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

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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**

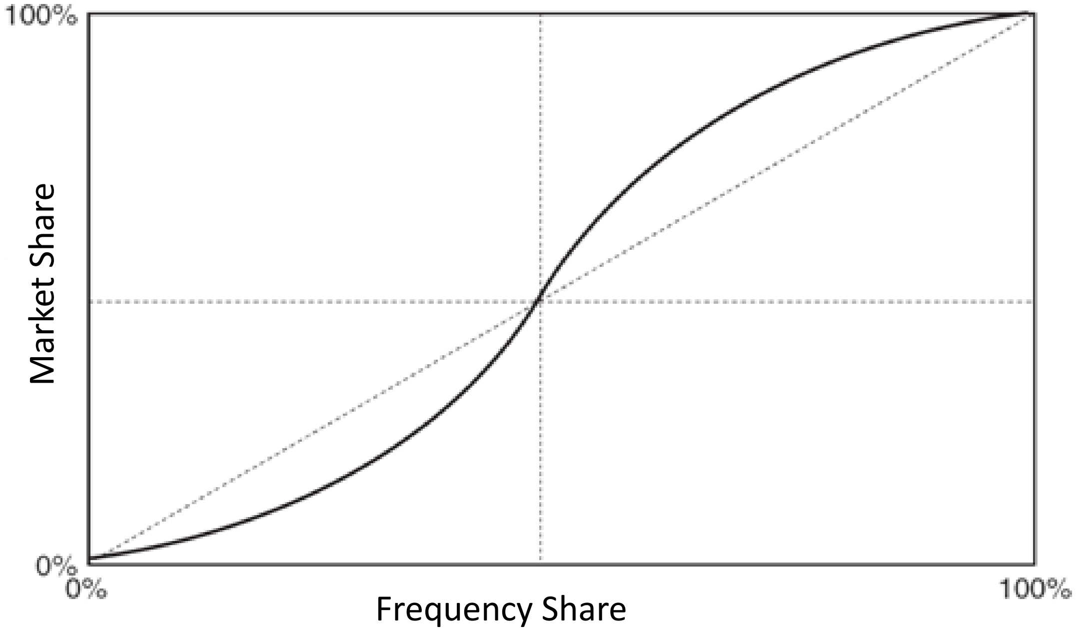
Year	Number of Passengers	Number of Flights	Total Arrival Delays to Flights (Minutes)
2000	100	100	100
2001	93.34	96.47	78.15
2002	92.06	102.32	59.75
2003	97.29	119.65	75.18
2004	105.04	126.09	103.58
2005	109.62	126.98	107.80
2006	109.81	122.86	120.99
2007	113.28	124.46	138.58
2008	108.70	118.60	119.11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

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

*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



$$MS_i = \frac{{FS_i}^{\alpha}}{\sum_{j=1}^{n} {FS_j}^{\alpha}}.$$

MS_i: Market share of airline i

FS_i: Frequency share of airline i

n: Number of competing airlines

α: 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)

