</tbody>
</table>

### Pij Matrix

<table>
<thead>
<tr>
<th></th>
<th>Small</th>
<th>Large</th>
<th>Heavy</th>
<th>Sum of Pij</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>0.490</td>
<td>0.000</td>
<td>0.210</td>
<td>0.70</td>
</tr>
<tr>
<td>Large</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.00</td>
</tr>
<tr>
<td>Heavy</td>
<td>0.210</td>
<td>0.000</td>
<td>0.090</td>
<td>0.30</td>
</tr>
</tbody>
</table>

### 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>33.00</td>
<td>33.00</td>
<td>33.00</td>
<td>B(Tij) 26.07</td>
</tr>
<tr>
<td>Large</td>
<td>0.00</td>
<td>33.00</td>
<td>33.00</td>
<td></td>
</tr>
<tr>
<td>Heavy</td>
<td>0.00</td>
<td>24.43</td>
<td>33.00</td>
<td></td>
</tr>
</tbody>
</table>
### Computer Program (Screen 3)

#### 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>141.00</td>
<td>110.14</td>
<td>105.00</td>
<td></td>
</tr>
<tr>
<td>Large</td>
<td>252.00</td>
<td>110.14</td>
<td>105.00</td>
<td>165.75</td>
</tr>
<tr>
<td>Heavy</td>
<td>300.00</td>
<td>165.00</td>
<td>129.00</td>
<td></td>
</tr>
</tbody>
</table>

**Arrivals Only Capacity (per hour):** 21.72

---

#### Departure-Departure Separation Matrix (nm)

<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></td>
</tr>
<tr>
<td>Large</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>78</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):** 46.15

---

#### Estimation of Critical Departure Gaps

<table>
<thead>
<tr>
<th>Departures</th>
<th>Gap (EΔTij)</th>
<th>E(ROT)</th>
<th>E(δ/Vj)</th>
<th>log*qv</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>120.70</td>
<td>46.00</td>
<td>64.80</td>
<td>9.90</td>
</tr>
<tr>
<td>2</td>
<td>198.70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>276.70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>354.70</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Computer Program (Screen 4)

<table>
<thead>
<tr>
<th>Departures per Gap</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>666.70</td>
<td>744.70</td>
<td>822.70</td>
<td>900.70</td>
<td></td>
</tr>
</tbody>
</table>

### Departures per hour with 100% Arrival Priority

<table>
<thead>
<tr>
<th></th>
<th>Small</th>
<th>Large</th>
<th>Heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Large</td>
<td>2.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Heavy</td>
<td>3.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

### Summary for Arrival - Departure Diagram

<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>10.15</td>
<td>0.00</td>
<td>0.00</td>
<td>10.15</td>
</tr>
<tr>
<td>Large</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Heavy</td>
<td>13.05</td>
<td>0.00</td>
<td>1.86</td>
<td>14.92</td>
</tr>
</tbody>
</table>

Total Departures:

25.07
Computer Program (Screen 5)

Arrival - Departure Diagram

Arrivals (per hour)

Departures (per hour)

Virginia Tech
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 for operations on the runways.
Example 2 - 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

#### Departure-Departure 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>111.52</td>
<td>93.99</td>
<td>89.70</td>
<td>$E(T_{ij}) + B(T_{ij})$</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>

#### Departures Only Capacity (per hour) | 47.06

#### Departure-Departure Separation Matrix (seconds)

<table>
<thead>
<tr>
<th></th>
<th>Small</th>
<th>Large</th>
<th>Heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Large</td>
<td>90</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Heavy</td>
<td>120</td>
<td>120</td>
<td>120</td>
</tr>
</tbody>
</table>

#### Departures Only Capacity (per hour) | 47.06

### Augmented Matrix

<table>
<thead>
<tr>
<th></th>
<th>Trailing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td></td>
</tr>
<tr>
<td>Large</td>
<td></td>
</tr>
<tr>
<td>Heavy</td>
<td></td>
</tr>
</tbody>
</table>

#### Departure-Departure Separation Matrix

<table>
<thead>
<tr>
<th></th>
<th>Trailing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td></td>
</tr>
<tr>
<td>Large</td>
<td></td>
</tr>
<tr>
<td>Heavy</td>
<td></td>
</tr>
</tbody>
</table>
Results of CLT Analysis

