Estimation of Arrival Capacity and Utilization at Major Airports

June 27, 2005

Antony Evans
Husni Idris

6th USA/Europe ATM R&D Seminar
Baltimore, MD
Background and Scope

• Assessment of potential throughput benefits through improved efficiency
  – Requires estimating airport achievable capacity and current utilization levels
• Focus on near term solutions to increase utilization of achievable capacity by improving efficiency of operations
  – E.g. through decision support tools (such as TMA, TMA-MC)
  – Assume current infrastructure and separation requirements
• This paper presents methodology for estimating airport arrival capacity and utilization
• Applied to major airport: Boston MA (BOS) and secondary airports in area: Bradley CT (BDL), Providence RI (PVD), Manchester NH (MHT)
  – Traffic increasing at secondary airports to relieve major airport congestion
Definitions

• Runway utilization measured by:
  – Ratio of arrival throughput to achievable arrival capacity \( (\tau/\mu_{\text{achievable}}) \)
  – Achievable arrival capacity
    • Maximum arrival throughput that can be attained
    • Under key assumptions: Runway configuration, fleet mix and separation requirements
  – Underutilization is due to inefficiency of operations or lack of demand

• Runway underutilization due to inefficiency of operations measured by:
  – Ratio of effective arrival capacity to achievable arrival capacity \( (\mu_{\text{effective}}/\mu_{\text{achievable}}) \)
  – Effective arrival capacity
    • Arrival capacity operated at airport that results in current measured delay level
    • Under high demand

• Runway underutilization due to lack of demand measured by:
  – Ratio of arrival throughput to effective arrival capacity \( (\tau/\mu_{\text{effective}}) \)
**Approach**

**Overall Analysis Approach**

1. Historic Throughput
   - Airport runway saturation analysis
     - Saturates? Yes
       - Achievable capacity from historic throughput (e.g. 99th percentile)
     - No
       - Achievable capacity from simulation or historical throughput extrapolation (here used 100th percentile)

2. Historic Demand
   - Achievable Capacity

3. Effective Capacity
   - Airport Utilization
     - Vary capacity

4. Observed Delay
   - Historic Demand
   - Calibrated delay model

5. Achievable Capacity
   - Achievable Capacity from simulation or historical throughput extrapolation (here used 100th percentile)

6. Airport Utilization
   - Vary capacity
   - Achievable Capacity

---

**TITAN**

AIR TRAFFIC SYSTEMS DIVISION
Approach
Arrival Demand Modeling

Historic Throughput

Airport runway saturation analysis

Saturates?
Yes
Achievable capacity from historic throughput (e.g. 99th percentile)

No
Achievable capacity from simulation or historical throughput extrapolation (here used 100th percentile)

Achievable Capacity

Achievable Capacity

Effective Capacity

Calibrated delay model

Vary capacity

Observed Delay

Historic Demand

Historic Demand

Airport Utilization

Airport Utilization

Arrival demand modeling required
Arrival Demand Modeling

- Demand modeled from system boundary 80nm upstream of airport to runway threshold
  - Capability to model multiple tiers
- Estimated times of arrival at runway threshold based on track data (e.g. ASDI) at system boundary
- Unimpeded transition times filtered by:
  - Arrival flow
  - Aircraft type: Large, Heavy or B757, and Small
  - Capability to filter by wind and runway configuration, but data not available for this study

\[ \text{ETA}_{1}^{1} = t_{0}^{1} + \text{TT}_{01}^{1} \]

- Aircraft 1 (unimpeded)

- Aircraft \( t_{i}^{x} \) – Aircraft x actual time of arrival at fix i
- ETA\( t_{i}^{x} \) – Aircraft x estimated time of arrival at fix i
- TT\( t_{ij}^{x} \) – Nominal unimpeded transition time from fix i to j for aircraft x
Arrival Demand Modeling

- Demand modeling over multiple tiers of arrival flow metering
  - E.g. Flow network for Philadelphia (PHL)
Arrival Demand Modeling