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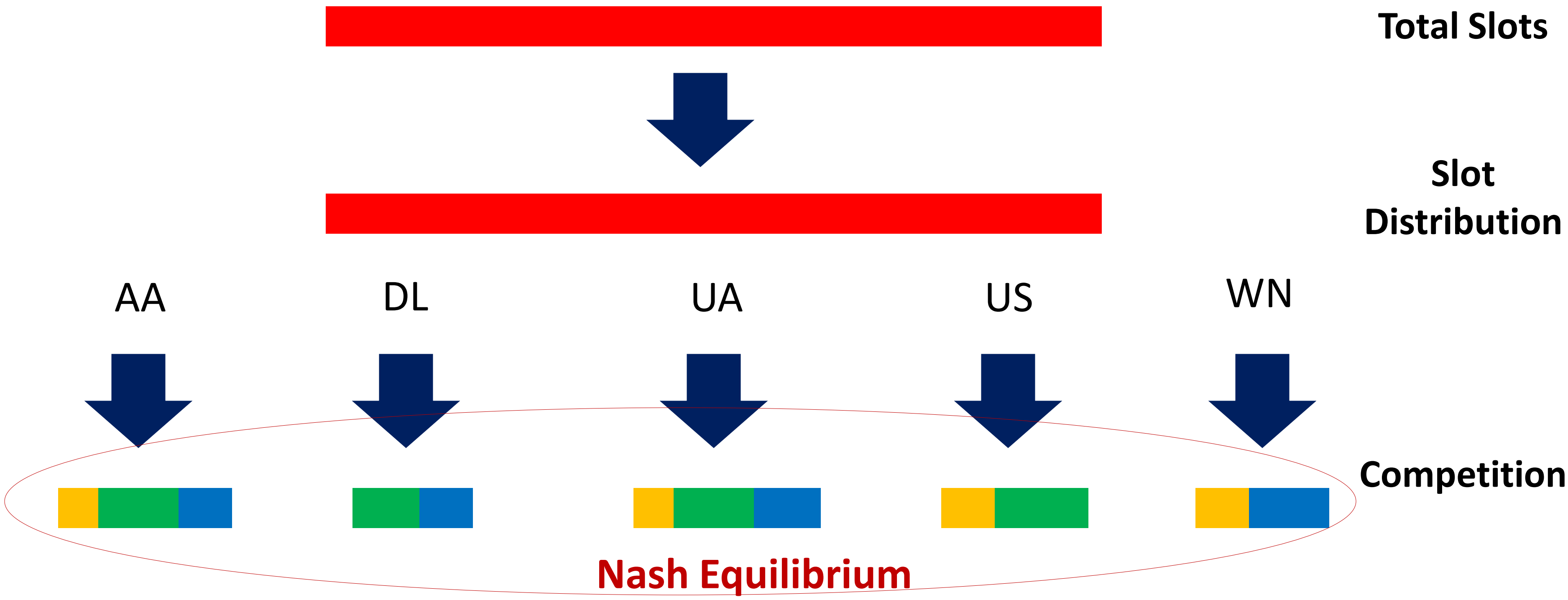
Administrative Slot Controls at Airports

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



Model of Frequency Competition

The Basic Model

maximize:	$$\sum_{s \in \mathbb{S}_a} (p_{as} Q_{as} - C_{as} f_{as})$$	Total profit = fare revenue – operating cost
subject to:	$$Q_{as} \leq \frac{f_{as}^{\alpha_s}}{\sum_{a' \in \mathbb{A}_s} f_{a's}^{\alpha_s}} M_s \ \forall s \in \mathbb{S}_a$$	S-curve relationship
	$$Q_{as} \leq LF_{max} S_{as} f_{as} \ \forall s \in \mathbb{S}_a$$	Seating capacity constraint
	$$\sum_{\forall s \in \mathbb{S}_a} f_{as} \leq U_a$$	Upper bound on total slots
	$$\sum_{\forall s \in \mathbb{S}_a} f_{as} \geq L_a$$	Lower bound on total slots
	$$f_{as} \in \mathbb{Z}^+ \ \forall s \in \mathbb{S}_a$$	

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 ≈ 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
- #stages = #markets
- #states per stage = maximum # slots

