Air Travel at the Edge of Chaos

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Air Transportation is a CAS
NOT an Aircraft Design!

The National Air Transportation System is a Network of Networks
National Air Transportation Capacity Growth & Congestion Management is a Complex Adaptive System
Stochastic Network Control Problem
NYC Metroplex is a Current Example of a Major Problem that will Illustrate a General Solution Approach
Key Nodes in these Networks are Predicted to be Saturated – Even with New Runways and Technology!

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2015</th>
<th>2025</th>
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</thead>
<tbody>
<tr>
<td>New York</td>
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<tr>
<td>Los Angeles</td>
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<tr>
<td>San Francisco</td>
<td>Las Vegas</td>
<td>Phoenix</td>
<td>San Diego</td>
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</table>

Predicted Congested Metropolitan Regions with all NEXTGEN Technology and Runway Improvements

FAA FACT 2 Report May 2007
Air Transportation System (ATS) is a CAS with 6 Interacting Network Layers

- The ATS is a Public - Private Partnership with conflicting objective functions:
  - Public – Commerce and safety; interest groups
  - Private – Profit maximization

 layers:
- Passenger/Cargo Layer (Delays, Cancellations)
- Airline Layer (Routes, Schedules, A/C size)
- TSA/FAA Layer (ATC Radar, Radios, Ctr’s, Unions)
- Weather Layer (Thunderstorms, Ice Storms)
- Physical Layer (i.e. Cities, Airports, Demographics)
- Government Regulatory Control Layer
Outline

• How Bad and widespread is the Problem
  • What Has Changed Since 1947
  • Passenger QOS
  • NYC Example

• What are the Underlying Causes
  • Too Many Scheduled Flights into Too Few Runways

• Why the Airlines cannot fix the Problem Themselves
  • Prisoners Dilemma and Curse of the Commons

• Safety is the Underlying Capacity Constraint
  • Current Safety Trends
  • Airport Arrival Time Slot Auctions
  • Economic Impact

• High Payoff Research Topics
  • NextGen ATM system
What has Changed since 1947?

- Transonic vs. Subsonic Aircraft
- 40,000 ft vs. 20,000 ft Altitude
- Avionics:
  - Flight Management Systems
  - Required Navigation Perf. 0.1nm
  - Required Time of Arrival
  - Traffic Collision Avoidance System – On the Aircraft!
  - AOC Data Links
  - Zero Visibility Landing Systems
- ATC radar Separation

WHAT HAS NOT CHANGED
- Air Traffic Controllers talking to Pilots using WW II AM Radio Technology
Some Little Known Facts

- Modern Jet Aircraft “Gate-to-Gate” Travel Time is the Same or Longer than Propeller aircraft (DC-6 circa 1947) for many routes in NE Triangle
  - Typical Jet Aircraft is 70% Faster and fly's 80% Higher
- Jet Aircraft can fly Over most bad weather
- Modern Commercial Jet Aircraft can land in very low visibility
- Airport Congestion Causes Most ATC Delays and Airline Schedule Padding Masks Real “Gate-to-Gate” Delay
Airline Load Factors are Increasing
Air Transportation System is Designed to Move *Passengers* and Cargo

Passenger Tier Performance = f (Vehicle Tier Performance, Passenger Factors i.e. Aircraft Gauge, Load Factor, Cancellations)
Passenger Total Delay – Airports

- 10 of the OEP-35 airports → 50% Total EPTD
- some airports significantly impact Passenger Delay more than others (e.g. ORD, ATL, DFW and MCO)
NYNJ comparison to Comparable European Airports

<table>
<thead>
<tr>
<th>Airport</th>
<th>Total Movements</th>
<th>Total Passengers</th>
<th>Average Delays</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frankfurt, Gr (FRA)</td>
<td>490,147</td>
<td>458,731</td>
<td>52,219,412</td>
</tr>
<tr>
<td>London, UK (LHR)</td>
<td>477,884</td>
<td>466,815</td>
<td>67,915,403</td>
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<tr>
<td>Newark (EWR)</td>
<td>437,402</td>
<td>450,187</td>
<td>33,999,990</td>
</tr>
<tr>
<td>Amsterdam, NL (AMS)</td>
<td>420,736</td>
<td>432,480</td>
<td>44,163,098</td>
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<tr>
<td>New York Laguardia (LGA)</td>
<td>404,853</td>
<td>384,554</td>
<td>&lt;29,000,000</td>
</tr>
<tr>
<td>Munich (MUC)</td>
<td>398,838</td>
<td>-</td>
<td>&lt;29,000,000</td>
</tr>
<tr>
<td>New York Kennedy (JFK)</td>
<td>&lt;353,000</td>
<td>&lt;384,000</td>
<td>41,885,104</td>
</tr>
<tr>
<td>Madrid, Sp (MAD)</td>
<td>415,677</td>
<td>&lt;384,000</td>
<td>41,940,059</td>
</tr>
</tbody>
</table>