Single runway analysis - mixed operations

![Graph showing the relationship between departures and arrivals per hour. The graph illustrates a linear decrease in arrivals with an increase in departures.](image-url)
Results of CLT Analysis

Two-parallel runway analysis - mixed operations

Arrivals per Hour

Departures per Hour

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>108–116</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 3 - 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 > 4,3000 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 (2.5/4/5/6 nm)
11) IMC weather conditions
Results of CLT Analysis

Two-parallel runway analysis - segregated operations

Arrivals per Hour

Departures per Hour

Original Runway Configuration

New Runway Configuration

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Example 4 - 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 (2/3/4/5 nm)
11) VMC weather conditions
Results for CLT VMC Scenario

Single runway analysis - mixed operations
Results of CLT VMC Analysis

Two-parallel runway analysis - mixed operations

Arrivals per Hour

Departures per Hour

VMC

IMC

0

23

26

95

118

63

54
Airport Capacity Model (ACM)

- Model developed by FAA to expedite computations of runway saturation capacity
- Later modified by MITRE to be more user friendly
- 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

Windows Desktop

AIRFRAME (Ver. 2.0) COPYRIGHT 1991

Help Refresh Save-Quit Change-Data New-Model Print-Screen Show-Other-Data

ARRIVALS

Classes: SMALL MEDIUM LARGE HEAVY
Class Mix (%): RWY 1: 10 20 50 20
      RWY 2: 10 20 50 20
ARYL ROT [s]: RWY 1: 15 15 15 15
      RWY 2: 15 15 15 15
SPEEDS [km]: 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

WEATHER IS: IMC

5: TWO PARALLEL RUNWAYS - MIXED MODE ON BOTH

<table>
<thead>
<tr>
<th>ARR</th>
<th>DEP</th>
<th>TOTAL</th>
<th>ARR%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>52</td>
<td>6</td>
<td>58</td>
</tr>
<tr>
<td>2</td>
<td>52</td>
<td>18</td>
<td>70</td>
</tr>
<tr>
<td>3</td>
<td>52</td>
<td>47</td>
<td>99</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>48</td>
<td>54</td>
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<td>6</td>
<td>25</td>
<td>75</td>
<td>100</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>98</td>
<td>98</td>
</tr>
</tbody>
</table>

ARRIVAL PRIORITITY
50-50 CAPACITY
MAXIMUM DEPARTURES

Virginia Tech
Example 5 - Non-towered Airport Capacity Using Advanced High-Volume Operations Technologies (SATS program)

- Existing airports without a control tower have very small runway saturation capacities (4-5 arrivals per hour)

- These airports require large headways (10-12 minutes) between aircraft because ATC cannot see the aircraft in radar (ATC applies *procedural separations*)

- NASA is developing technologies to help pilots space themselves at these non-towered airports (using an airport sequence manager and Automated Depedence Surveyance mode B - ADS-B)
HVO Scenario (Uncontrolled Airport)

Plan View

IAF
Initial Segment (3-6 nm)
IF (FAF)
Intermediate Segment
Final Segment (5 nm)
FAF
MAP
Runway

Missed Approach Holding Fix
IAF

Critical Area of Study

Virginia Tech
Example 5 - HVO Airport

Operational Conditions

1) Single runway
   used in mixed operations mode
2) HVO technology with Airport Manager and ADSB technology
3) With and without parallel runway
4) No radar
5) Aircraft mix
   a) TERP A - 60%
   b) TERP B - 40%
   c) No TERP C
6) Approach speeds
   a) TERP A - 90 knots
   b) TERP B - 110 knots
   c) No TERP C
7) Runway occupancy times
   Variable with availability of runway taxiways and parallel taxiway (use REDIM model)
8) Common approach length - 10 nm
9) In-trail delivery error standard deviation - 30 s.
10) Arrival-arrival separation criteria (5 nm)
11) IMC weather conditions