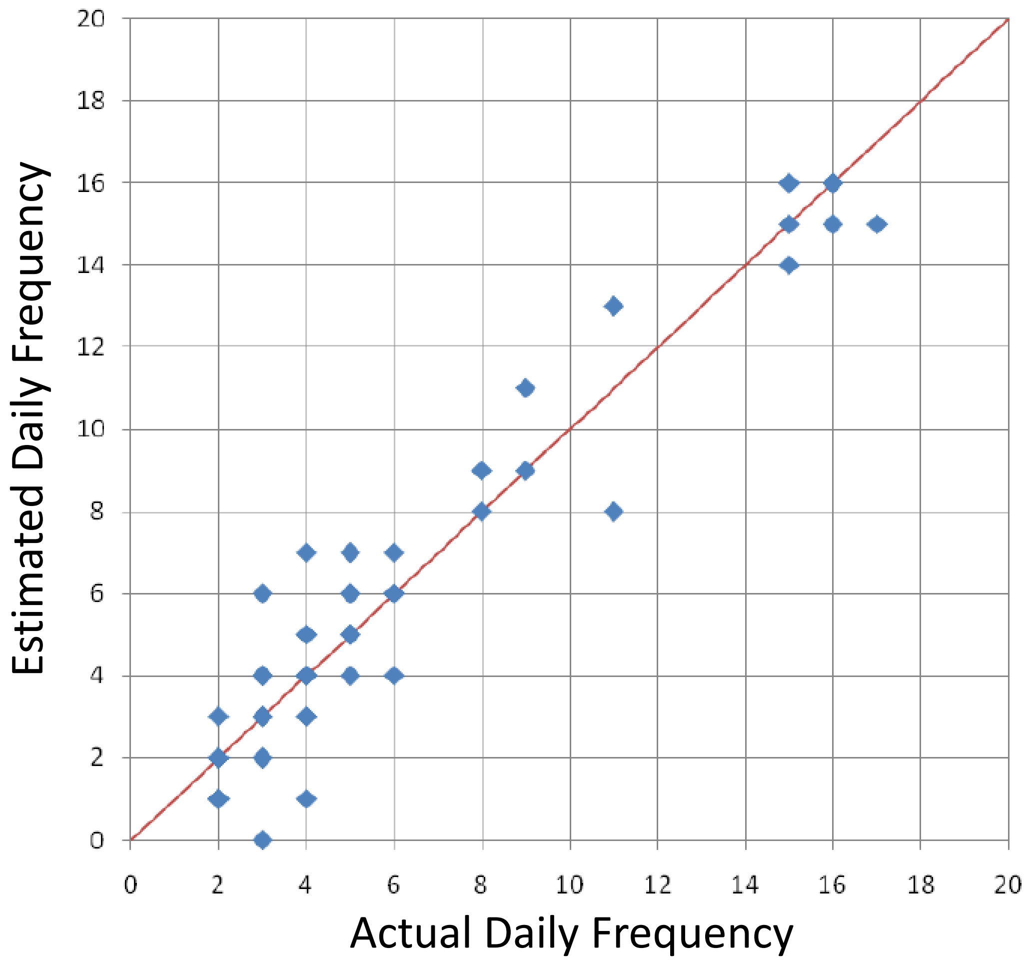
Experimental Setup

- 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

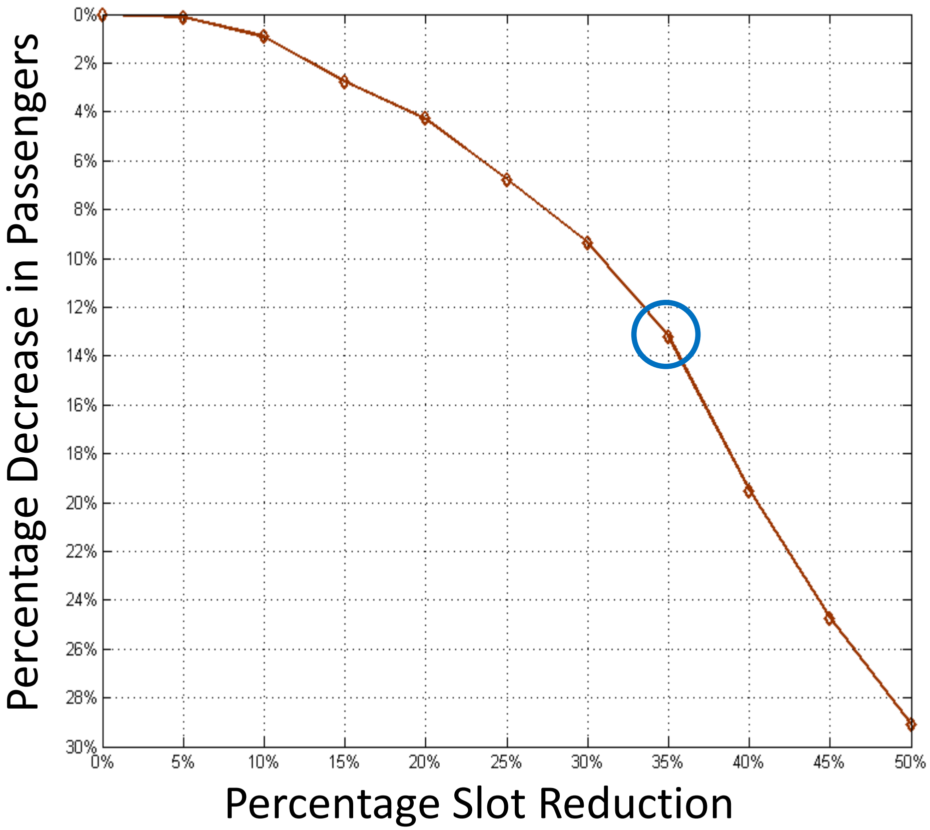
Empirical Validation

