Air Transportation Network Load Balancing using Auction-Based Slot Allocation for Congestion Management

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NEXTOR Wye River Conf

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Outline

- Description of the Congestion Problem
  - Chicago O'Hare Airport
  - NY La Guardia Airport
- History of Congestion Management in the US
- Auction model for airport arrival slots
- Chicago ORD airport case study
  - simulated scenarios
  - results and interpretation
- Observations and Recommendations

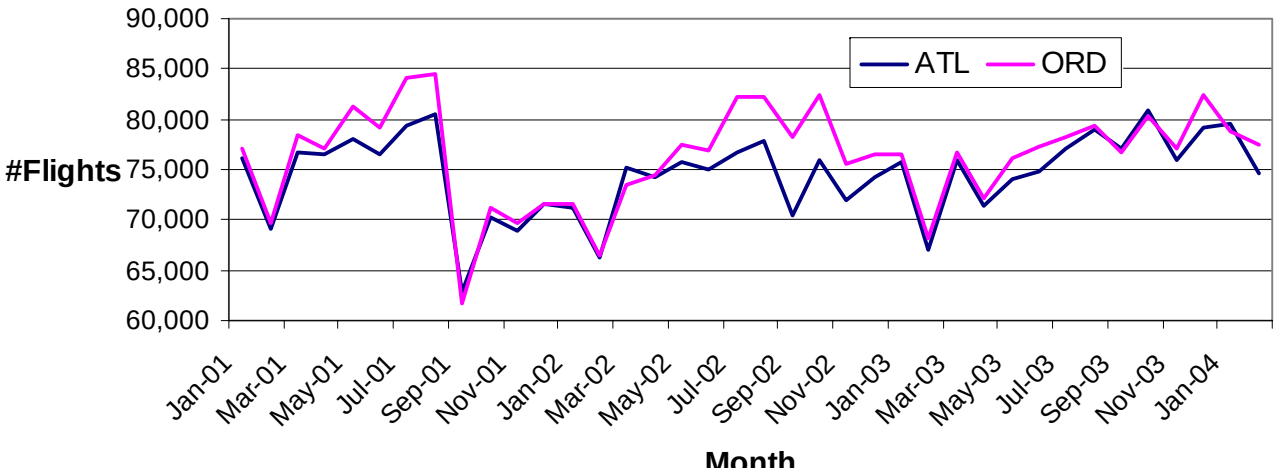
National Airspace System Characteristics

- **The NAS is a Stochastic Adaptive Network**
  - **Stochastic: The system is characterized by PDF's**
  - **Adaptive: These PDF's are a function of the System State and Airline Market Decisions**
- **Reasons that the NAS Cannot be Deterministic:**
  - **Weather (winds, hazardous weather)**
  - **Mechanical Equipment Characteristics**
  - **Air Traffic Control System (including Controllers)**
  - **Aircraft Control System (including Pilots)**
  - **Airline Schedules set by varying Market Conditions**
- **All Analysis and FAA Rules Must Acknowledge this Fundamental Nature in the Future**

Operations are Back but ORD Delays are Worse

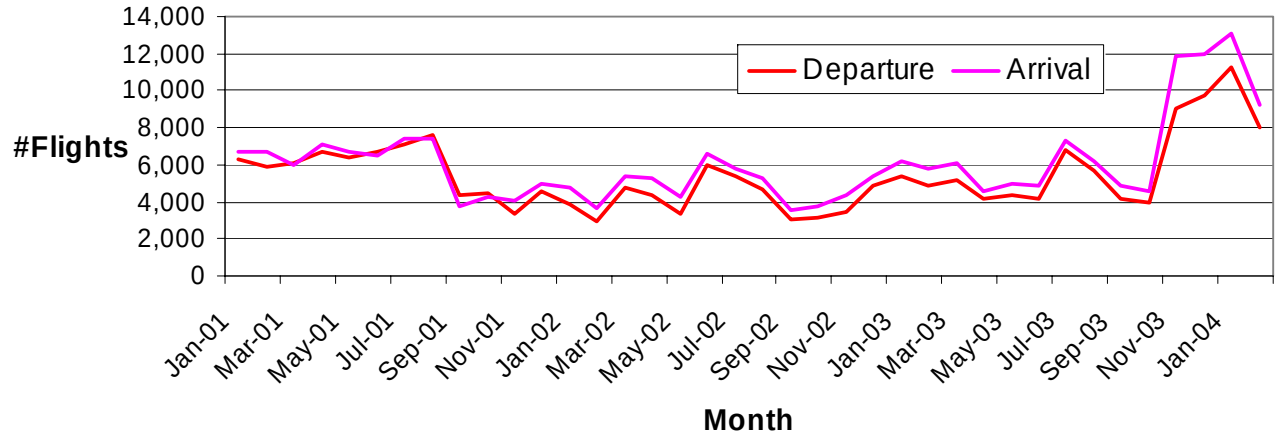
Air travel is gradually picking up

Monthly Total Operations at Major US Airports (Source: ETMS)



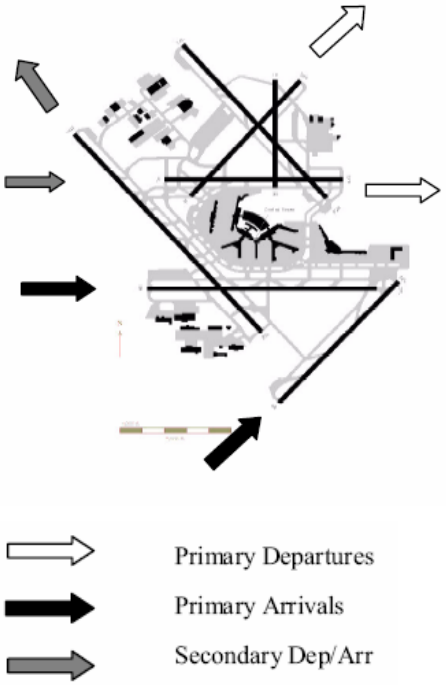
Congestion is coming back

Delayed Flights of Major US Air Carriers at ORD (Source: BTS)

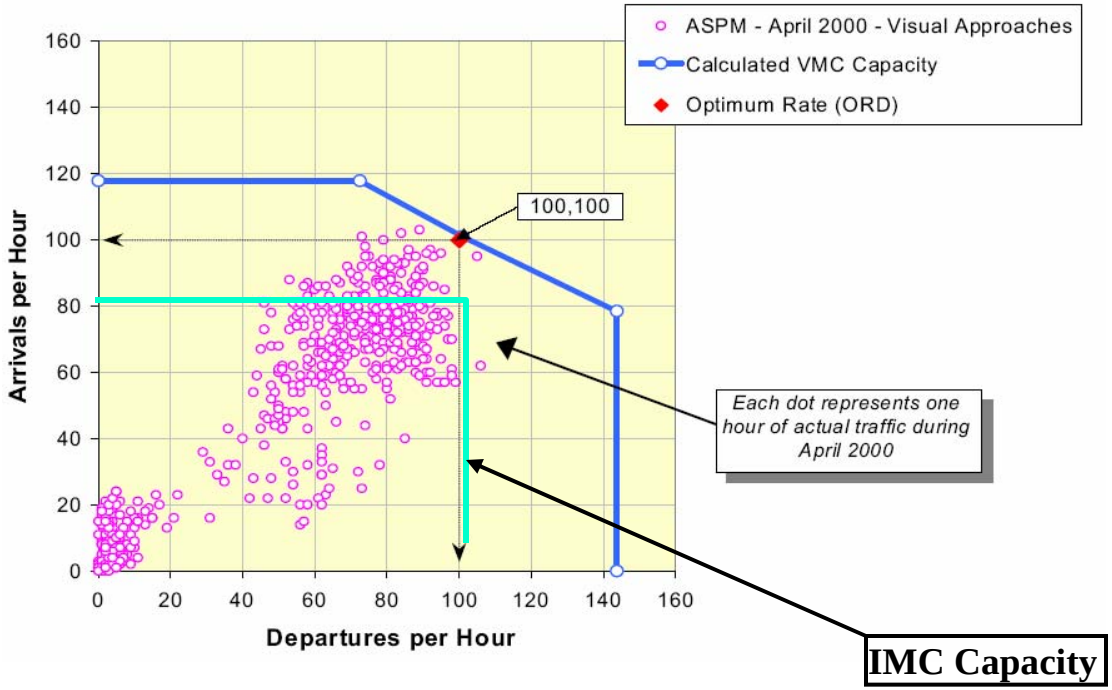


Chicago O'Hare: A Maximum Capacity Hub Airport

Runway layout:

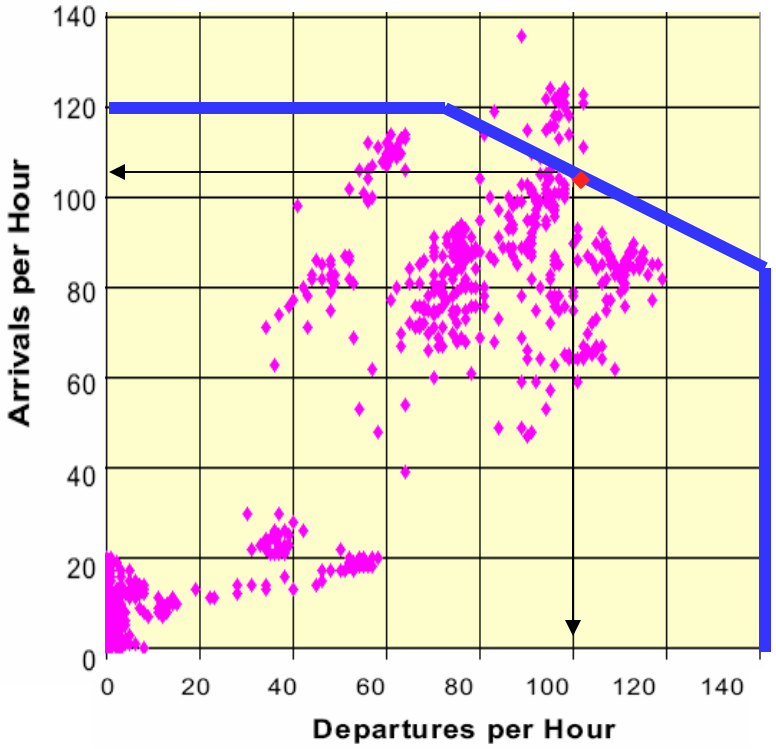


Departure/Arrival Pareto Trade-off:
FAA/DoT 2001 Benchmark Report
ASPM Data April 2000 VMC

