RUNWAY OPERATIONS:
Computing Runway Arrival Capacity

SYST 560/460

USE Runway Capacity Spreadsheet

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Background

- Air Transportation System Infrastructure is composed of:
  - Airports
    - “Airside” (runways, taxiways, ramps, …)
    - “Landside” (terminals, passenger lounges, access roads, rental cars, busses, parking,
  - Air Traffic Control
    - Tower
    - Terminal Area
    - En-route
# Runway Capacity

<table>
<thead>
<tr>
<th>Definition</th>
<th>Assumptions and Notes</th>
<th>% of MTC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum Throughput Capacity (MTC)</strong></td>
<td>• Expected number of movements performed in 1 hour</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Does not violate ATC separation rules</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Continuous Demand</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• No limits on delays</td>
<td></td>
</tr>
<tr>
<td><strong>Practical Hourly Capacity (PHCAP)</strong></td>
<td>• Expected number of movements performed in 1 hour</td>
<td>• Avg of 4 min delay, means some vehicles &gt;&gt; 4 mins</td>
</tr>
<tr>
<td></td>
<td>• Delay set to average 4 min delay per vehicle</td>
<td>• Runway capacity achieved when avg delay = 4 mins</td>
</tr>
<tr>
<td><strong>Declared Capacity</strong></td>
<td>• Number of movements per hour at a reasonable LOS (i.e. delay minutes = 3 min)</td>
<td>• Used for “Schedule Coordination” (in Europe). Sets limit on scheduled arrivals/departures</td>
</tr>
<tr>
<td><strong>Sustained Capacity</strong></td>
<td>• Number of movements per hour than can be reasonably sustained over period of several hours</td>
<td>• Split in Airport Arrival Rate (AAR) and Airport Departure Rate (ADR)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• 100% of MTC with bad weather MTC</td>
</tr>
</tbody>
</table>

See deNeufville/Odori (2004) pages 370 to 374
Runway Operations

- Arriving aircraft land
- Departing aircraft takeoff
- Runway capacity determined by:
  - Separation distance between arriving aircraft
    - Separation Distance Violation
  - Separation distance between departing aircraft
    - Separation Distance Violation
  - Only **one** aircraft on runway at any time
    - Simultaneous Runway Occupancy
- Separation distance and Runway Occupancy Time (ROT) determined by aircraft type (weight/lift, landing speed, …)
  - Heavy (e.g. 747-400)
  - Large (e.g. 777, 767)
  - Medium (e.g. 737)
  - Small (e.g. RJ)
Runway Arrivals
Runway Arrivals
Model for Runway Arrivals

n – length of final approach
i(j) – type of leading (trailing) aircraft
$V_i$ – landing speed of aircraft type $i$ (defined as speed on the ground)
$O_i$ – runway occupancy time of aircraft type $i$
$S_{ij}$ – minimum separation distance between two airborne aircraft $i$ and $j$
$T_{ij}$ – minimum acceptable time interval between successive arrivals at runway of aircraft type $i$ and type $j$
Homogeneous Fleet

\[ MCT = \frac{3600}{\text{ROT}} \quad \text{(Simultaneous Runway Occupancy – SRO)} \]

\[ MCT = \frac{3600}{(S_{i,j}/V_j)} \quad \text{(Wake Vortex Sep Distance)} \]

\[ MCT = \frac{3600}{[(S_{i,j}/V_j) + b]} \quad \text{(Wake Vortex + ATC Buffer)} \]
Non-Homogeneous Fleet Mix

\[ \text{MCT} = \frac{3600}{E[\text{ROT}]} \quad \text{(Simultaneous Runway Occupancy – SRO)} \]

\[ E[\text{ROT}] = \sum_i \sum_j (p_{ij} \times \text{ROT}_i) \]

\[ \text{MCT} = \frac{3600}{E[T_{i,j}]} \quad \text{(Wake Vortex Sep Distance)} \]

\[ E[T_{i,j}] = \sum_i \sum_j (p_{ij} \times (S_{i,j}/V_j)) \]

\[ \text{MCT} = \frac{3600}{E[T_{i,j}]} \quad \text{(Wake Vortex + ATC Buffer)} \]

\[ E[T_{i,j}] = \sum_i \sum_j ((p_{ij} \times (S_{i,j}/V_j)) + b) \]
## Separation Distance (nm)

<table>
<thead>
<tr>
<th>Lead (Approach Speed)</th>
<th>Follow (Approach Speed)</th>
<th>H (150)</th>
<th>L (130)</th>
<th>M (110)</th>
<th>S (90)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H (150)</td>
<td></td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>L (130)</td>
<td></td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>4</td>
</tr>
<tr>
<td>M (110)</td>
<td></td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>4</td>
</tr>
<tr>
<td>S (90)</td>
<td></td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>
## Separation (Expanding, Decreasing)

<table>
<thead>
<tr>
<th>Lead</th>
<th>Follow</th>
<th>H (150)</th>
<th>L (130)</th>
<th>M (110)</th>
<th>S (90)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H (150)</td>
<td>Same</td>
<td>Expanding</td>
<td>Expanding</td>
<td>Expanding</td>
<td></td>
</tr>
<tr>
<td>L (130)</td>
<td>Decreasing</td>
<td>Same</td>
<td>Expanding</td>
<td>Expanding</td>
<td></td>
</tr>
<tr>
<td>M (110)</td>
<td>Decreasing</td>
<td>Decreasing</td>
<td>Same</td>
<td>Expanding</td>
<td></td>
</tr>
<tr>
<td>S (90)</td>
<td>Decreasing</td>
<td>Decreasing</td>
<td>Decreasing</td>
<td>Same</td>
<td></td>
</tr>
</tbody>
</table>
Arrival Two Cases