Data taken from ACI-NA, EC PR2006 and FAA ASPM
Domestic Markets served by NYC Major Airport Networks: 104
Airspace Analysis – 3 Airports as One
DOT/FAA response to NYC Congestion Problem

• Cap Operations at LGA, JFK & EWR
  • Loss of Market Competition & Efficiency

• Offer Airports the Option to Charge Congestion Pricing Landing Fees
  • PANYNJ rejecting offer

• Considering using Slot Auctions to find Market Clearing Prices
  • Congressional Authorization may be Required
90 Yr. Lease of Stewart International Airport

- $79 million + $17 million Improvements
- 2 Parallel Runways
- November 1, 2007 assumed control
- Skybus Airline will connect to Columbus and N.C. Piedmont Triad International Airports
- Other Airlines offer service to Atlanta, Florida, Detroit and Philadelphia
Some Outstanding Issues with these Solutions

- What are the Airport/Airline/DOT Property Rights?
- What is the Best Equity Metric?
- How should Max. Capacity be Determined?
- What Fraction of Max. Capacity should be Allocated?
- How Should these Airport Operations be Coordinated?
- How should Small and Medium sized Communities be Served?
- How will Market Allocation affect Service?
- Desired Market Service Redundancy?
- Desired Market Service Frequency?
- Desired Aircraft Gauge Distribution?
### NYC airports Quarter Hour Over-scheduling Percentage (6:00am-10:00pm) in 2007 summer

<table>
<thead>
<tr>
<th>Airport</th>
<th>Actual Arr. (%)</th>
<th>Actual Dep. (%)</th>
<th>Scheduled Arr. (%)</th>
<th>Scheduled Dept. (%)</th>
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</thead>
<tbody>
<tr>
<td>EWR</td>
<td>1.8%</td>
<td>4.8%</td>
<td>6.5%</td>
<td>6.6%</td>
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<tr>
<td>JFK</td>
<td>2.9%</td>
<td>8.9%</td>
<td>5.4%</td>
<td>13.8%</td>
</tr>
<tr>
<td>LGA</td>
<td>5.1%</td>
<td>10.3%</td>
<td>9.3%</td>
<td>12.2%</td>
</tr>
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</table>

\[
O = \frac{\sum_{i=1}^{n} I_{Demand > \text{max Capacity}}}{n}
\]
### Airports Served by Multiple NYC Airports

<table>
<thead>
<tr>
<th># of airports served by</th>
<th>1</th>
<th>2</th>
<th>3</th>
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<tbody>
<tr>
<td># of NYC airports</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># of airports served by</td>
<td>29</td>
<td>37</td>
<td>38</td>
</tr>
<tr>
<td>% of airports served by</td>
<td>27.9%</td>
<td>35.6%</td>
<td>36.5%</td>
</tr>
</tbody>
</table>

- What Property Rights?
- What Equity Metric?
- What Frequency?
- What Aircraft Gauge?
- What Load Factor?
- What Competition?
- What Profitability?
Efficiency vs. Profitability?
Frequency vs. Seat Size & Unit Revenue

NYC Metroplex Flight Frequency versus Seat Size

- High Unit Revenues For Small A/C & High Frequency
Reduction in Average Number of Aircraft Seats by Airport – All Departures

- 12.7%  -6.8%  9.9%  18.9%  -15.5%  10.4%  -11.4%  -4.2%

July 2002 vs. July 2007

Dorothy Robyn
The Brattle Group
Interim Observations

Airlines are filling planes
Flights with low load capacity are mostly to small profitable airports or BOS and DCA
Airlines made money in Summer of 2007
So, what's the problem?
- Delays!
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  • Economic Impact

• High Payoff Research Topics
  • NextGen ATM system
Jet Blue and Delta AL are Competing for the JFK Market: Passengers Pay the Price in Flight Delays and Cancellations

![Graph of JFK Summer 2007 Departures]

- **FAA Announced Departure Rate (weekday AVG +/- 2)**
- **Airline's Scheduled Departures**

24 Hours in 15 min. Epochs

Flight Departures per 15 Minute Epoch
JFK Scheduled Gate-In/Gate-Out Demand Distribution (Count - Summer 07 ASPM)