- Unimpeded transition times determined by fitting curve to historic transition times plotted against queue size
  - Flights with small arrival queues representative of unimpeded transition time
  - Mean unimpeded transition time estimated as zero queue intercept of best fit
  - Unimpeded transition times sampled from normal distribution with standard deviation equal to that of data with low queue size

Example: BDL west arrival flow
ASDI data from - May 1 to July 21, 2004, Large, Heavy or B757 weight classes

Average Unimpeded Transition Time = 13.2 minutes
Standard Deviation = 2.27 minutes
Arrival Demand Modeling
Airport / Runway Configuration Saturation Analysis

- Demand and throughput per half hour
  - BOS and BDL – ASPM data, April 2003 to September 2004
  - PVD and MHT – ASDI data, May 1 to July 21, 2004
- Excluding periods during GDPs and nighttime
Saturation Analysis

- Data filtered by runway configuration and meteorological condition

  - Spread in throughput at high demand reduced by filtering by runway configuration
    - Drop in average throughput due mainly to low capacity configurations
  - BOS configuration and meteorological condition data available
  - BDL meteorological condition data available, but not configuration data
  - No configuration or meteorological condition data available for PVD or MHT
Saturation Analysis

Metric

- Hyperbolic curve fitted to average throughput
  - As demand tends to zero, asymptotes to throughput = demand
  - As demand tends to infinity, asymptotes to constant throughput
- Ratio of hyperbolic curve fit asymptote to 99th percentile of throughput used to represent degree of saturation
  - The lower the percentile selected, the stricter the requirement for throughput to show saturation
  - 99th percentile used consistently across all airports and configurations
  - Ratio < 1 implies saturation
  - Ratio > 1 implies no saturation

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>BOS</td>
<td>22L</td>
<td>15R</td>
<td>VMC</td>
</tr>
<tr>
<td></td>
<td>4R</td>
<td>9</td>
<td>IMC</td>
</tr>
<tr>
<td></td>
<td>33L,33R</td>
<td>27,33L</td>
<td>VMC</td>
</tr>
<tr>
<td></td>
<td>22L,27</td>
<td>22L,22R</td>
<td>VMC</td>
</tr>
<tr>
<td></td>
<td>4L,4R</td>
<td>4L,4R,9</td>
<td>VMC</td>
</tr>
<tr>
<td>BDL</td>
<td>All</td>
<td>VMC</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>IMC</td>
<td>0.85</td>
</tr>
<tr>
<td>PVD</td>
<td>All</td>
<td>All</td>
<td>1.6</td>
</tr>
<tr>
<td>MHT</td>
<td>All</td>
<td>All</td>
<td>2.1</td>
</tr>
</tbody>
</table>
Approach

Arrival Capacity Modeling

Historic Throughput

Airport runway saturation analysis

Saturates?

Yes

Achievable capacity from historic throughput (e.g. 99th percentile)

No

Achievable capacity from simulation or historical throughput extrapolation (here used 100th percentile)

Achievable Capacity

Effective Capacity

Calibrated delay model

Observed Delay

Historic Demand

Historic Demand

Vary capacity

Vary capacity required
Arrival Capacity Modeling
Capacity Envelopes

- Percentiles of arrival throughput plotted against departure throughput
  - Envelope generated shows tradeoff between arrival capacity & departure throughput

- Achievable capacity modeling:
  - For airports that saturate – Achievable capacity modeled by 99th percentile capacity envelopes
    - 100th percentile may represent ideal wind and fleet mix conditions
    - Lower than 99th percentile considered to be too conservative
  - For airports that do not saturate – Achievable capacity modeled by 100th percentile capacity envelope
    - Even 100th percentile may underestimate ideal conditions
    - In future may estimate achievable capacity by simulating arrival operations
Approach
Delay Modeling

1. Historic Demand
   - Historic Throughput
     - Airport runway saturation analysis
       - Saturates?
         - Yes: Achievable capacity from historic throughput (e.g. 99th percentile)
         - No: Achievable capacity from simulation or historical throughput extrapolation (here used 100th percentile)