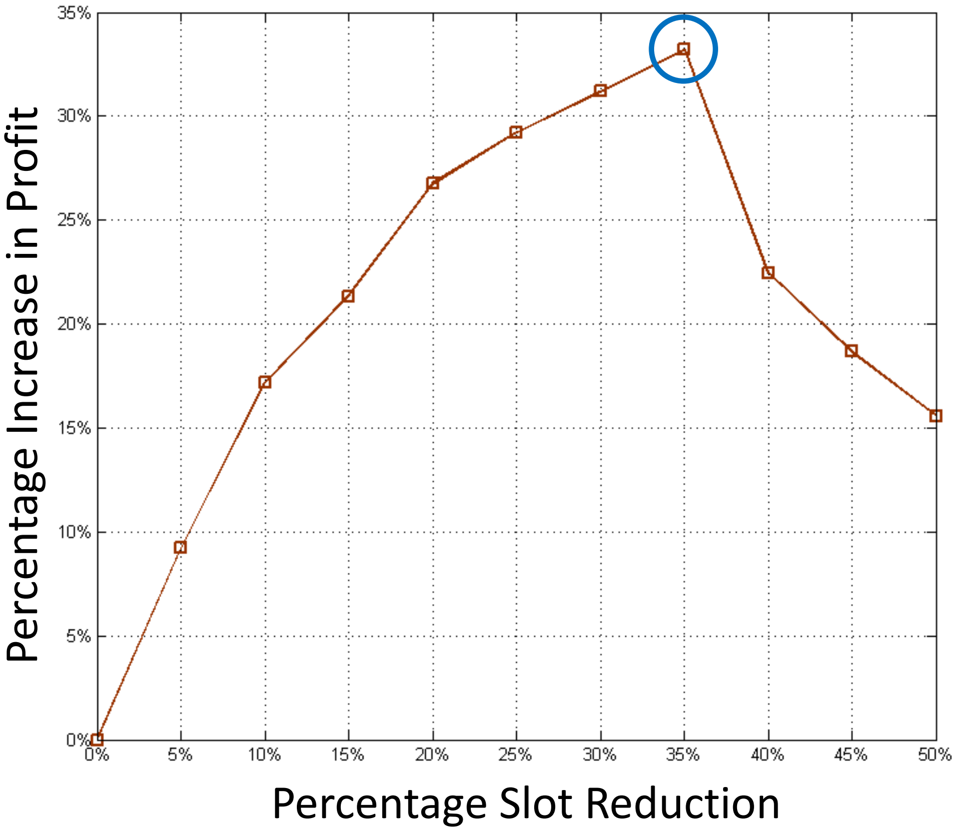


Model results provide good fit to actual frequencies

Explorative Analysis

Slot Reduction with Proportionate Allocation

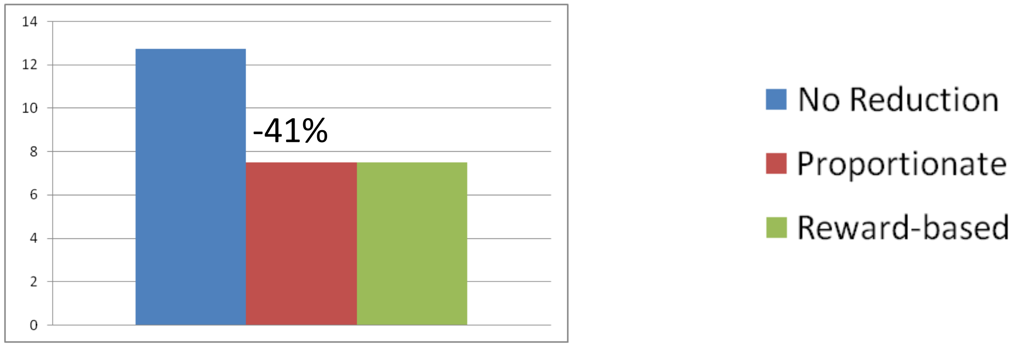