Key change from procedural separation
Computer Program Screen 1

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Runway Saturation Capacity Estimation</strong></td>
<td><strong>HVO SATS Technology</strong></td>
<td><strong>Using the Analytical Model (Time-space model)</strong></td>
<td><strong>Programmer: A. Trani (January 2004)</strong></td>
<td><strong>Amendments:</strong></td>
<td><strong>1</strong> 13-Jan-04</td>
<td><strong>Added specific parameters for SATS untowered air</strong></td>
<td><strong>2</strong> 5-Jul-04</td>
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<table>
<thead>
<tr>
<th>Technical Parameters (inputs)</th>
<th>Parameter</th>
<th>Values</th>
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<tbody>
<tr>
<td>Dep-Arrival Separation (nm)</td>
<td>δ</td>
<td>5</td>
</tr>
<tr>
<td>Common Approach Length (nm)</td>
<td>γ</td>
<td>30</td>
</tr>
<tr>
<td>Standard deviation of Position Delivery Error (s)</td>
<td>σ</td>
<td>30</td>
</tr>
<tr>
<td>Probability of Violation</td>
<td>Πν</td>
<td>1</td>
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<tr>
<td>Cumulative Normal at Πν</td>
<td>ην</td>
<td>2.95</td>
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<table>
<thead>
<tr>
<th>TERP A</th>
<th>TERP B</th>
<th>TERP C</th>
<th>Base ROT</th>
<th>TERP A</th>
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<td>118</td>
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<td>134</td>
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<table>
<thead>
<tr>
<th>Percent Mix</th>
<th>Vapproach (knots)</th>
<th>Minimum Separation Matrix (nm)</th>
<th>Airport Type</th>
</tr>
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<tbody>
<tr>
<td>60</td>
<td>90</td>
<td>40</td>
<td>100</td>
</tr>
<tr>
<td>40</td>
<td>110</td>
<td>0</td>
<td>100</td>
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<tr>
<td>0</td>
<td>130</td>
<td>0</td>
<td>100</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Trailing Weather Conditions</th>
<th>TERP A</th>
<th>TERP B</th>
<th>TERP C</th>
<th>Separation Multiplier for Weather Conditions</th>
</tr>
</thead>
<tbody>
<tr>
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<td>5</td>
<td>Weather Conditions</td>
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<td>Separation Multiplier for Weather Conditions</td>
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</table>
## Computer Program (Screen 2)

### Error Free Separation Matrix

<table>
<thead>
<tr>
<th></th>
<th>TERP A</th>
<th>TERP B</th>
<th>TERP C</th>
<th>Expected Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TERP A</td>
<td>200</td>
<td>164</td>
<td>138</td>
<td>E(Tij)</td>
</tr>
<tr>
<td>TERP B</td>
<td>273</td>
<td>164</td>
<td>138</td>
<td>202.91</td>
</tr>
<tr>
<td>TERP C</td>
<td>323</td>
<td>214</td>
<td>138</td>
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</table>

### Pij Matrix

<table>
<thead>
<tr>
<th></th>
<th>TERP A</th>
<th>TERP B</th>
<th>TERP C</th>
<th>Sum of Pij</th>
</tr>
</thead>
<tbody>
<tr>
<td>TERP A</td>
<td>0.360</td>
<td>0.240</td>
<td>0.000</td>
<td>0.60</td>
</tr>
<tr>
<td>TERP B</td>
<td>0.240</td>
<td>0.160</td>
<td>0.000</td>
<td>0.40</td>
</tr>
<tr>
<td>TERP C</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>1.00</td>
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### Buffer Matrix

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<tr>
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<th>TERP A</th>
<th>TERP B</th>
<th>TERP C</th>
<th>Expected Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TERP A</td>
<td>89</td>
<td>89</td>
<td>89</td>
<td>B(Tij)</td>
</tr>
<tr>
<td>TERP B</td>
<td>52</td>
<td>89</td>
<td>89</td>
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<tr>
<td>TERP C</td>
<td>27</td>
<td>63</td>
<td>89</td>
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### Computer Program (Screen 3)

#### Augmented Matrix

<table>
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<tr>
<th></th>
<th>TERP A</th>
<th>TERP B</th>
<th>TERP C</th>
<th>Expected Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TERP A</td>
<td>289</td>
<td>252</td>
<td>227</td>
<td>E(Tij) + B(Tij)</td>
</tr>
<tr>
<td>TERP B</td>
<td>325</td>
<td>252</td>
<td>227</td>
<td></td>
</tr>
<tr>
<td>TERP C</td>
<td>350</td>
<td>277</td>
<td>227</td>
<td>283</td>
</tr>
</tbody>
</table>

