RUNWAY OPERATIONS:
Computing Runway Arrival Capacity

OR750 / SYST660

USE Runway Capacity Spreadsheet

Spring 2008

Lance Sherry
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</strong> (MTC)</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</strong> (PHCAP)</td>
<td>• Expected number of movements performed in 1 hour</td>
<td>80-90% of MTC</td>
</tr>
<tr>
<td></td>
<td>• Delay set to average 4 min delay per vehicle</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Avg of 4 min delay, means some vehicles &gt;&gt; 4 mins</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Runway capacity achieved when avg delay = 4 mins</td>
<td></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>85-90% of MTC</td>
</tr>
<tr>
<td></td>
<td>• Used for “Schedule Coordination” (in Europe). Sets limit on scheduled arrivals/ departures</td>
<td></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>• 90% of MTC with good weather MTC</td>
</tr>
<tr>
<td></td>
<td>• Split in Airport Arrival Rate (AAR) and Airport Departure Rate (ADR)</td>
<td>• 100% of MTC with bad weather MTC</td>
</tr>
</tbody>
</table>

See deNeufville/Odoni (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)
Model for Runway Arrivals

- $n$ – length of final approach
- $i(j)$ – type of leading (trailing) aircraft
- $V_i$ – ground speed of aircraft type $i$
- $O_i$ – 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 $j$
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 $i$
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 ($v_i > v_j$)

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

max of

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

2. $o_i$ occupancy time of lead aircraft

\[
\begin{align*}
\text{Runway} \\
\text{Runway}
\end{align*}
\]
Constant Separation ($v_i = v_j$)

Expanding Separation ($v_i > v_j$)

\[
\frac{(n + s_{ij})}{v_j} - \frac{n}{v_i}
\]
Decreasing Separation \((v_i < v_j)\)

\[ T_{ij} = \text{Minimum Acceptable Time Interval between successive Arrivals} \]
\[ \text{max of} \]
\[ 1. \quad (\frac{s_{ij}}{v_j}) \]
\[ \quad - \quad (\text{time for faster follow aircraft (j) to fly separation distance}) - \]
\[ \quad (\text{time of lead aircraft (i) to fly final approach path}) \]
\[ 2. \quad o_i \quad \text{occupancy time of lead aircraft} \]
Constant Separation ($v_i = v_j$)

Contracting Separation ($v_i < v_j$)

\[
\begin{align*}
S_{ij} & \quad \text{Distance} \\
\text{Rwy Exit} & \quad \text{Rwy Threshold} \\
11 & \\
\end{align*}
\]

\[
\begin{align*}
(n + s_{ij})/v_j & \quad \text{Distance} \\
\text{Rwy Exit} & \quad \text{Rwy Threshold} \\
(n/v_i) & \\
\end{align*}
\]
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</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>

<table>
<thead>
<tr>
<th>Lead (i)</th>
<th>H</th>
<th>L</th>
<th>M</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Follow (j)</td>
<td>H</td>
<td>4</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>L</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>4</td>
</tr>
<tr>
<td>M</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>4</td>
</tr>
<tr>
<td>S</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

\[
S = \begin{pmatrix}
H & 0.0 & 0.07 & 0.07 & 0.02 \\
L & 0.07 & 0.1225 & 0.1255 & 0.035 \\
M & 0.07 & 0.1225 & 0.1255 & 0.035 \\
S & 0.02 & 0.035 & 0.035 & 0.01
\end{pmatrix}
\]

\[
\delta = 10 \text{ secs}
\]

\[
E[T_{ij}] = 116.3
\]

**Sustained Capacity Throughput**

\((\text{Arrivals/Hour}) = 30.9 \text{ aircraft/hours}\)
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
END
Use Runway Operations – Arrival Spreadsheet

1. Plot a graph with Max # Arrivals/Hour on y-axis, Aircraft Type (i,j) on the x-axis (H-H, L-L, M-M, S-S).
   - What aircraft type pairing generates the highest number of operations?
   - What aircraft type pairing generates the highest number of operations?

   Plot a graph with Total # Seats on y-axis, Aircraft Type (i,j) on x-axis (H-H, L-L, M-M, S-S). Assume seats for aircraft type as follows:
     \( H=524, L=304, M=44, S=36 \).
   - What aircraft type pairing generates the highest number of seats for arrivals?
   - What aircraft type pairing generates the lowest number of seats for arrivals?