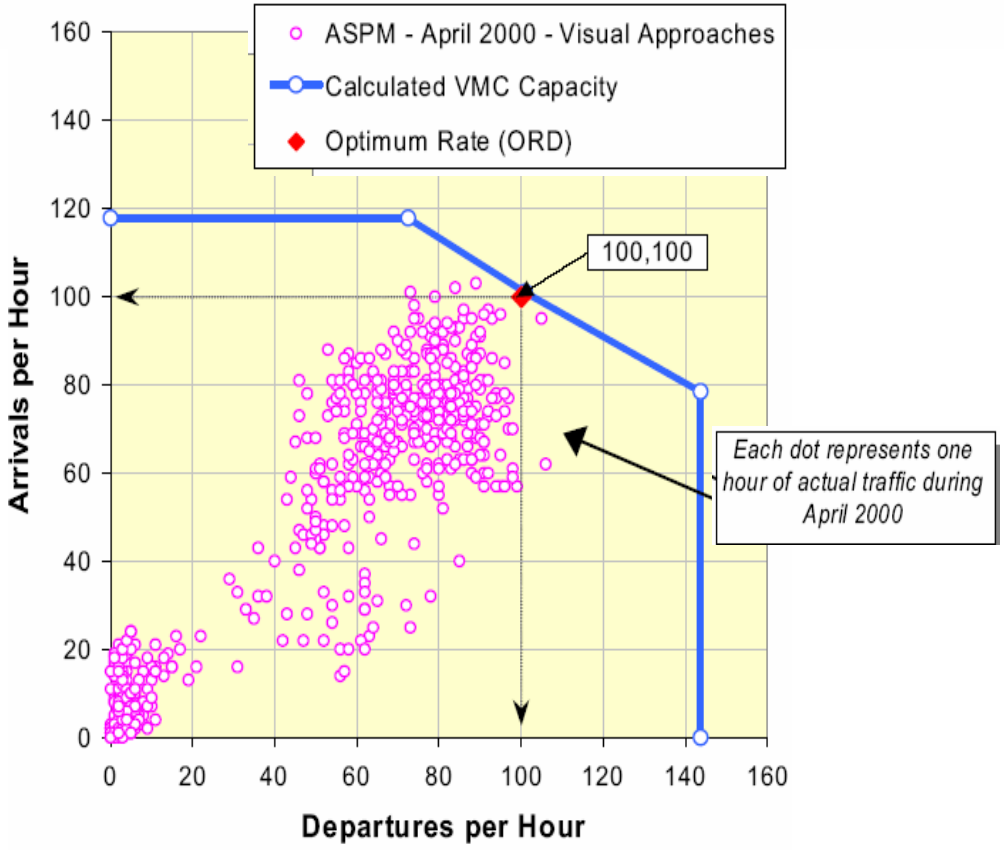


ORD in Dec 2003: Result of HDR Removal

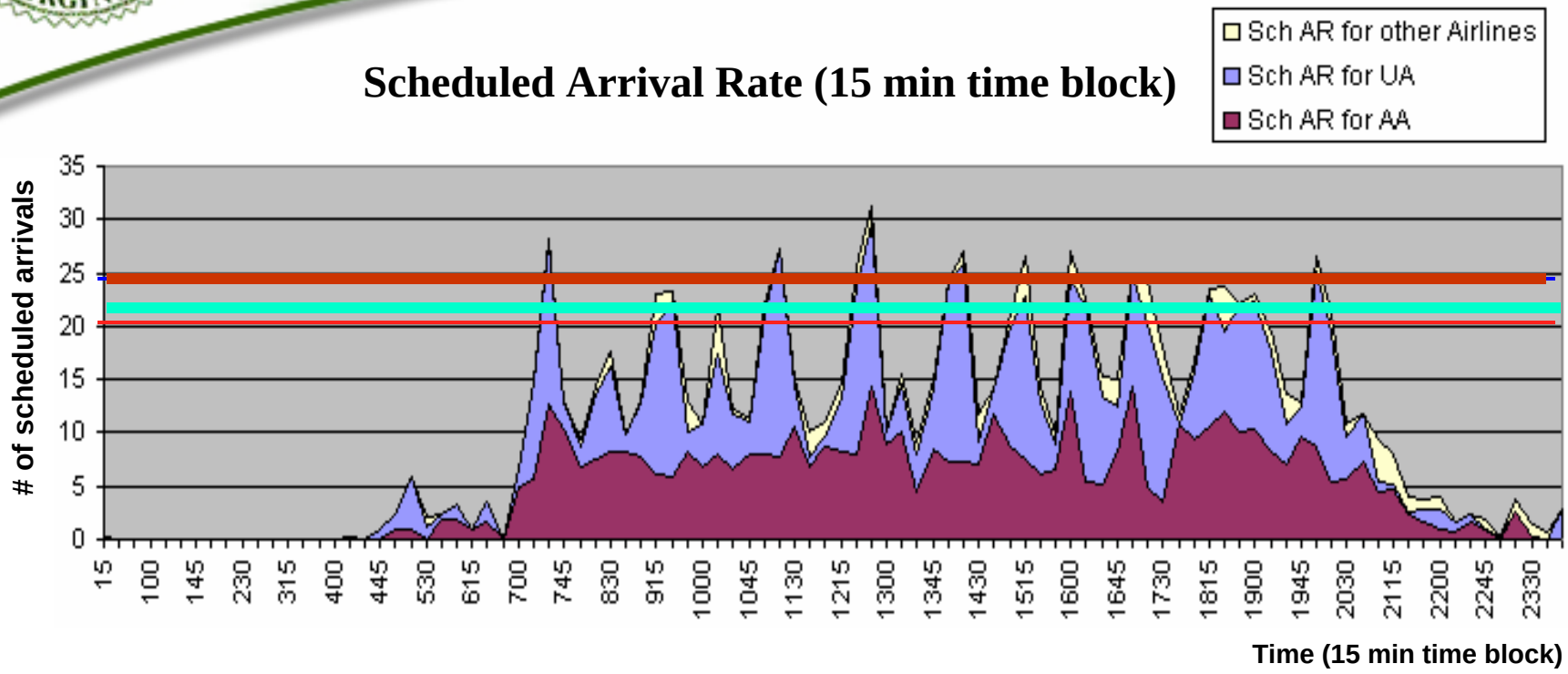
ASPM Data Dec 2003



DoT/FAA 2001 Benchmark Report: Data April 2000 VMC



Scheduled Arrival Rate for Different Airlines at ORD in Nov. and Dec. 2003

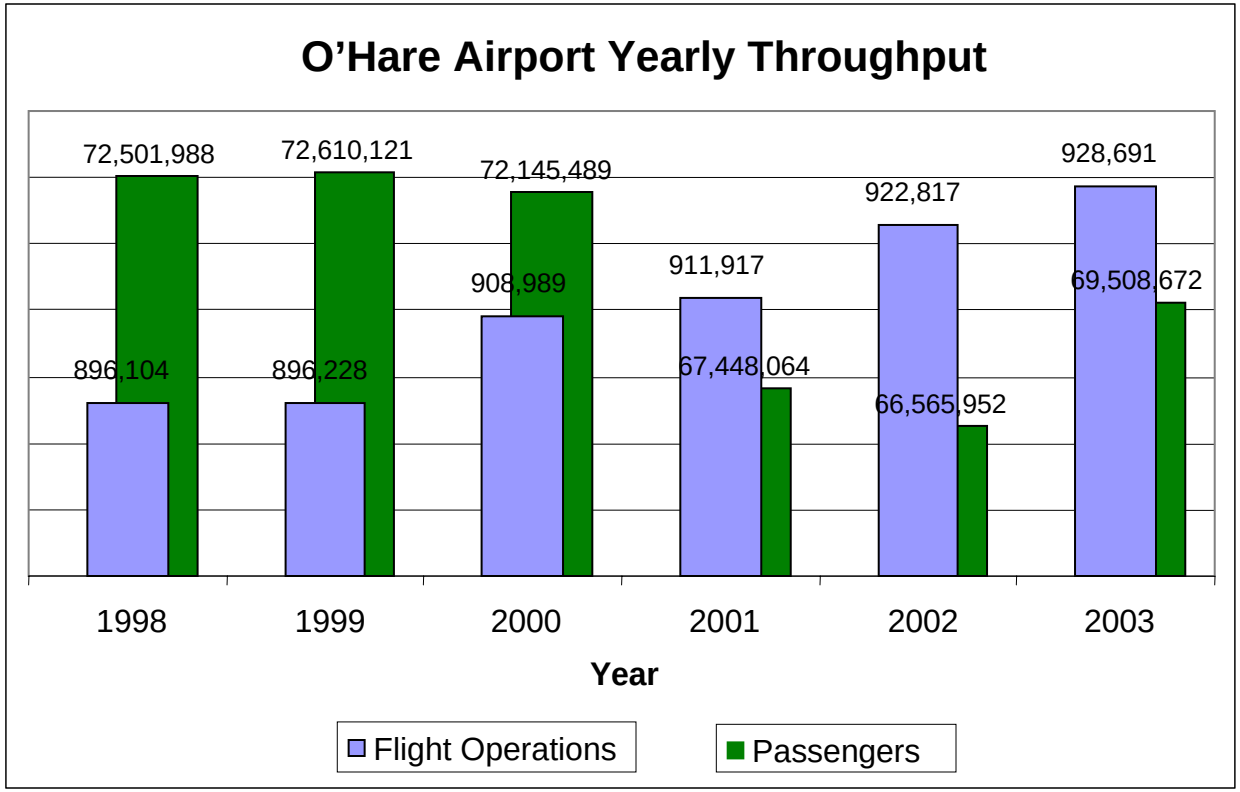


- **The Green line = 21 arr. /15 min, upper-bound of IMC AR at ORD in Nov. and Dec. 2003**
- **The Red line = 25 arr./15 min, Max AR from FAA Benchmark Report for all arrivals**

- **Data from BTS which only includes domestic flight data for 15 certificated airlines**

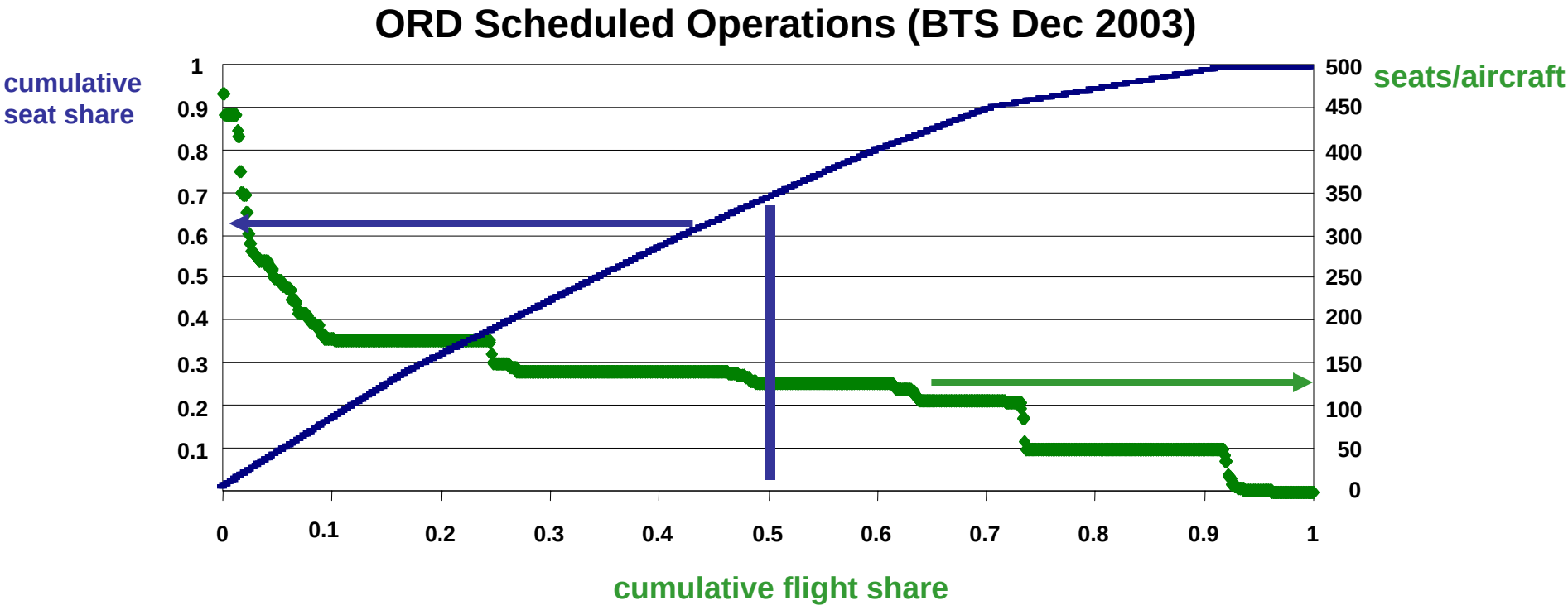
Smaller Aircraft trend Exacerbates Congestion