#### Arrivals Only Capacity (per hour)

- 12.74

#### Departure-Departure Separation Matrix (seconds)

<table>
<thead>
<tr>
<th></th>
<th>TERP A</th>
<th>TERP B</th>
<th>TERP C</th>
<th>Expected Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TERP A</td>
<td>180</td>
<td>240</td>
<td>240</td>
<td>E(Td)</td>
</tr>
<tr>
<td>TERP B</td>
<td>180</td>
<td>200</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>TERP C</td>
<td>180</td>
<td>180</td>
<td>200</td>
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</table>

#### Departures Only Capacity (per hour)

- 18.22

#### Estimation of Critical Departure Gap

<table>
<thead>
<tr>
<th>Departures</th>
<th>Gap (EΔTij)</th>
<th>E(ΔVij)</th>
<th>ω&lt;sub&gt;g&lt;/sub&gt;*ω&lt;sub&gt;v&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>331</td>
<td>122</td>
<td>24</td>
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<tr>
<td>2</td>
<td>529</td>
<td>185</td>
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</tr>
<tr>
<td>3</td>
<td>726</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>924</td>
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<tr>
<td>5</td>
<td>1121</td>
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</tbody>
</table>
### Computer Program (Screen 4)

#### Departures per Gap

<table>
<thead>
<tr>
<th></th>
<th>TERP A</th>
<th>TERP B</th>
<th>TERP C</th>
</tr>
</thead>
<tbody>
<tr>
<td>TERP A</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>TERP B</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>TERP C</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

#### Departures per hour with 100% Arrival Priority

<table>
<thead>
<tr>
<th></th>
<th>TERP A</th>
<th>TERP B</th>
<th>TERP C</th>
<th>Expected Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TERP A</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>TERP B</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>TERP C</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00 Total Departures with 100% arrive</td>
</tr>
</tbody>
</table>

#### Summary for Arrival - Departure Diagram

<table>
<thead>
<tr>
<th>Arrivals</th>
<th>Departures</th>
<th>Operation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>98</td>
<td>0.00</td>
<td>Arrivals Only</td>
</tr>
<tr>
<td>99</td>
<td>0.00</td>
<td>100% Arrivals + Departures</td>
</tr>
<tr>
<td>100</td>
<td>2.48</td>
<td>Second Iteration</td>
</tr>
<tr>
<td>101</td>
<td>6.84</td>
<td>Third Iteration</td>
</tr>
<tr>
<td>102</td>
<td>18.22</td>
<td>Departures Only</td>
</tr>
</tbody>
</table>
HVO Single Runway Airport Capacity (no parallel taxiway)
HVO Single Runway Airport Capacity (with parallel taxiway)
Validation of Results (using FAA Airport Capacity Model)

Classes: SMALL MEDIUM LARGE HEAVY
Class Mix [%]: RWY 1: 60 40 0 0
ARVL ROT [s]: RWY 1: 60 63 68 65
SPEEDS [kn]: 90 110 130 140
DEP ROT’s [s]: 34 34 45 49
Wake Vortex Separations [nm]
5 5 5.2 5.2
5 5 5.2 5.2
5.2 5.2 4.8 5.2
8 6 5 4
Minimum Time Between Departures [s]
185 185 180 60
185 240 209 60
185 240 192 60
120 120 120 90
Length of Common Path: 10 nm
ARR-DEP SEPARATION: 5 nm
ARRIVAL R.O.T. Std. Dev.: 13 s
INTER-ARRIVAL TIME Std. Dev.: 30 s
DEPARTURE R.O.T. Std. Dev.: 12 s
CLEARED-TO-ROLL Std. Dev.: 17 s

1: SINGLE RUNWAY MIXED MODE

<table>
<thead>
<tr>
<th>ARR</th>
<th>DEP</th>
<th>TOTAL</th>
<th>ARR%</th>
</tr>
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<tbody>
<tr>
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</tr>
<tr>
<td>1</td>
<td>13</td>
<td>6</td>
<td>19</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>9</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>14</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>19</td>
<td>19</td>
</tr>
</tbody>
</table>

50-50 CAPACITY
MAXIMUM DEPARTURES
Summary of Results

• The saturation capacity of an airport with HVO (ADS-B) technology depends on the safety buffers allowed and the delivery accuracy of pilots/AMM system

• 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 consistent with analyses done by TSAA in 2003 (Milsaps, 2003)

• The results compare well with those obtained using the FAA Airport Capacity Model

• The availability of a parallel taxiway has a large influence in the mixed mode saturation capacities
Recapitulation

• 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 with delay results (use deterministic queueing theory or FAA AC 150/5060 to estimate delay)