A Multi-stakeholder Evaluation of Strategic Slot Allocation Schemes under Airline Frequency Competition

Ninth USA/Europe Seminar on Air Traffic Management Research and Development (June 2011)

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**Extent and Causes of Airport Congestion**

- Cost of domestic flight delays to US economy in 2007≈ $31.2 billion*
- 84.5% of National Aviation System (NAS) delays attributed to demand exceeding the realized airport capacity**

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of Passengers</th>
<th>Number of Flights</th>
<th>Total Arrival Delays to Flights (Minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>2001</td>
<td>93.34</td>
<td>96.47</td>
<td>78.15</td>
</tr>
<tr>
<td>2002</td>
<td>92.06</td>
<td>102.32</td>
<td>59.75</td>
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<tr>
<td>2003</td>
<td>97.29</td>
<td>119.65</td>
<td>75.18</td>
</tr>
<tr>
<td>2004</td>
<td>105.04</td>
<td>126.09</td>
<td>103.58</td>
</tr>
<tr>
<td>2005</td>
<td>109.62</td>
<td>126.98</td>
<td>107.80</td>
</tr>
<tr>
<td>2006</td>
<td>109.81</td>
<td>122.86</td>
<td>120.99</td>
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<tr>
<td>2007</td>
<td><strong>113.28</strong></td>
<td><strong>124.46</strong></td>
<td><strong>138.58</strong></td>
</tr>
<tr>
<td>2008</td>
<td>108.70</td>
<td>118.60</td>
<td>119.11</td>
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<tr>
<td>2009</td>
<td>103.07</td>
<td>110.73</td>
<td>91.82</td>
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<tr>
<td>2010</td>
<td>105.00</td>
<td>110.03</td>
<td>88.30</td>
</tr>
</tbody>
</table>

- Increase in number of flights much greater than that in passengers
- ~9% reduction in #passengers/flight

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*NEXTOR, Total Delay Impact Study (Ball, et al., 2010)  **Bureau of Transportation Statistics (www.bts.gov, 2008)
Frequency Competition

- More frequent flights attract more passengers
- Higher frequency shares associated with disproportionately higher market shares
  - Sigmoidal (or S-shaped) relationship

![Graph showing the relationship between frequency share and market share]

\[ MS_i = \frac{FS_i^\alpha}{\sum_{j=1}^{n} FS_j^\alpha} \]

- \( MS_i \): Market share of airline \( i \)
- \( FS_i \): Frequency share of airline \( i \)
- \( n \): Number of competing airlines
- \( \alpha \): Model parameter
Prior Research

a. In the absence of competition,
   – existing capacity more than enough to satisfy all passenger demand, with a similar level-of-service
   – over 80% reduction in congestion related delays
     (Vaze and Barnhart, 2011)

b. In the presence of competition,
   – level of congestion introduced by competition is directly proportional to
     1. profit margin
     2. number of competitors
     3. curvature of the S-curve
     (Vaze and Barnhart, 2010)
Contents

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4. Computation Results
5. Sensitivity to Assumptions
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Administrative Slot Controls at Airports

- Slot controls: common at major airports
  - Five congested airports in United States
  - Many major airports in Europe and Asia

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**Nash Equilibrium**

**Total Slots**

**Slot Distribution**

**Competition**
Model of Frequency Competition

The Basic Model

maximize: \[ \sum_{s \in S_a} (p_{as} Q_{as} - C_{as} f_{as}) \]

subject to:
\[ Q_{as} \leq \sum_{a' \in A_s} f_{a's} M_s \quad \forall s \in S_a \]
\[ Q_{as} \leq LF_{\text{max}} S_{as} f_{as} \quad \forall s \in S_a \]
\[ \sum_{\forall s \in S_a} f_{as} \leq U_a \]
\[ \sum_{\forall s \in S_a} f_{as} \geq L_a \]
\[ f_{as} \in \mathbb{Z}^+ \quad \forall s \in S_a \]

Total profit = fare revenue \(-\) operating cost
S-curve relationship
Seating capacity constraint
Upper bound on total slots
Lower bound on total slots
Extensions to the Basic Model

• Extension I: Fare Differentiation
  – Divides passengers into segments
  – Market share is a function of frequencies, fares, and airlines specific factors
  – Used for markets with asymmetric competition,
    • e.g. a Regional Carrier Vs. a Legacy Carrier

• Extension II: Market Entry Deterrence
  – Used for markets with a single airline
  – Possibility of market entry if existing frequency is not adequate
  – 2-stage Stackelberg model
Solution Methodology

• Size of the overall strategy space $\approx 10^{50}$
• Successive optimizations heuristic:
  – While there exists an airline whose current decision is not optimal: Re-optimize
• Individual optimization problems
  – Solved to optimality using dynamic programming
• Structure suitable for dynamic programming because:
  – slot restrictions: additive coupling constraints across markets
  – objective function: additive across markets
• $\#\text{stages} = \#\text{markets}$
• $\#\text{states per stage} = \text{maximum } \# \text{ slots}$
Experimental Setup

• All flights out of LGA airport
• Passenger demands, operating costs, fares, and seating capacities obtained from BTS website

Obtain Nash equilibrium solution for:
1. Existing slot controls (empirical validation)
2. Varying levels of slot reduction (explorative analysis)
3. 12.3% slot reduction (multi-stakeholder evaluation)
   a. Proportionate allocation: slots distributed in same ratio as current slots
   b. Reward-based allocation: slots distributed in same ratio as current passengers
Empirical Validation

Model results provide good fit to actual frequencies
Explorative Analysis

Slot Reduction with Proportionate Allocation

Percentage Decrease in Passengers

Percentage Increase in Profit

Percentage Slot Reduction

Percentage Slot Reduction
Multi-Stakeholder Evaluation

12.3% Slot Reduction

Large Reduction in Flight and Passenger Delays

Avg. Delays (min.)

-41%

No Reduction
Proportionate
Reward-based

Small Reduction in Passengers Carried

Passengers Carried

-2%

Considerable Increase in Airline Profits

Profit ($)

+19%
+16%
Profits of Individual Airlines

12.3% Slot Reduction

Each airline’s profit increases under both strategies
Sensitivity to Maximum Load Factor Assumption

Slot reduction impacts are NOT very sensitive to the maximum load factor assumptions.
Relaxing the Constant Aircraft Size Assumption

Impact of Limited Upgauging

Most of the reduction in passengers carried disappears.
Conclusions

- Slot reduction benefits passengers, airlines and airport operators
  - Almost all passengers carried with
    - negligible increase in schedule displacement and
    - large reduction in passenger delays
  - All airlines benefit through
    - considerable increase in operating profits and
    - large reduction in flight delays
  - Airport operators benefit from
    - reduction in airport congestion

- Results not too sensitive to assumptions
  - Main conclusions are robust
  - Often conservative: actual benefits likely even higher
References