2. Achievable Capacity
   - Achievable Capacity
     - Calibrated delay model
       - Vary capacity

3. Effective Capacity
   - Airport Utilization

4. Observed Delay
   - Historic Demand
     - Calibrated delay model
       - Vary capacity

5. Delay modeling required
Arrival Delay Modeling

- Delay model calibrated to identify effective airport capacity that results in current observed delay level
- Arrival flows delayed to meet applied AAR (capacity envelope)
  - First come first serve allocation of time slots based on ETAs
- Model calibrated by adjusting applied AAR until matching means of distributions of actual and modeled delay
  - Used standard t-test
- Only considered delays during 15 minute periods in which arrival queues were simulated to ensure high demand
Results
Achievable and Effective Capacity Envelopes: BOS

Runway Configuration 4R | 9 IMC (ASPM)
(Low capacity configuration that saturates)

Runway Configuration 22L, 27 | 22L, 22R VMC (ASPM)
(High capacity configuration that does not saturate)
## Airport Arrival Utilization

- Ratio of throughput to effective capacity ($\tau/\mu_{\text{effective}}$) measures underutilization due to lack of demand only.
- Ratio of effective capacity to achievable capacity ($\mu_{\text{effective}}/\mu_{\text{achievable}}$) measures underutilization due to inefficiency of operations only.
- Ratio of throughput to achievable capacity ($\tau/\mu_{\text{achievable}}$) measures underutilization due to both lack of demand and inefficiency of operations.

*Estimated achievable capacities (100th percentile) may underestimate actual achievable capacities. These measures of utilization may thus be overestimated.*

<table>
<thead>
<tr>
<th>Airport</th>
<th>Runway Configuration</th>
<th>Met. Cond.</th>
<th>Throughput Saturation</th>
<th>Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\tau/\mu_{\text{effective}}$ (Due to $\lambda$ only)</td>
</tr>
<tr>
<td>BOS</td>
<td>22L</td>
<td>15R VMC</td>
<td>Saturates</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>4R</td>
<td>9 IMC</td>
<td>Saturates</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>33L,33R</td>
<td>27,33L VMC</td>
<td>Saturates</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>22L,27</td>
<td>22L,22R VMC</td>
<td>Does not saturate</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>4L,4R</td>
<td>4L,4R,9 VMC</td>
<td>Does not saturate</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>All</td>
<td>Saturates</td>
<td>0.74</td>
</tr>
<tr>
<td>BDL</td>
<td>All</td>
<td>VMC</td>
<td>Does not saturate</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>IMC</td>
<td>Saturates</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>All</td>
<td>Saturates</td>
<td>0.33</td>
</tr>
<tr>
<td>PVD</td>
<td>All</td>
<td>All</td>
<td>Saturates</td>
<td>0.36</td>
</tr>
<tr>
<td>MHT</td>
<td>All</td>
<td>All</td>
<td>Does not saturate</td>
<td>0.33</td>
</tr>
</tbody>
</table>

7/13/2005
Conclusions

- Approach presented for estimating arrival capacity achievable at an airport, and degree to which it is underutilized by lack of demand or inefficient operations
  - Underutilization at secondary airports dominated by lack of demand, while at BOS it is due to a combination of lack of demand and inefficient operations
- Utilization due to demand at secondary airports BDL, PVD and MHT on average 50% of that at BOS
  - Suggests that demand is well below capacity at BDL, PVD, and MHT
  - Suggests that metering is not necessary at these secondary airports under current demand levels
- For configurations at BOS that saturate – effective to achievable capacity ratio below 1 indicates that potential throughput benefits exist from DSTs or improved procedures that increase operation efficiency
Future Work

- Investigate analytical or simulation techniques for estimation of achievable capacities
  - Particularly for airports that do not saturate where 100th percentile throughput may underestimate achievable capacity
  - Investigate effectiveness of hyperbolic curve fit asymptote as a measure of achievable capacity
- Perform sensitivity analysis of effective capacities and utilization to factors such as:
  - System boundary, selection of high demand periods, accounting for runway configuration and wind, threshold for saturation metric
General Edward Lawrence Logan International Airport
Boston, Massachusetts