- **Frequency competition Reduces Seat Capacity and Increases FAA Operational Load**



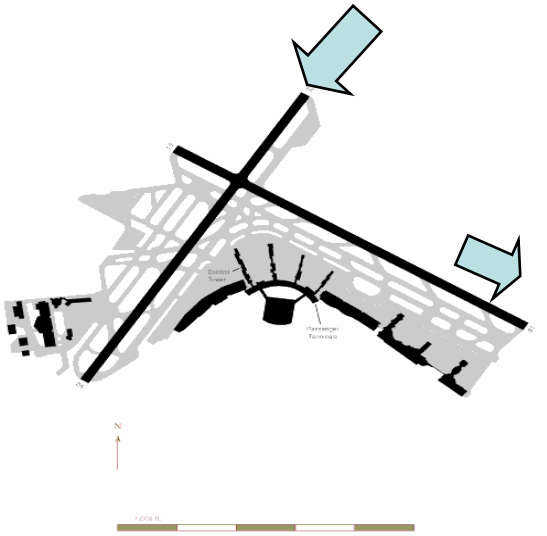
Enplanement Capacity vs. Operational Capacity

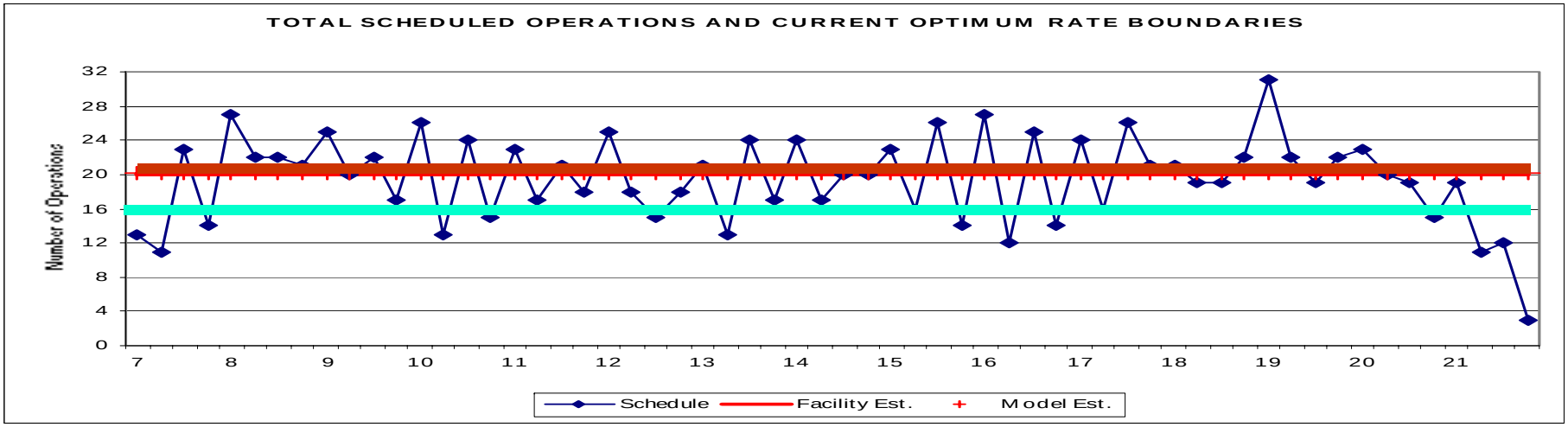
- **Small aircraft make inefficient use of runway capacity: 50% Flights Provide 70% Enplanement Opportunities**



NY LaGuardia: A Maximum Capacity non-Hub Airport

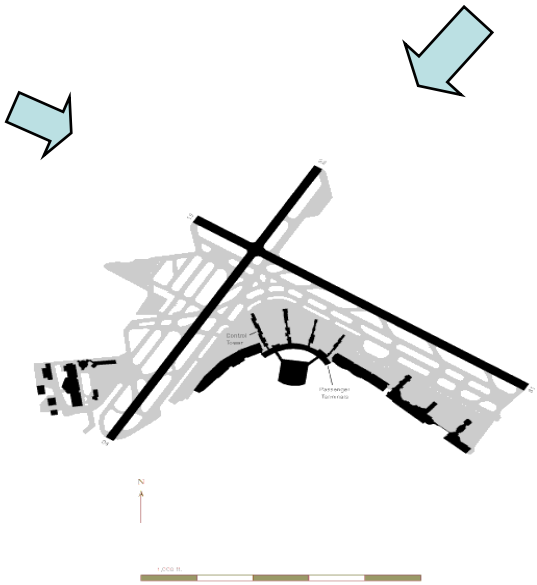
- 1 Arrival Runway
- 1 Departure Runway
- 45 Arrivals/Hr (Max)
- 80 Seconds Between Arrivals
- 11.3 minute Average Delay
- 77 Delays/1000 Operations
- 40 min./Delay





NY LaGuardia :A Maximum Capacity Non-Hub Airport

Runway layout:



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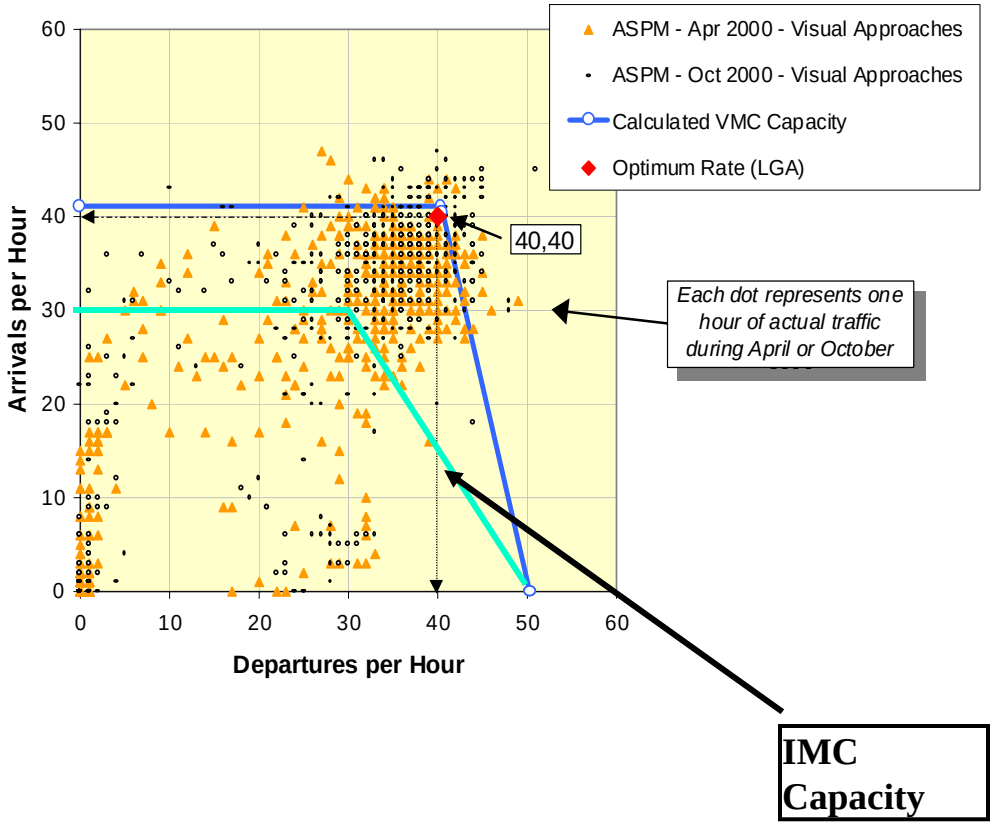
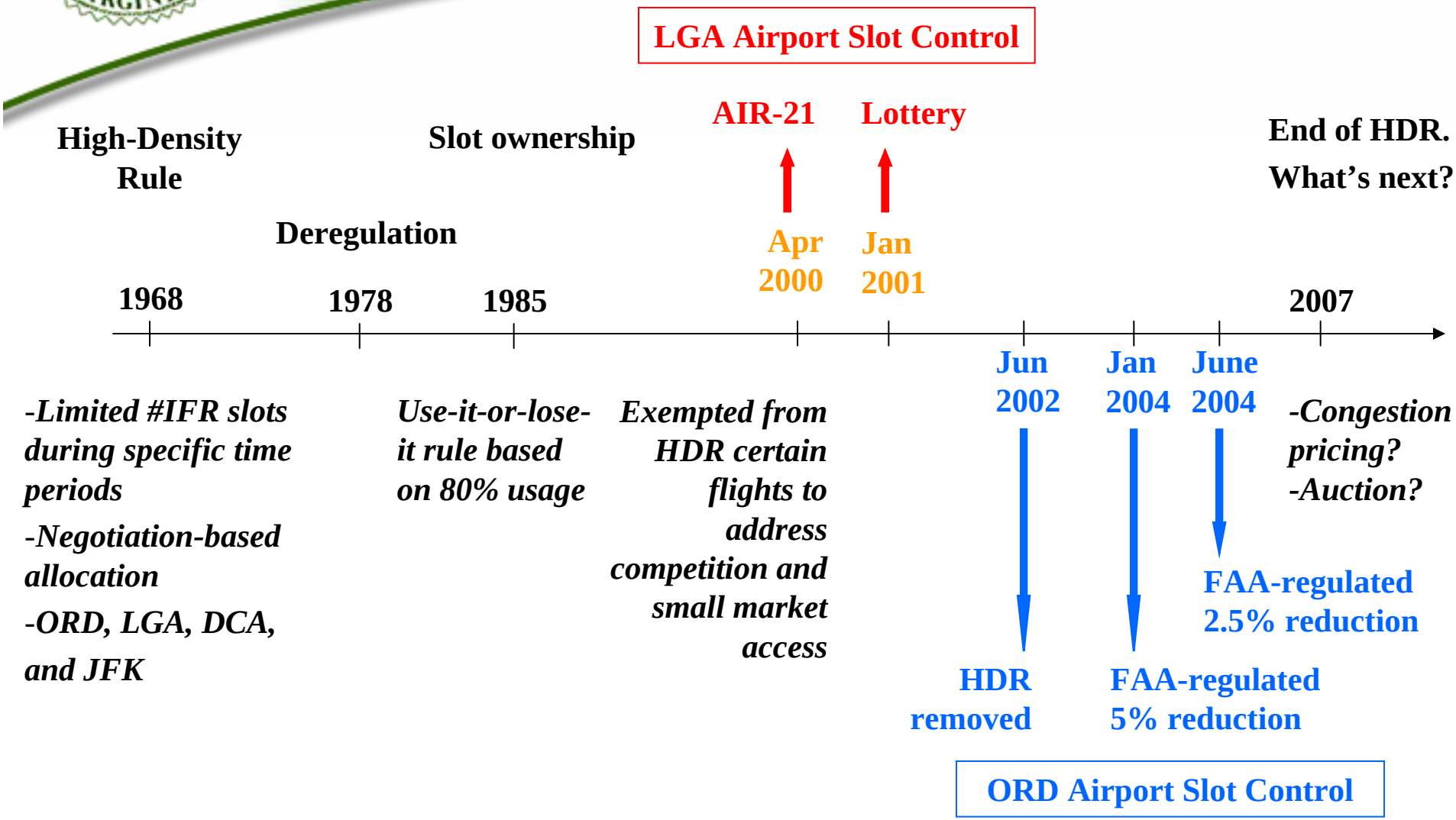