• Lead aircraft of type i is faster than follow aircraft of type j
  • Case: Expanding Separation

• Lead aircraft of type i is slower than follow aircraft of type j
  • Case: Decreasing Separation
Expanding Separation \((v_i > v_j)\)

\[ T_{ij} = \text{Minimum Acceptable Time Interval between successive Arrivals} \]

\[
\text{max of } \begin{align*}
1. & \quad \frac{(n + s_{ij})}{v_j} - \frac{n}{v_i} \\
& \quad (\text{time for follow aircraft (j) to fly separation distance plus final approach path}) - (\text{time of lead aircraft (i) to fly final approach path}) \\
2. & \quad o_i \quad \text{occupancy time of lead aircraft}
\end{align*}
\]
Constant Separation ($v_i = v_j$)

Expanding Separation ($v_i > v_j$)

\[
\begin{align*}
S_{i,j} & \quad \text{Time} \\
\frac{S_{i,j}}{v_j} & \quad \text{Distance} \\
(n + s_{ij})/v_j & \quad (n/v_i) \\
\end{align*}
\]
Decreasing Separation \((v_i < v_j)\)

\[ T_{ij} = \text{Minimum Acceptable Time Interval between successive Arrivals} \]

\[ \text{max of} \]

1. \(s_{ij}/v_j\) 
   - (time for faster follow aircraft (j) to fly separation distance) – 
   (time of lead aircraft (i) to fly final approach path)

2. \(o_i\) occupancy time of lead aircraft
Constant Separation \((v_i = v_j)\)

\[ S_{i,j} \]

\[ \text{Rwy Threshold} \]

\[ \text{Rwy Exit} \]

\[ 16 \]

\[ \text{Distance} \]

\[ o_i \]

Contracting Separation \((v_i < v_j)\)

\[ (n/vi) \]

\[ ((n + sij)/vj) \]

\[ S_{i,j}/v_j \]

\[ \text{Rwy Exit} \]

\[ \text{Distance} \]

\[ o_i \]

NOT DRAWN TO SCALE
Minimum Time Separation Between 2 Aircraft

- Runway can only have single aircraft at a time
- Minimum separation distance between arriving aircraft must be maintained at all times
- $T_{ij} > O_i$
  - minimum acceptable time interval between successive arrivals at runway of lead aircraft type $i$ and follow aircraft type $j >$ runway occupancy time of aircraft type $i$
Mixed Fleet Arrivals

- **Average Minimum Acceptable Inter-arrival Time**

\[
E[T_{ij}] = \sum_{i}^{K} \sum_{j}^{K} p_{ij} \cdot T_{ij}
\]

- \( K \) – number of aircraft types
- \( K^2 \) – number of aircraft type \( i \) followed by aircraft type \( j \) (pairs)
- \( p_{ij} \) – probability of aircraft type \( i \) followed by aircraft type \( j \)

- **Maximum Capacity Throughput (MCT) = arrivals/hour = 1/E[T_{ij}]**
  - Assumes continuous supply of arriving aircraft
  - Assumes no arrival queueing delays

- **Sustained Capacity Throughput (SCT) = arrivals/hour = 1/E[T_{ij} + \delta]**
  - \( \delta = 10 \) secs = additional distance (padding) used by Air Traffic Controllers to avoid violating separation distance
Example

<table>
<thead>
<tr>
<th>Aircraft Type i</th>
<th>$p_i$</th>
<th>$v_i$</th>
<th>$o_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>0.2</td>
<td>150</td>
<td>70</td>
</tr>
<tr>
<td>L</td>
<td>0.35</td>
<td>130</td>
<td>60</td>
</tr>
<tr>
<td>M</td>
<td>0.35</td>
<td>110</td>
<td>55</td>
</tr>
<tr>
<td>S</td>
<td>0.1</td>
<td>90</td>
<td>50</td>
</tr>
</tbody>
</table>

$S = \begin{bmatrix}
    H & 4 & 5 & 5 & 6 \\
    L & 2.5 & 2.5 & 2.5 & 4 \\
    M & 2.5 & 2.5 & 2.5 & 4 \\
    S & 2.5 & 2.5 & 2.5 & 2.5 
\end{bmatrix}$

$\delta = 10$ secs

$P = \begin{bmatrix}
    0.0 & 0.4 & 0.07 & 0.07 & 0.02 \\
    0.07 & 0.1225 & 0.1255 & 0.035 \\
    0.07 & 0.1225 & 0.1255 & 0.035 \\
    0.02 & 0.035 & 0.035 & 0.01 
\end{bmatrix}$

$E[T_{ij}] = 116.3$

Sustained Capacity Throughput
(Arrivals/Hour) = 30.9 aircraft/hours
Limitations of Model

- Model assumes:
  - independent runway (no intersections or parallel)
  - Landing aircraft only
  - Wind speed and direction
  - $v_i$ and $o_i$ should be random variables
  - Separation distance should be random variables