- FAA identifier: BOS
- Runways:
  - 15R/33L
  - 4R/22L
  - 4L/22R
  - 9/27
  - 15L/33R
- Average aircraft operations per day: 1073 (source: airnav.com)
Bradley International Airport
Windsor Locks, Connecticut

• FAA identifier: BDL
• Runways:
  – 6/24
  – 15/33
  – 1/19
• Average aircraft operations per day: 387 aircraft
  (source: airnav.com)
Theodore Francis Green State Airport
Providence, Rhode Island

- FAA identifier: PVD
- Runways:
  - 5/23
  - 16/34
- Average aircraft operations per day: 406 aircraft
  (source: airnav.com)
Manchester Airport
Manchester, New Hampshire

- FAA identifier: MHT
- Runways:
  - 17/35
  - 6/24
- Average aircraft operations per day: 263 aircraft
  (source: airnav.com)
### Comparison of ASPM and ASDI Data

**BOS**

<table>
<thead>
<tr>
<th></th>
<th>ASPM</th>
<th>ASDI</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum of flts 5/1/04 to 7/21/04</td>
<td>45,857</td>
<td>41,479</td>
<td>9.5 %</td>
</tr>
<tr>
<td>Mean arrivals per day</td>
<td>559</td>
<td>506</td>
<td>9.5 %</td>
</tr>
<tr>
<td>Std deviation of arrivals per day</td>
<td>70.6</td>
<td>129</td>
<td>-83 %</td>
</tr>
<tr>
<td>Max arrivals per day</td>
<td>694</td>
<td>655</td>
<td>5.6 %</td>
</tr>
<tr>
<td>Min arrivals per day</td>
<td>369</td>
<td>90</td>
<td>76 %</td>
</tr>
<tr>
<td>Mean arrivals per half hour</td>
<td>11.5</td>
<td>10.5</td>
<td>8.7 %</td>
</tr>
<tr>
<td>Std deviation of arrivals per half hour</td>
<td>7.0</td>
<td>7.4</td>
<td>5.7 %</td>
</tr>
<tr>
<td>Max arrivals per half hour</td>
<td>29</td>
<td>33</td>
<td>14 %</td>
</tr>
<tr>
<td>99th percentile of arrivals per half hour</td>
<td>24</td>
<td>25</td>
<td>4.2 %</td>
</tr>
<tr>
<td>95th percentile of arrivals per half hour</td>
<td>21</td>
<td>21</td>
<td>0 %</td>
</tr>
<tr>
<td>90th percentile of arrivals per half hour</td>
<td>20</td>
<td>20</td>
<td>0 %</td>
</tr>
<tr>
<td>85th percentile of arrivals per half hour</td>
<td>19</td>
<td>19</td>
<td>0 %</td>
</tr>
</tbody>
</table>

- ASDI data captures slightly fewer flights than ASPM, but not enough to invalidate analyses
### Comparison of ASPM and ASDI Data

**BDL**

<table>
<thead>
<tr>
<th></th>
<th>ASPM</th>
<th>ASDI</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum of flts 5/1/04 to 7/21/04</td>
<td>13,731</td>
<td>12,678</td>
<td>7.7%</td>
</tr>
<tr>
<td>Mean arrivals per day</td>
<td>167</td>
<td>154</td>
<td>7.7%</td>
</tr>
<tr>
<td>Std deviation of arrivals per day</td>
<td>29.8</td>
<td>33.4</td>
<td>-12%</td>
</tr>
<tr>
<td>Max arrivals per day</td>
<td>213</td>
<td>207</td>
<td>2.8%</td>
</tr>
<tr>
<td>Min arrivals per day</td>
<td>106</td>
<td>42</td>
<td>60%</td>
</tr>
<tr>
<td>Mean arrivals per half hour</td>
<td>3.5</td>
<td>3.2</td>
<td>7.7%</td>
</tr>
<tr>
<td>Std deviation of arrivals per half hour</td>
<td>2.6</td>
<td>2.6</td>
<td>0.4%</td>
</tr>
<tr>
<td>Max arrivals per half hour</td>
<td>14</td>
<td>15</td>
<td>7.1%</td>
</tr>
<tr>
<td>99th percentile of arrivals per half hour</td>
<td>10</td>
<td>10</td>
<td>0%</td>
</tr>
<tr>
<td>95th percentile of arrivals per half hour</td>
<td>8</td>
<td>8</td>
<td>0%</td>
</tr>
<tr>
<td>90th percentile of arrivals per half hour</td>
<td>7</td>
<td>7</td>
<td>0%</td>
</tr>
<tr>
<td>85th percentile of arrivals per half hour</td>
<td>6</td>
<td>6</td>
<td>0%</td>
</tr>
</tbody>
</table>