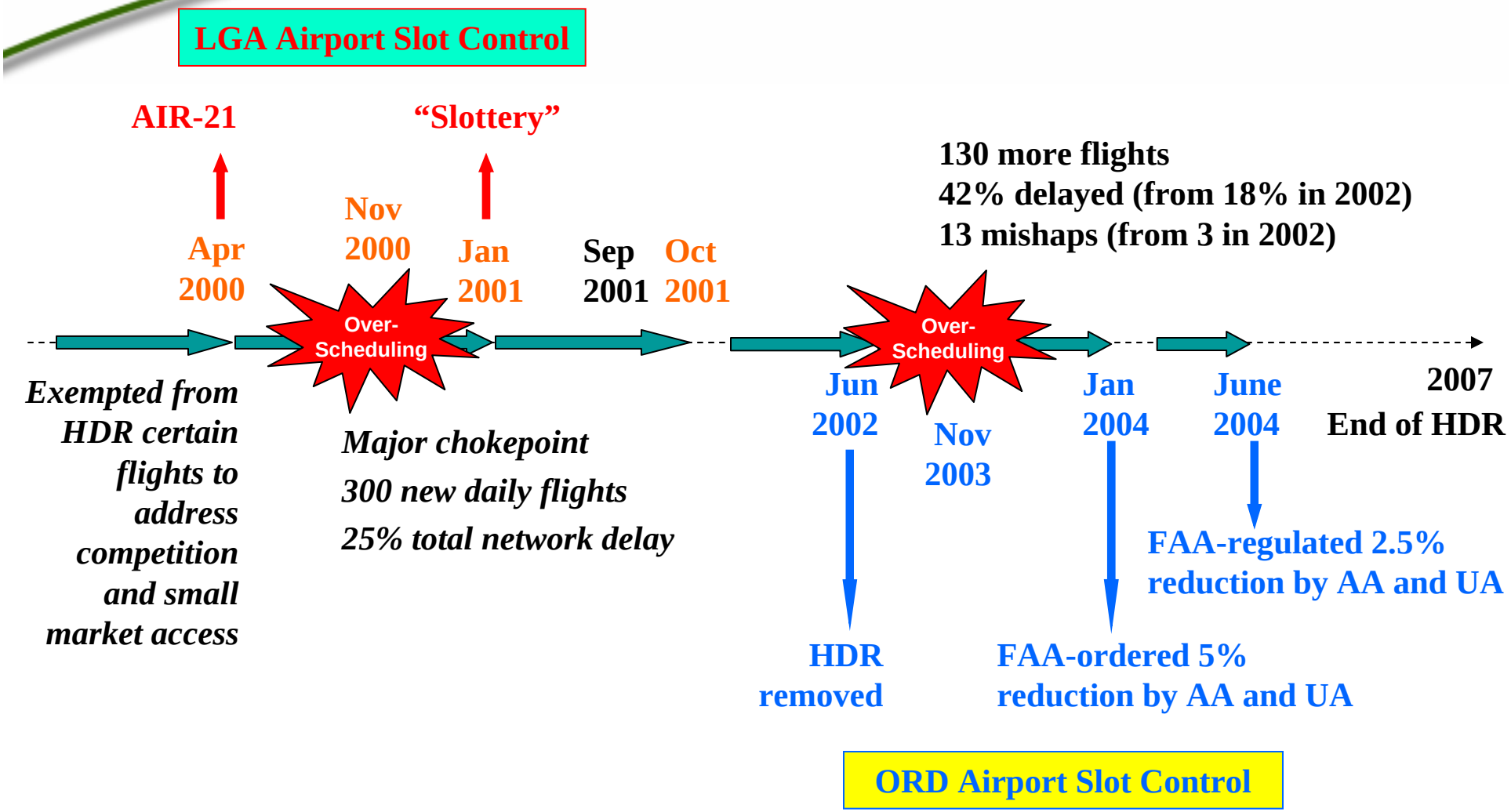
Factors that Determine Capacity

- **Local Airport Authority**
  - **#Runways, #Taxiways, High-speed turnoffs, #Gates, RW spacing, RW configuration, Noise Restrictions, etc.**
- **FAA**
  - **ATM/CNS Equipage, Separation Standards, ATC Procedures and Airspace Design**
- **Weather**
  - **Winds, Ceiling, Visibility, Severe weather**
- **Airline Schedules**
  - **Network Banking Requirements**
  - **Market Competition Strategies**

History of US Slot Management



DOT's congestion management



Congestion Management Approaches

- **Administrative**
  - negotiation-based IATA biannual conferences
- **Market Based**
  - weight-based landing fee: no incentive for large aircraft – inefficient Enplanement capacity
  - time-based congestion pricing: not reveal the true value of scarce resources
  - DoT/FAA supervised Market-based Auctions of Arrival Metering-Fix Time Slots
- **Hybrid**

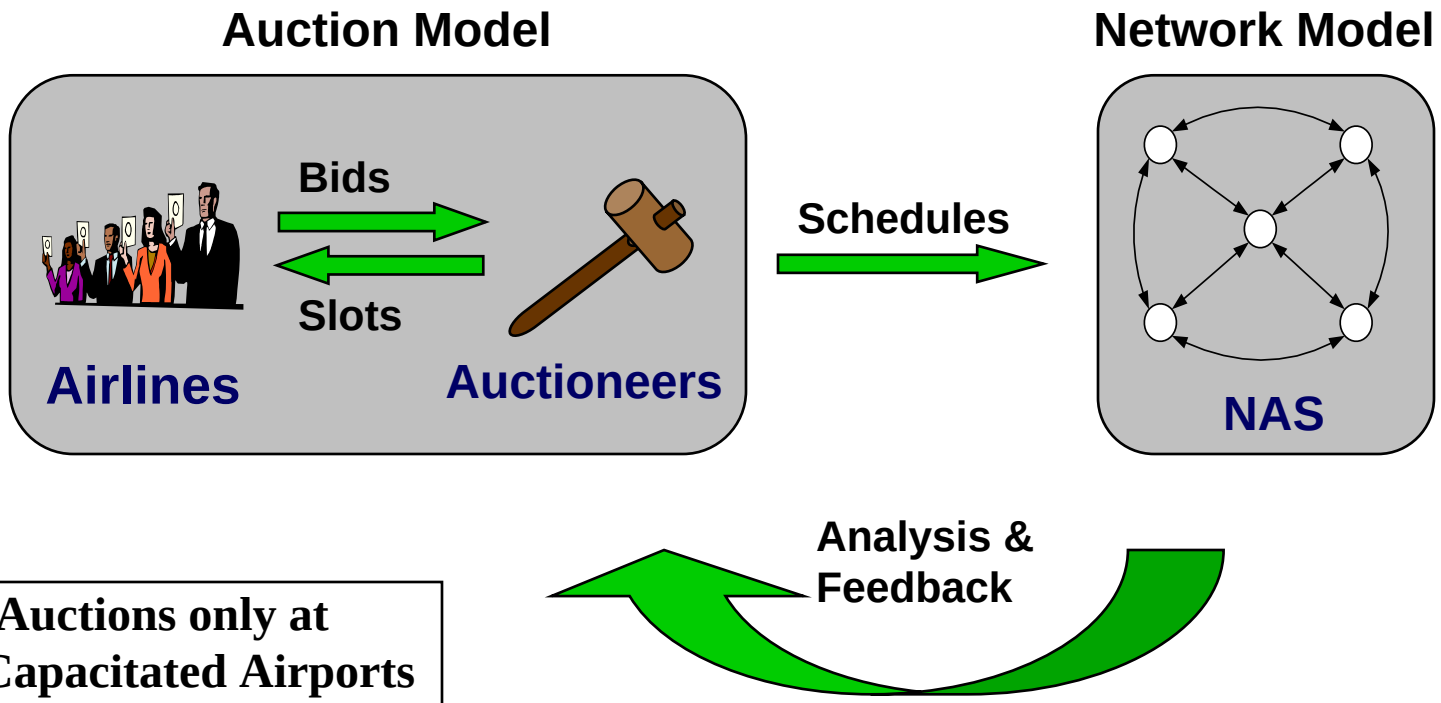
Auction Model Design Issues

- **Feasibility**
  - Package slot allocation for arrival slots
  - Politically acceptable net prices
- **Optimality**
  - Efficiency: i.e. Match Customer value to Cost
    - Maximum Schedule Predictability
    - Optimum airline schedule and aircraft assignment
    - Minimum passenger ticket price
  - Regulatory standards: capacity, international flight priorities
  - Equity:
    - Stability in schedule
    - Airlines' need to leverage Prior Investments
    - Airlines' competitiveness : new-entrants vs. incumbents
- **Flexibility**
  - Primary market at strategic level
  - Secondary market at tactical level

Design Approach

- **Objective:**
  - **Obtain Better Utilization of Nation's Airport Network Infrastructure – Network Load Balancing**
  - **Provide Cities an Optimum Fleet Mix**
  - **Ensure Fair Market Access Opportunity**
  - **Increase Schedule Predictability - reduced queuing delays**
- **Assumptions**
  - **Airlines will make optimum use of slots they license**
- **Auction rules: Bidders Could Be Ranked using a linear combination of:**
  - **Monetary offer (combination of A/C equipage credit and cash)**
  - **Flight OD pair (e.g. international agreements, etc.)**
  - **Airline's prior investment ?**
  - **On-time performance ?**