Multi-Stakeholder Evaluation

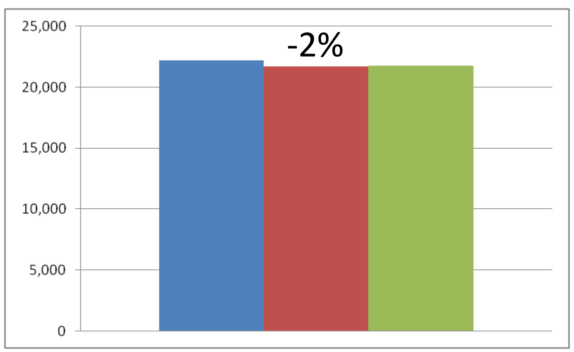
12.3% Slot Reduction

Large Reduction in Flight and Passenger Delays

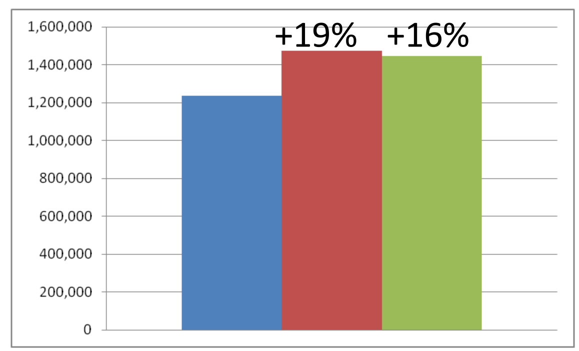


Avg. Delays (min.)