- ASDI data captures slightly fewer flights than ASPM, but not enough to invalidate analyses
Results
Capacity Envelopes: BOS

- Difference between effective and achievable capacity envelopes is less for 15R | 22L (low capacity configuration that saturates) than 4L, 4R | 4L, 4R, 9 (high capacity configuration that does not saturate)
Results
Achievable and Effective Capacity Envelopes: Secondary Airports

BDL VMC (ASPM) (Does not saturate)

BDL IMC (ASPM) (Does saturate)

PVD (ASDI) (Does not saturate)

MHT (ASDI) (Does not saturate)
Simulation of Runway Operations

- Assuming infinite demand, fraction of arrivals to departures varied to generate a capacity envelope
- Each flight is assigned a class based on distribution of fleet mix
- Capacity is calculated by forcing aircraft to fly at minimum separation requirements
- Additional Inputs for Arrivals
  - Approach separations per class – from regulations (deterministic)
  - Approach speed per class – normal distribution
  - Runway occupancy time on arrival – normal distribution
  - Approach distance for runway – from approach plates
- Additional Inputs for Departures
  - Runway occupancy time on departure – normal distribution
  - Departure separations per class
    - from regulations
Simulation of Runway Operations
Occupancy Time

- Mean calculated from runway and aircraft characteristics.
- Std. deviation = 10s
- Occupancy time calculations may also be simulated with inputs represented by distributions.
Simulation of Runway Operations
Modeling Regulations

- **Arrivals**
  - If trailing aircraft is faster:
    - Minimum Temporal Spacing = \( \text{Max} \left( \frac{r+s_{ij} - r}{v_j}, o_i \right) \)
  - If leading aircraft is faster or of equal speed:
    - Minimum Temporal Spacing = \( \text{Max} \left( s_{ij}, o_i \right) \)
  - \( s_{ij} \) is given in regulations
Simulation of Runway Operations
Modeling Regulations

• Departures
  – If leading aircraft is a Large or a Small, Minimum temporal spacing is the minimum of:
    • Time for leading aircraft to clear runway OR
    • Time to get 6,000ft (for Large) (4,500ft for Small) away from trailing aircraft
  – If leading aircraft is a Heavy or a B757, Minimum temporal spacing is minimum of:
    • 2 minutes
    • Separation $s$ when trailing aircraft becomes airborne
    • $s_{ij}$ is given in regulations
Simulation of Runway Operations
Calibration

• Run simulation at LGA
  – ASPM arrival & departure data available for 3 months
  – Single runway configuration: 31/31
  – Estimated parameters varied within reasonable limits:
    • Arrivals:
      – Approach Speed
      – Runway Exit Speed
      – Deceleration
    • Departures
      – Take Off Speed
      – Acceleration

![Graph showing arrivals and departures with averages and maximums.](image)
Simulation of Runway Operations
Continuing Work

• Use calibrated parameters at other airports.
• Extend simulation to crossing runways.
  – (Already done for a deterministic analytical model)
• Calculate capacity envelopes at BDL, PVD, MHT and BOS
• Potential model improvements:
  – Give arrivals priority over departures
  – Simulate occupancy time by representing inputs with distributions
  – Other