Strategic Auction Analytical Approach

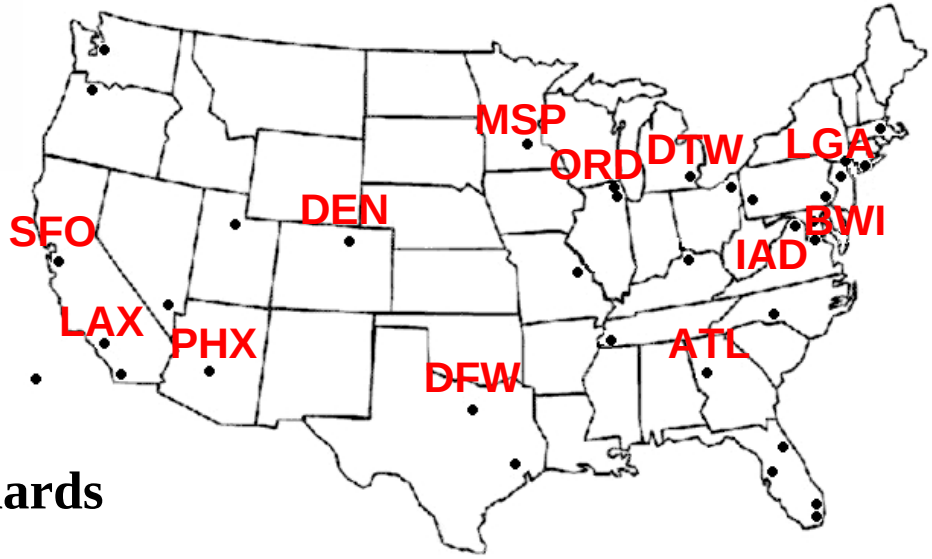


-Auctions only at Capacitated Airports

-Auction Licenses good for 5 to 10 years

Network Model used to Evaluate Auction Effectiveness

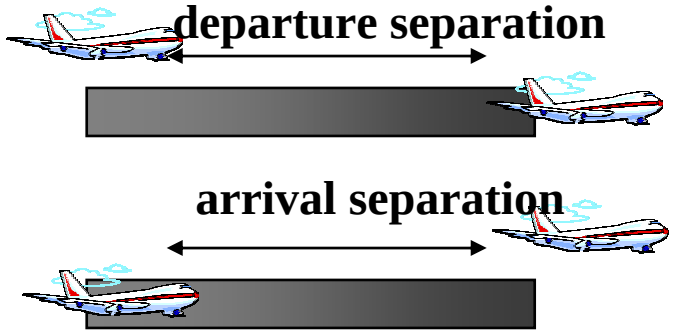
13-node network



Runway capacity determined by

- **Wake Vortex Separation Standards (nmiles/seconds) (M. Hanson)**

Leading aircraft \ Trailing aircraft	Small	Large	B757	Heavy
Small	2.5/80	2.5/68	2.5/66	2.5/64
Large	4/164	2.5/73	2.5/66	2.5/64
B757	5/201	4/115	4/102	4/101
Heavy	6/239	5/148	5/136	4/104

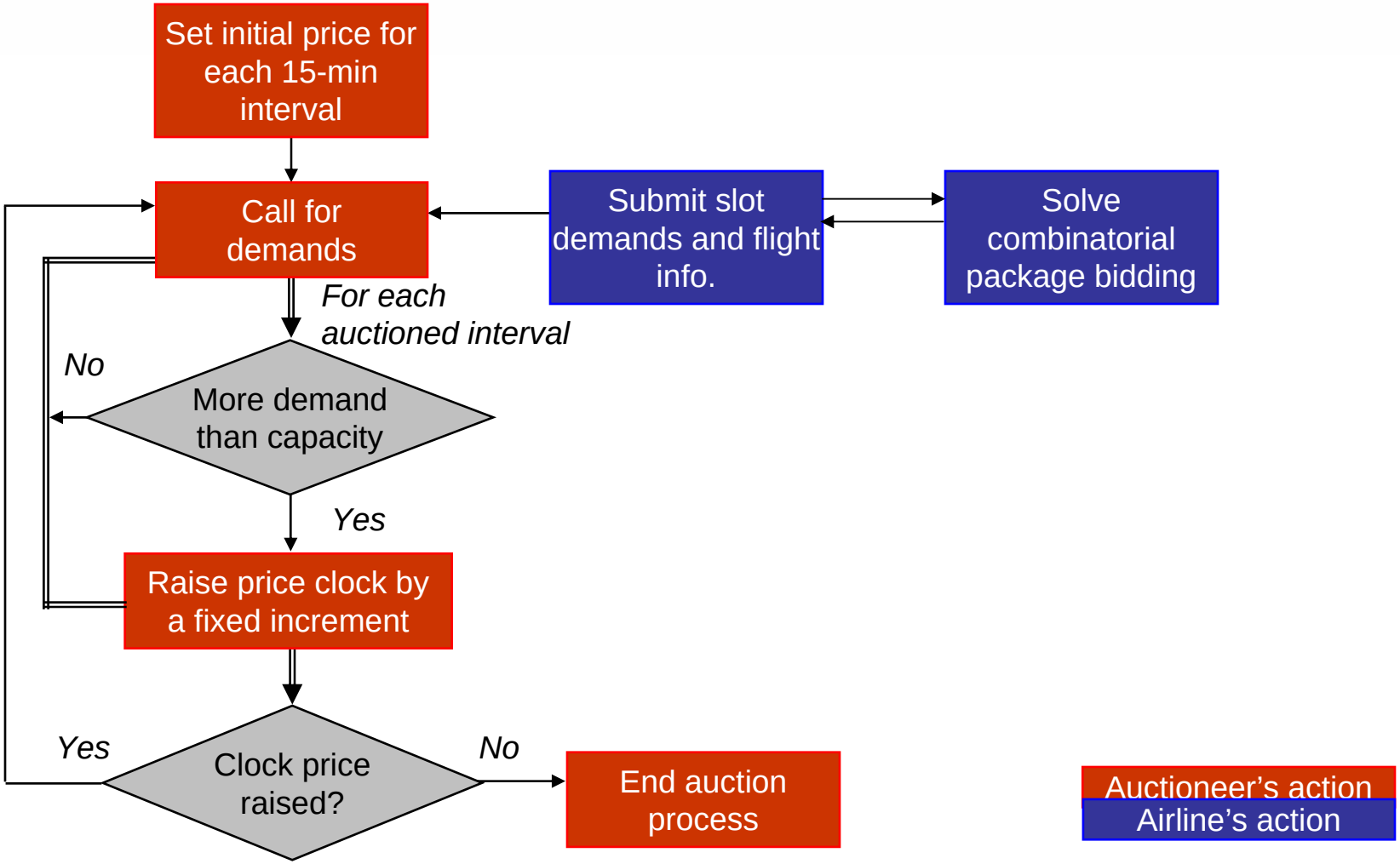


- **and a scale factor to account for runway dependency**

Auction Model Process

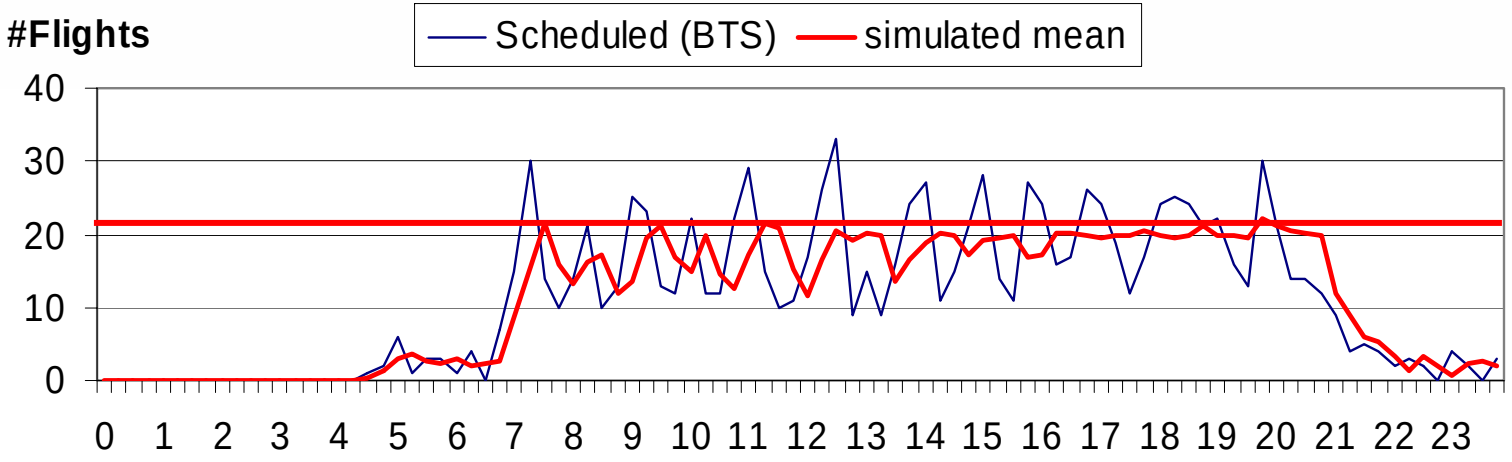
An adaptation of Clock Combinatorial Auction Model

(Porter, D., Rassenti, S., Roopnarine, A., and Smith, V.)