Small Reduction in Passengers Carried



Passengers Carried

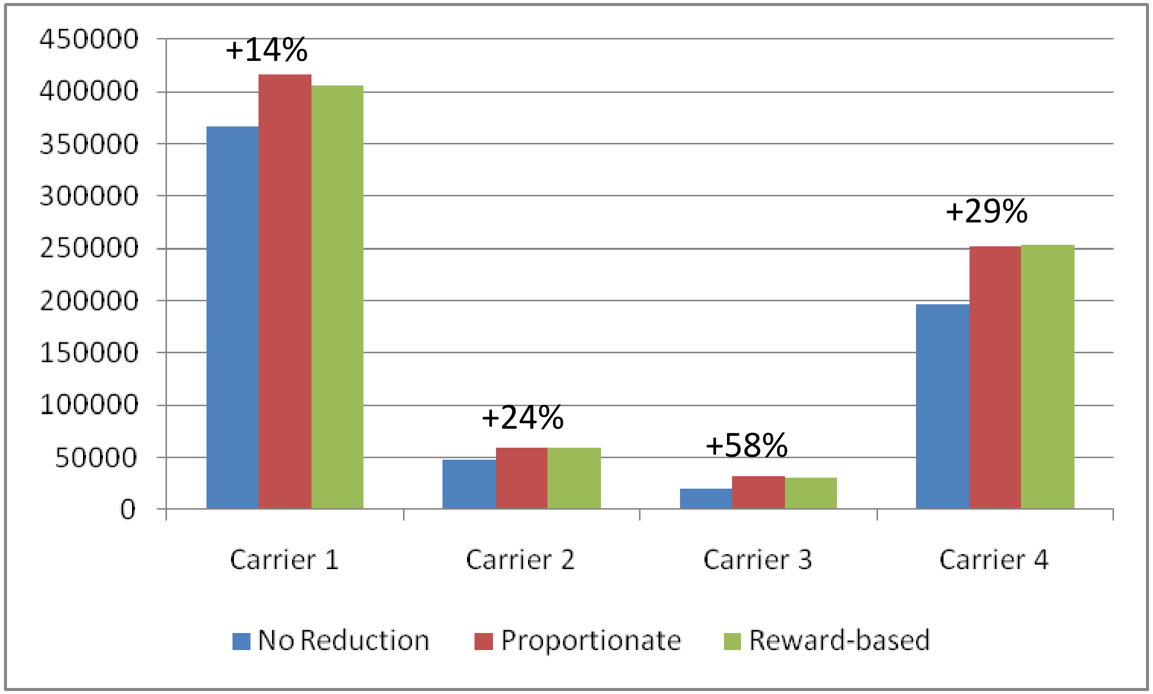


Profit ($)