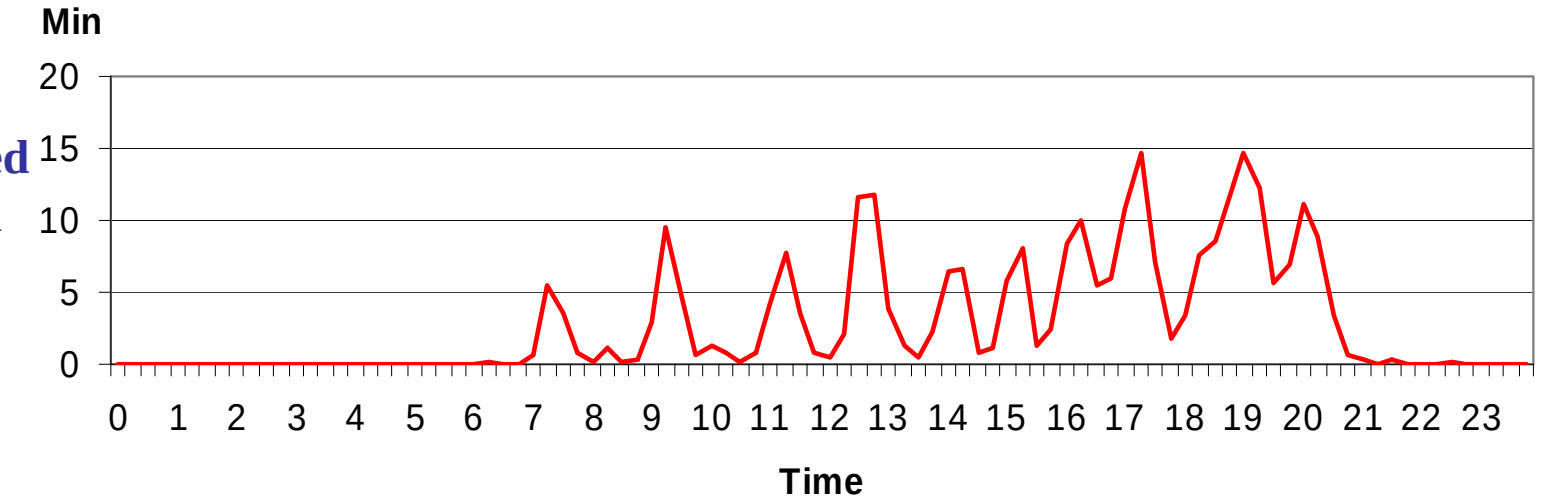


ORD Simulated Arrivals in VMC – No Auction

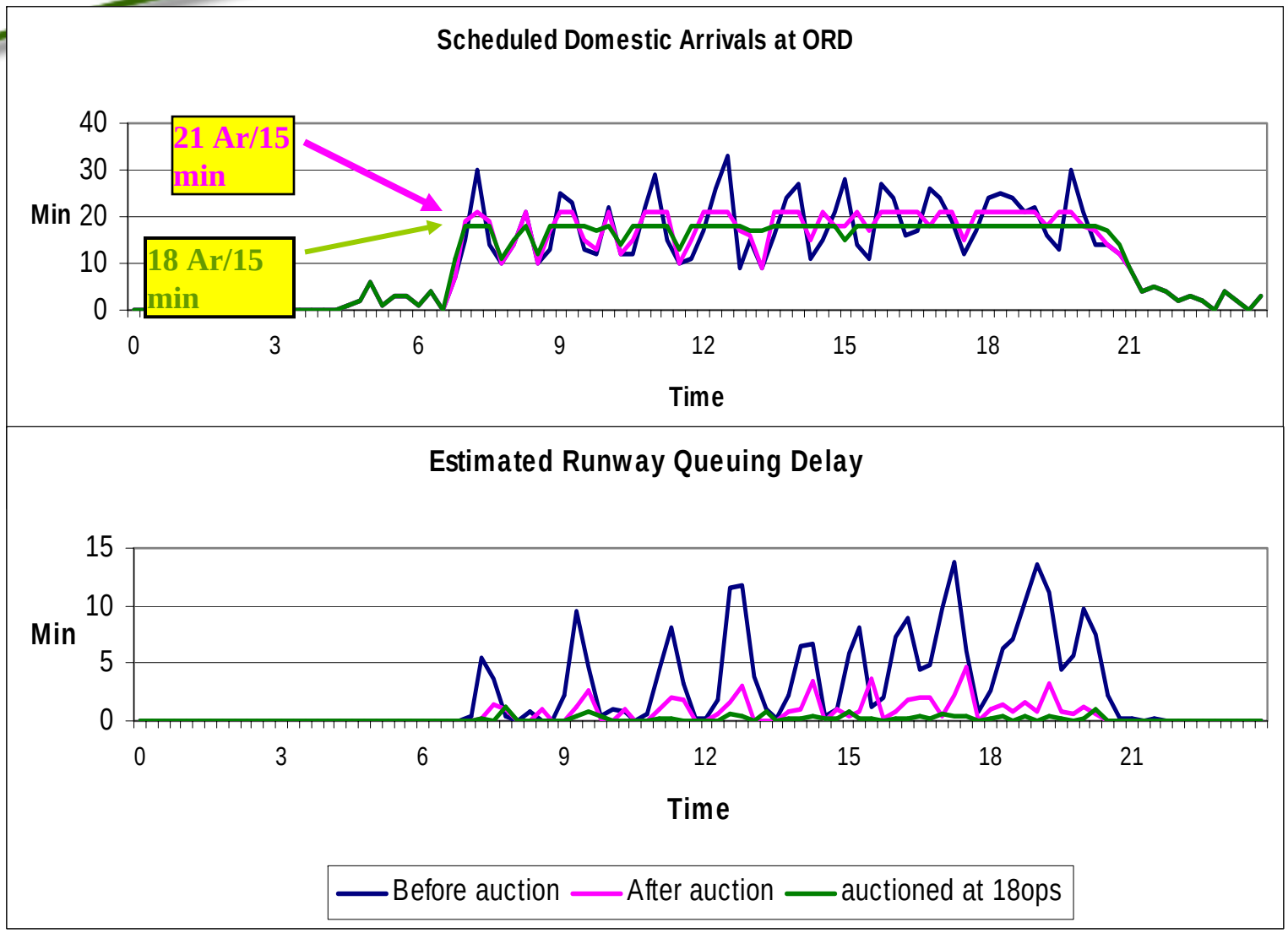
Domestic Arrivals (Dec 2003)



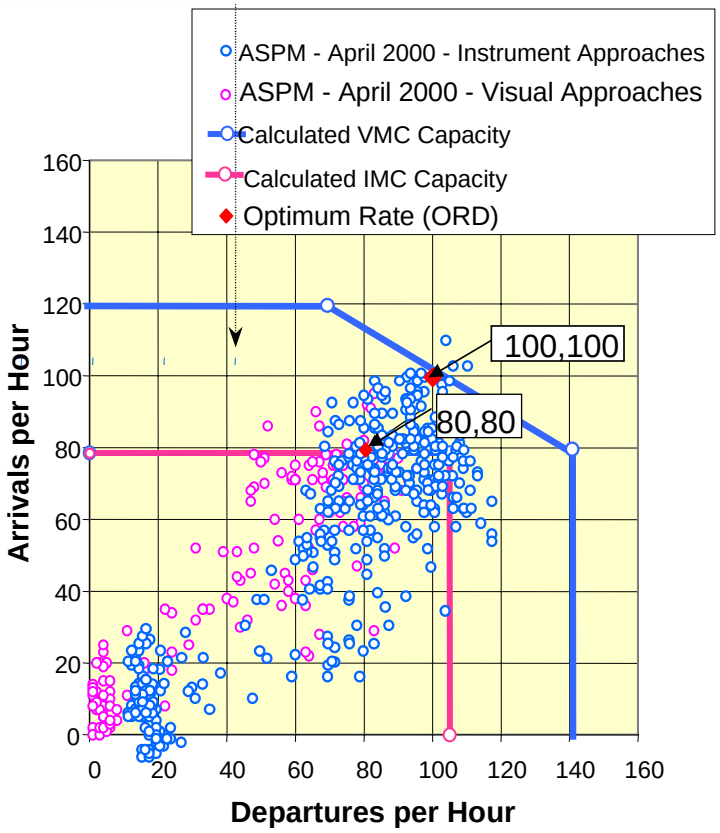
Mean of Estimated Average Arrival Delay (good weather)

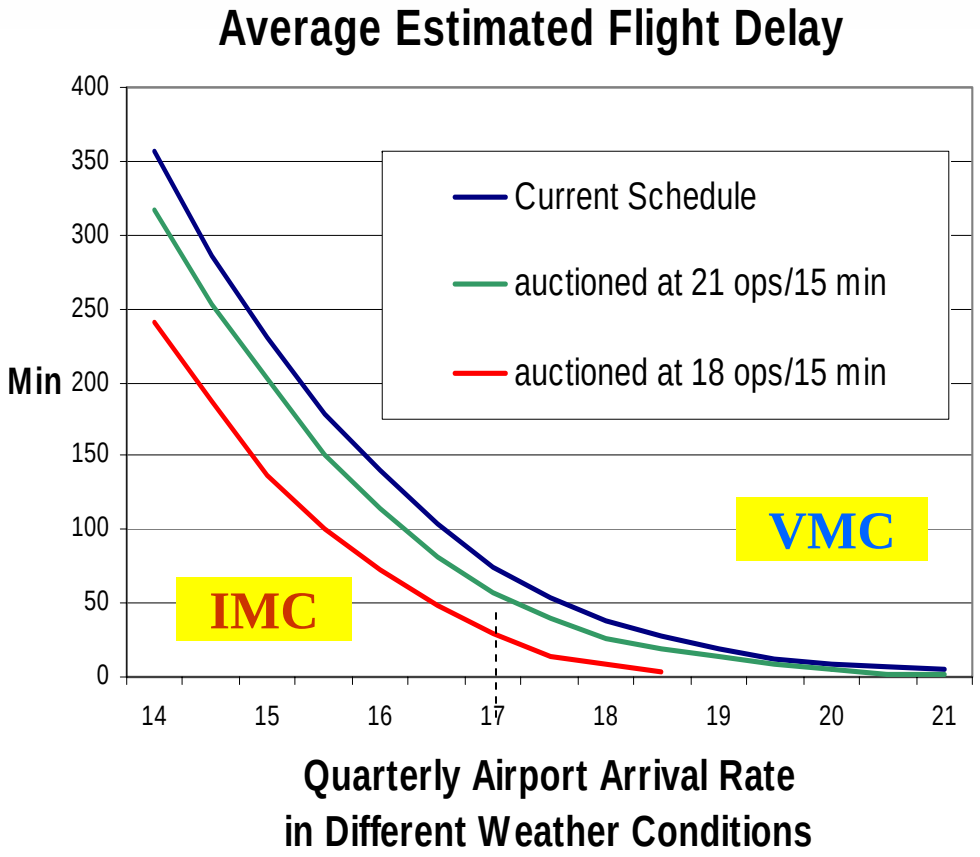


ORD Simulated Schedule and Delay: 3 Auctioned Capacity Limits (VMC-IMC)