Considerable Increase in Airline Profits

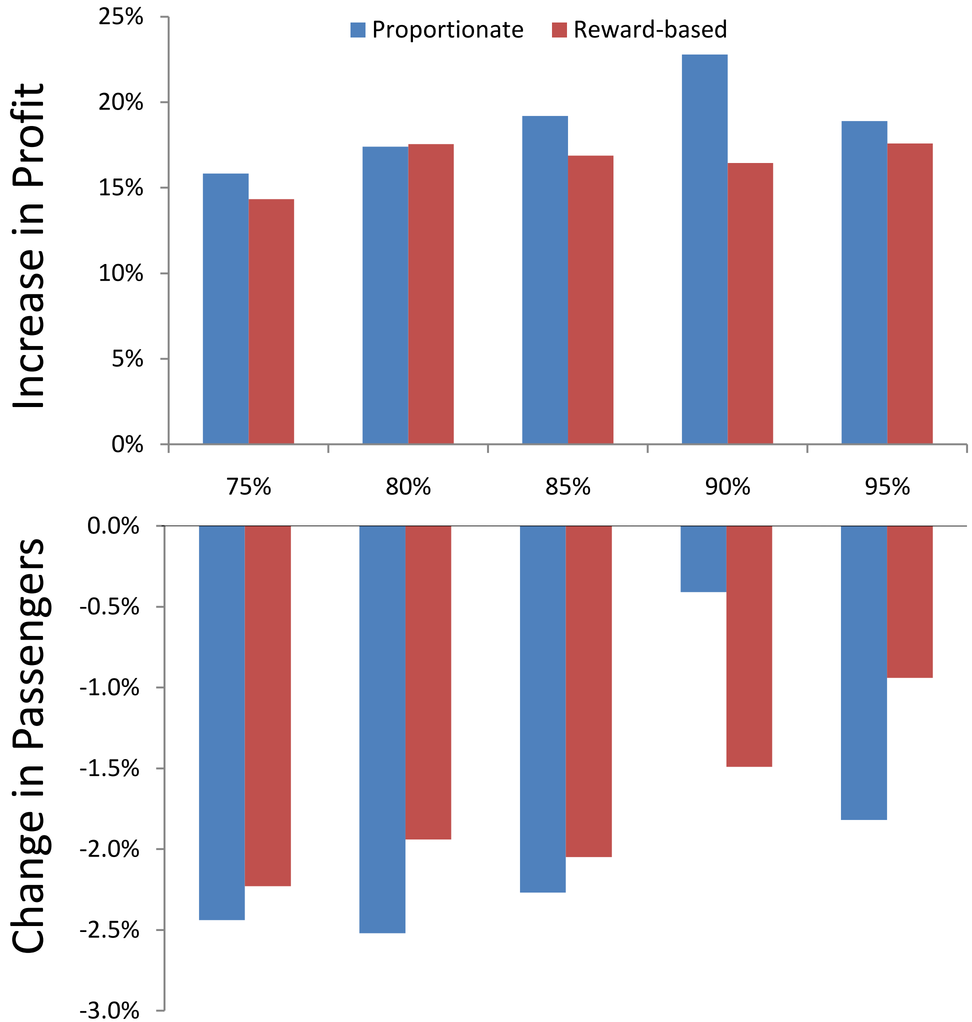
Profits of Individual Airlines

12.3% Slot Reduction



Each airline's profit increases under both strategies

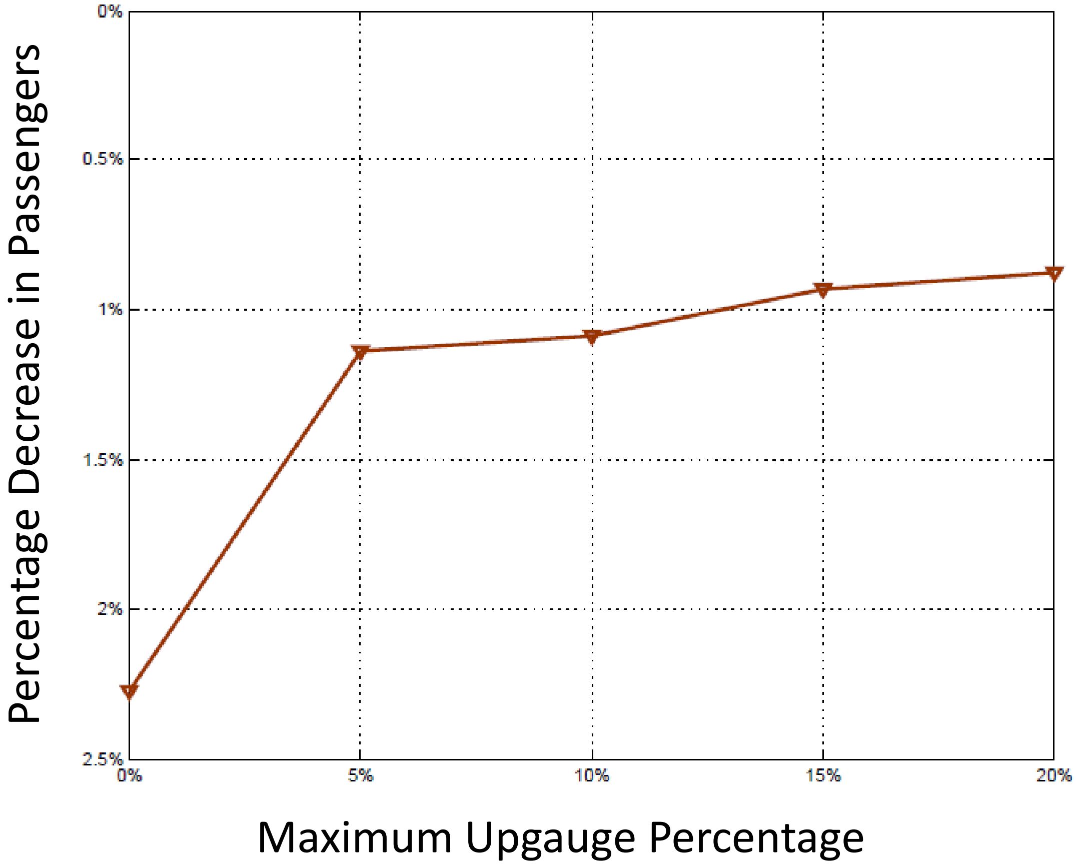
Sensitivity to Maximum Load Factor Assumption



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

Thank You

References

- V. Vaze and C. Barnhart, “An assessment of the impact of demand management strategies for efficient allocation of airport capacity”, *International Journal of Revenue Management*, Upcoming, 2011.
- V. Vaze and C. Barnhart, “Price of airline frequency competition”, Working Paper ESD-WP-2010-10, Engineering Systems Division, Massachusetts Institute of Technology, 2010.