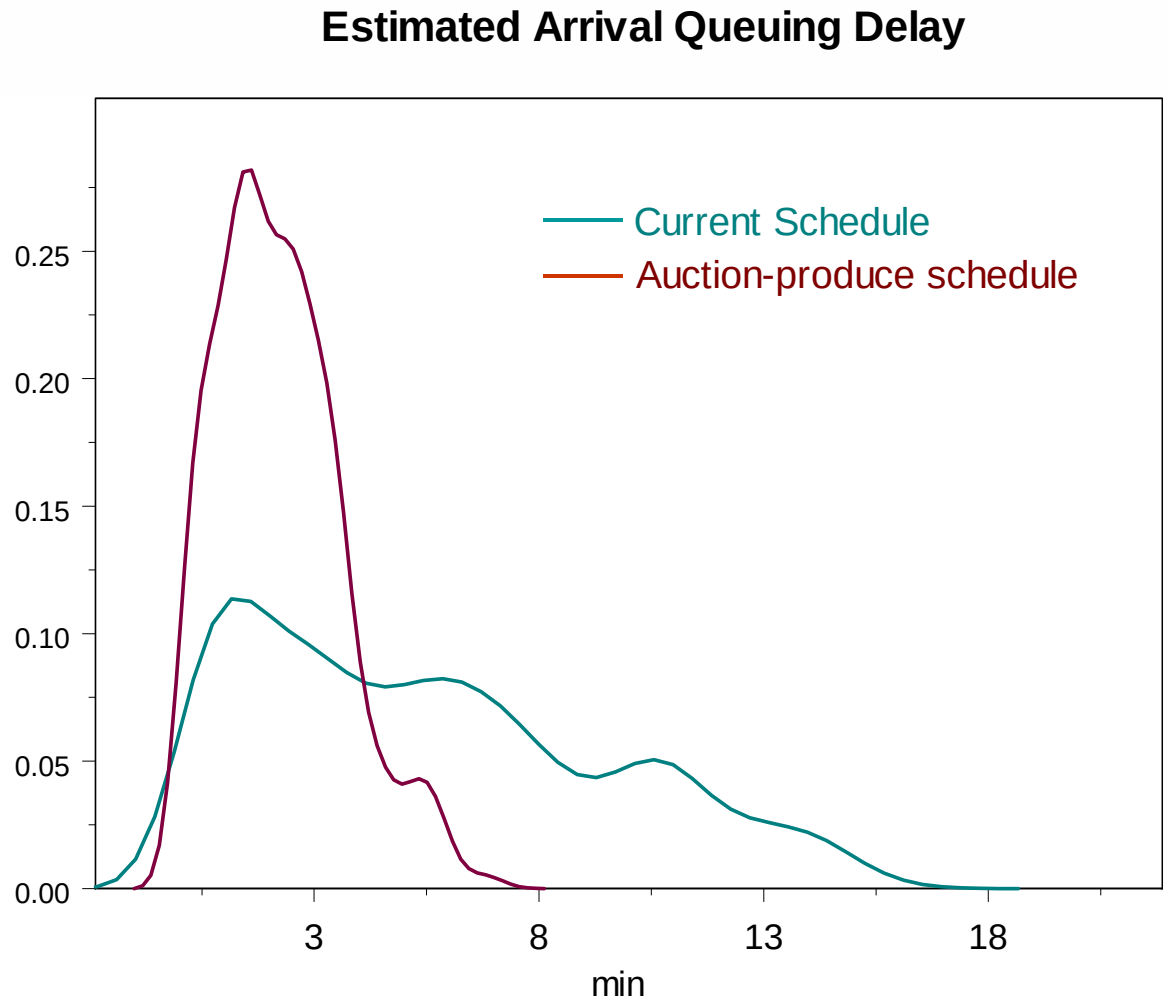


De-peaking results in Significantly Improved Passenger Schedule Predictability



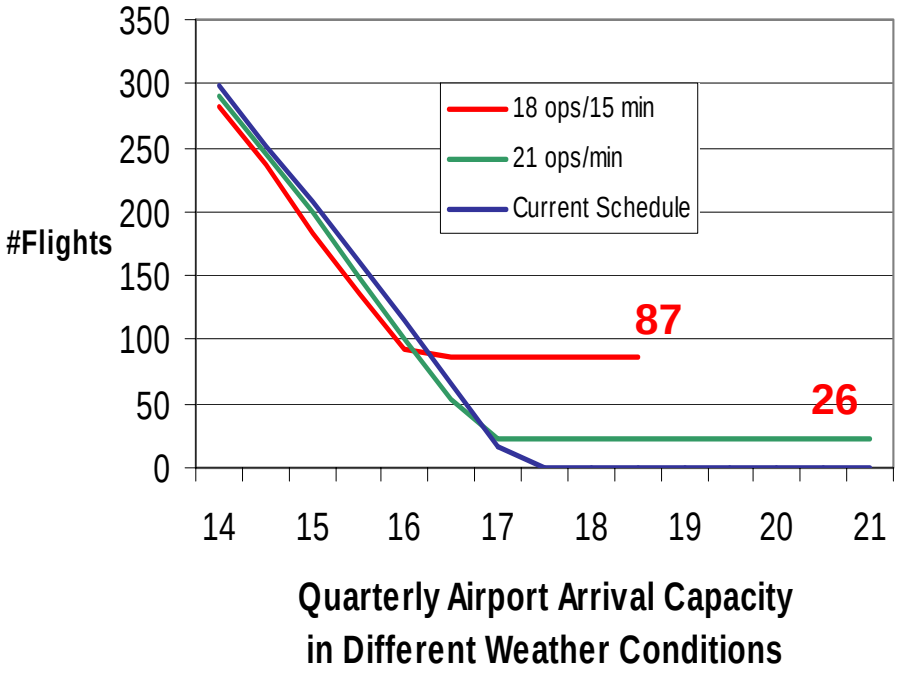


Auction Produced Rolling Banks Changes the Distribution of Delays

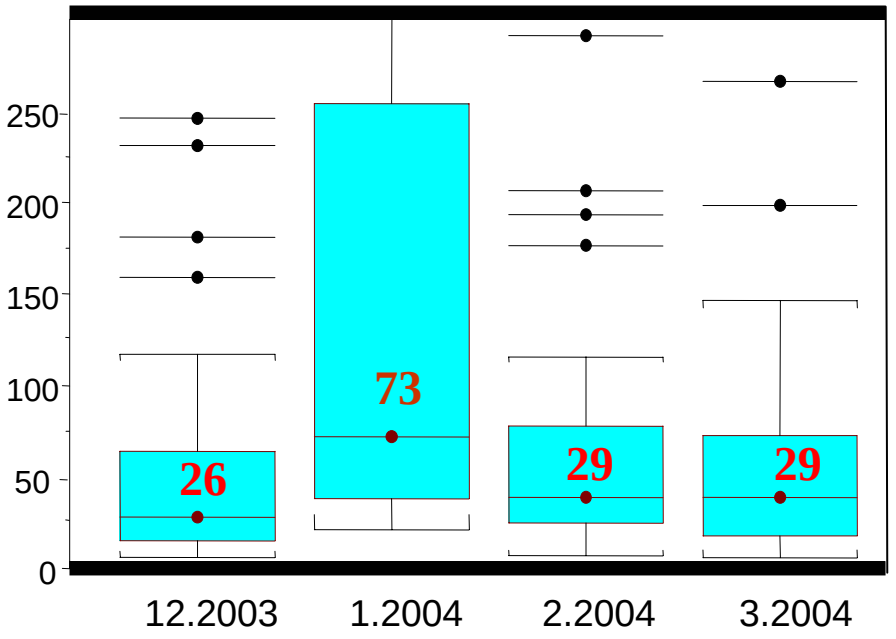


ORD Flights to be Rerouted vs. Average Actual Cancellations / day

Estimated #flights to be rerouted



Daily number of cancellations (BTS)



Significantly Improved ORD Passenger Schedule Predictability

- **Auction Produced a Coordinated Airline De-Peaked Schedule**
- **Simulated ORD Auction at 21 Arrivals/15 Min:**
  - **Reduced Delays by Over 80%**
  - **Required only 26 Flights to be Re-Scheduled through another Non-Capacitated Hub Airport**
  - **This Reduction is Comparable to the Reported Daily Flight Cancellation Rate**

Research Issues to be Addressed

- Who is Eligible to Bid?
  - Airlines, Airports, General Aviation, Investors
- What is the Fundamental Bidding Metric?
  - $/15 min Slot @ 95% Confidence, $-Passenger/Aircraft Slot…
- How Many Slots Should be Auctioned (arr @Prob. Delay (min))?
  - VMC ROT @ $N(4,2^2)$, IMC WV @ $N(8,4^2)$, IMC WV @ $N(15,8^2)$ …
- What Bid Combinations will be Allowed?
  - Packages w/ Ranked Priorities, Intercity Packages, etc.
  - Bidding Activity Rules
- What are the Payment Options?
  - Up Front for X yr. Lic., Monthly Royalty Payments for X Yrs.
- Who gets the Money?
  - Airports (PFC Sub.), Airlines (Equip. Vouchers), FAA (Ticket Tax Sub.)
- What are the Secondary Market Rights?
- What is the Winner Determination Algorithm?
- Auction Frequency/Duration of Slot License?
  - License for 5 yr., 10 yr., ?

Observations on Research to Date

- Combinatorial Clock Auctions Offer a Promising Market-Based approach to Congestion Management
- Auction Proceeds could be used as Incentives to the Airports for Infrastructure Investments and to the Airlines for Avionics Investments
- Congestion Management at Critical Network Node Airports will have a Profound Effect on Increasing Passenger Travel Predictability
- Simple Auctions might Exclude Small Aircraft and/or Small markets from Hub Airports
  - Simple Bidding Rules can Prevent this Problem

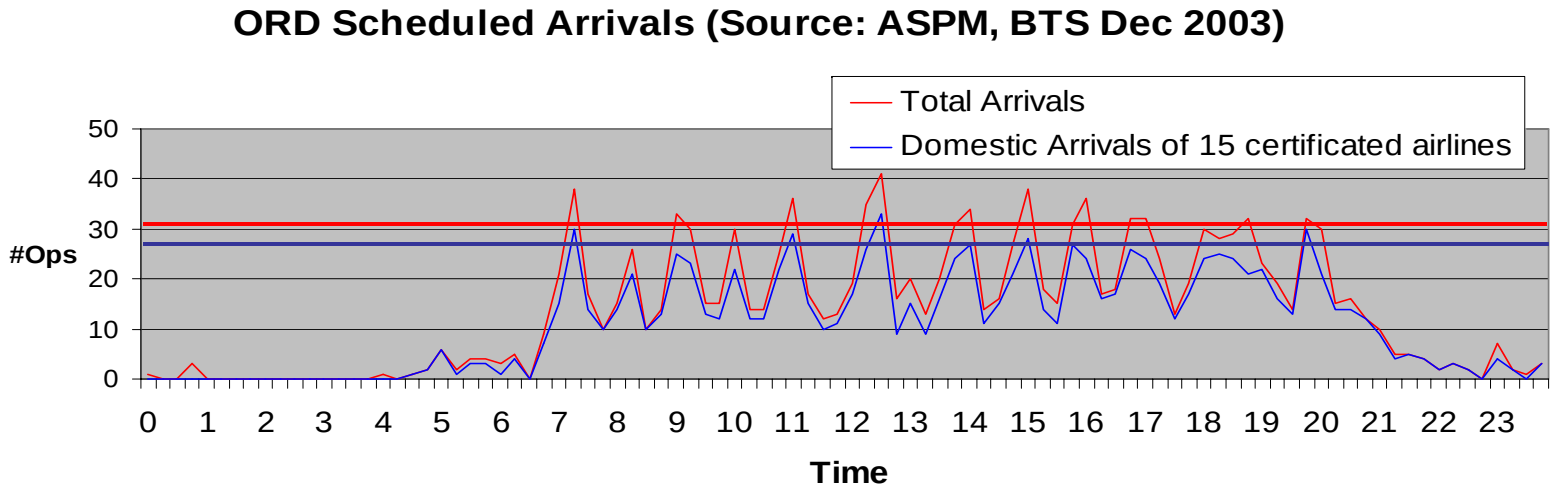
Future work

- Conduct 3 FAA Strategic Simulations to Resolve Slot Allocation Issues
  - First Simulation would Examine a Variety of Policy Problems/Options (Include a broad collection of Stakeholders)
  - Second Simulation would examine specific sets of auction rules and instruments
  - Third Simulation would use Results of first two to Evaluate Modified Congestion Mgt. Options
- Continue Model development to Refine Combinatorial Package Bidding Simulations to Evaluate Proposed Auction Rule Set

Backup

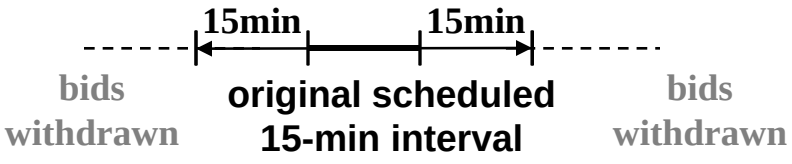
Simulation Model for Testing Auction Design

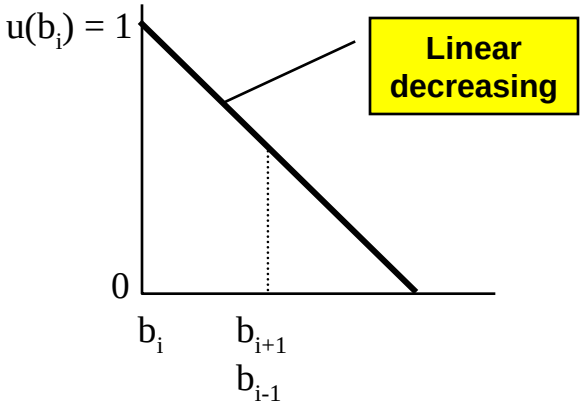
- **General Assumptions:**
  - Aircraft can arrive within allocated 15 min. Arrival Time slots with Required Time-of-Arrival errors of 20 seconds (using Aircraft RTA Capabilities)
  - Auction items: Metering Fix Arrival Slots in 76 15-min bins (5:00am till 24:00am) up to 21 arrivals/bin
- **Input:**
  - Dec 2003 BTS schedule of 2186 flights domestic flights to ORD (80% of total traffic)



Airline model assumptions

- **Single market, single item bidding**
- **Airlines' flexibility for changing schedule**: one 15-min bin

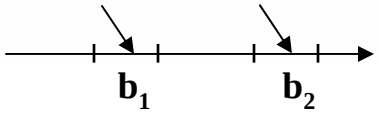




- **Homogenous and honest bidding with upper threshold proportional to aircraft size**

Airline Package Bidding Model

Target Slots P_j:



→ Possible packages P_j^k for P_j:

$$\begin{cases} b_i^{lb} \le b_i \le b_i^{ub} \\ \Delta b_{i,i+1}^{lb} \le b_{i+1} - b_i \le \Delta b_{i,i+1}^{ub} \end{cases}$$

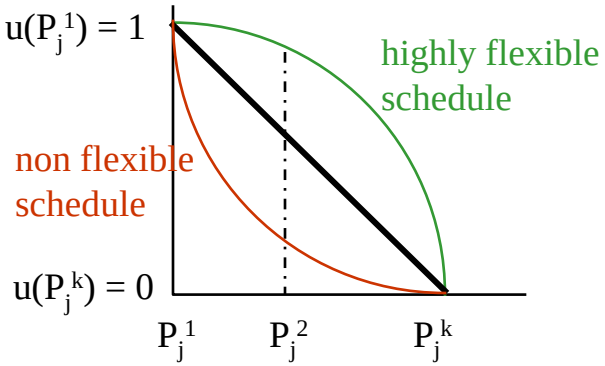
LP Model:

Maximise $\sum_j \sum_k u(P_j^k) \cdot x_j^k$

Subject to:

$$\begin{cases} \sum_k x_j^k \le 1 \qquad \forall j \\ \sum_j \sum_k \Pi \cdot P_j^k \cdot x_j^k \le B \end{cases}$$

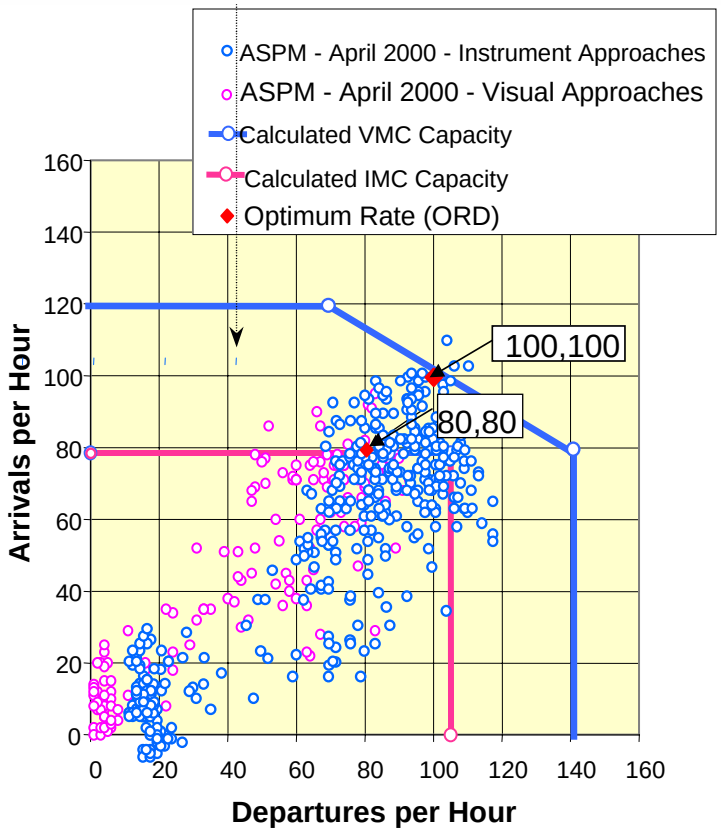
Utility Function



Variables:

$\{P_j^k\}$	set of package bids
B	airline bidding budget
$x_j^k = \begin{cases} 1 \\ 0 \end{cases}$	if airline bids for package P_j^k otherwise
Π	price vector

Network Simulation Model used to Evaluate Auction Effectiveness



– Stochastic Queuing Model

– 12 Capacitated Airports

–1 Airport Unconstrained sink and source

– ORD Runway capacity determined by

- **Wake Vortex Separation Standards (nmiles/seconds) (M. Hanson)**

Leading aircraft \ Trailing aircraft	Small	Large	B757	Heavy
Small	2.5/80	2.5/68	2.5/66	2.5/64
Large	4/164	2.5/73	2.5/66	2.5/64
B757	5/201	4/115	4/102	4/101
Heavy	6/239	5/148	5/136	4/104

- **and a scale factor to account**
  - ✓**for runway dependency**
  - ✓**weather effect**

– Delay = Arrival Delay + Queuing Delay

Good weather Condition:
$N(0,5^2)$

UP-Front Payment vs. Cash-Flow Royalty

- Auction Proceeds could be paid out to the FAA on a monthly basis (i.e. License Royalty Fee to Reserve Arrival Time Slot)
- FAA could retain a % to replace ATC ticket tax
- Airport could use a % to replace PFC tax and invest in New Runways, Taxiways, etc.

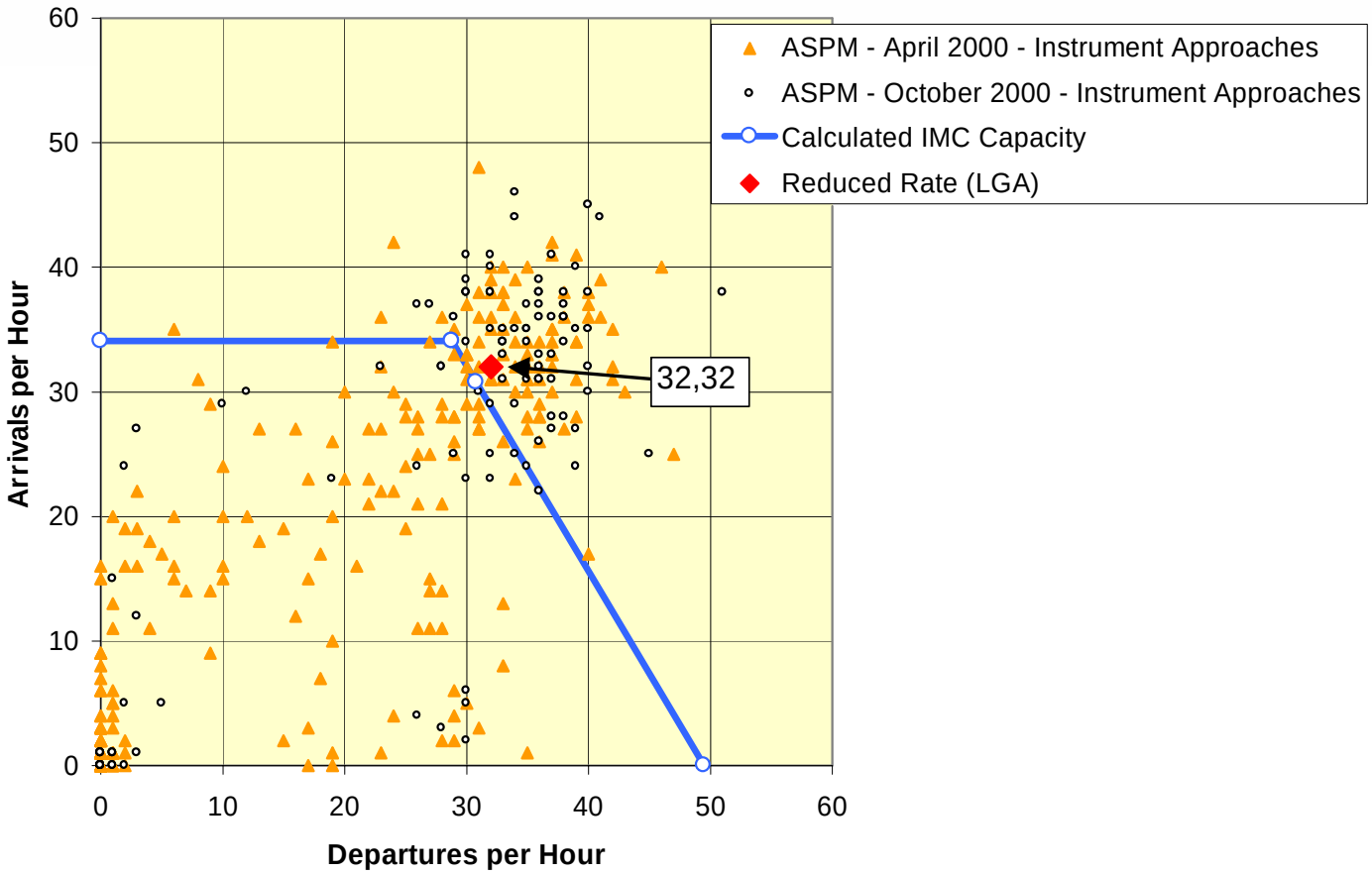
Airline Avionics Investments Required to Increase Airport Capacity

- **Flight Management Systems with Required Time of Arrival Capabilities**
- **ADS-B Cockpit Display of Traffic Information with the Capability of Providing Pilot Controlled Time-Based Separation**

Airlines Could bid with Avionics Investment Promissory Notes

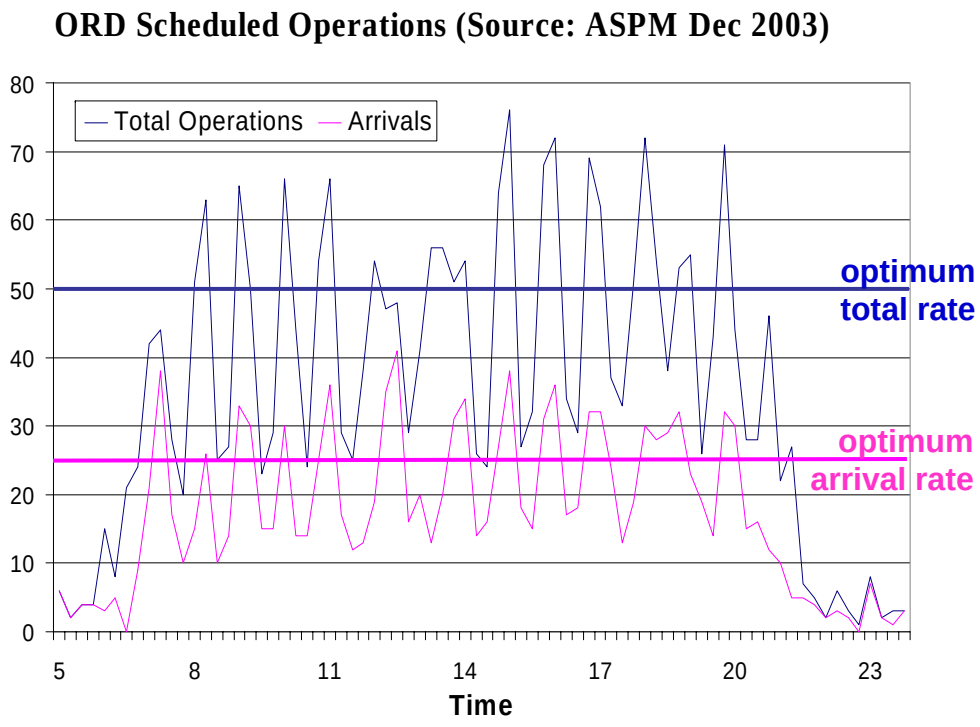
- Airlines could Bid with Script that constituted a contract to equip their Aircraft with-in X years (i.e. ½ bid price)
- Accepted Airline Bid constitutes a Contract with the FAA to provide Operational Procedures that Utilize Decreased Separation Capabilities

LGA Arrival - Departure IMC



Dynamics of Over-Scheduling

Flight banking creates inefficient runway utilization



Airline competition for market share