JFK Quarterly Scheduled Gate-Out/Gate-In Demands Statistics

Gross Over-Scheduling

Calculated Capacity
JFK Scheduled Wheels-On/Wheels-Off Demand Distribution (Count - Summer 07 ASPM)

JFK Quarterly Scheduled Wheels-On/Wheels-Off Demands Distribution

Schedule Padding for Expected Taxi Delays
JFK Actual Wheels-On/Wheels-Off Demand Distribution (Count - Summer 07 ASPM)
Result of this Schedule on Network Delay: AVG Wheels-Off Delays At JFK (ASPM)

95 Minutes!
Effect of LGA Slot Control Program: Still Unacceptably High Network Delays!

LGA Avg. Wheels-Off Delays for Departure Flights (07 Jun 01 – 07 Aug 30)

60 Minutes!
Delay Incurred at Major Airports Propagate *Network Wide* (Summer 2005)

*Total Delay* Ordered by Arrival Delay at Outbound Destination. (minute)

2,000 Flight Hours

34 OEP Airport

[宁宇 GMU 2007]
GMU Model Projects Passenger Delays to Greatly Exceed 2000 delays by 2010

Total Passenger Delays

- Delayed Flights
- Cancelled Flights
- Poly. (Delayed Flights)
- Poly. (Cancelled Flights)


D. Wang 2007
Outline

• How Bad and widespread is the Problem
  • What Has Changed Since 1947
  • Passenger QOS
  • Economic Impact
• What are the Underlying Causes
  • Too Many Scheduled Flights into Too Few Runways
• Why the Airlines cannot fix the Problem Themselves
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• Safety is the Underlying Capacity Constraint
  • Current Safety Trends
  • Airport Arrival Time Slot Auctions
• High Payoff Research Topics
  • NextGen ATM system
Why do the Airlines Schedule beyond the Maximum Safe RW Capacity with Flights that Loose Revenue?

- There is no government regulation to limit schedules for safety or compensate passengers for delays and cancellations
  - These were errors in the 1978 Deregulation Act
- Passenger surveys indicate that frequency and price are the most desirable characteristics of a flight
- Passengers are not told of consequences of schedule to travel predictability
- If any one airline decided to offer rational schedules, their competition will offer more frequency to capture market share
  - Thus, still producing delays and cancellations for all
- In Game Theory, this is called the **Prisoner’s Dilemma**
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Part 121 (Scheduled Commercial) Accident Rates are Increasing

Analysis from Zohreh Nazeri, PhD GMU 2007

\[ y = 0.0533x + 1.0647 \]
Trends of the factors in incident databases

- Pilot factors decreasing
- Aircraft factors slowly decreasing
- ATC factors increasing

Analysis from Zohreh Nazeri, PhD GMU 2007
ATC factors – Communication Errors

Top complexity factors associated with ATC factors:

- number of aircraft in airspace -- airspace design
- runway configuration -- controller experience

These factors will get worse over time:

- air transportation is projected to grow for the next 10 years
- majority of controllers will retire within next few years

Analysis from Zohreh Nazeri, PhD GMU 2007
Aircraft factors

“Flight Control System” problems growing
Other aircraft factors decreasing

Analysis from Zohreh Nazeri, PhD GMU 2007
Safety at Principle Network Nodes (i.e. Airports) is the Constraint

- Aircraft Safety Separation Time over the Runway Threshold sets the ATS capacity limits
- Critical Technical Parameters that Define Network Capacity:
  - Runway Occupancy Time (ROT)
  - Landing Aircraft Inter-Arrival Time (IAT)
  - $\text{Cap}_{\text{max}} = 90 \text{ sec IAT at } 10^{-3} P_{\text{SRO}} = 40 \text{ Arr/RW/Hr}$
  - Queuing Delay Onset at $\sim 80\% = 32 \text{ Arr/RW/Hr}$ limit for Predictable Performance
Queuing Delays set the Practical Capacity Limitation set by Safety Separation Standards

- Lack of Schedule Synchronization and 90 second IAT generate Queuing Delays above about 80% of Maximum Runway Capacity
Runway Scarcity/Value and Risk

- Runways are expensive
- Sometimes impossible to build because of shortage of space, etc
- Because of high demand for runways and their scarcity, runways are highly valuable
- *Thus, Maximizing runway utilization is vital*
- Increasing utilization implies potential for increased risks: wake vortex hazard and simultaneous runway occupancy

*Risk* is the other side of the *Throughput Coin*
ILS Approach to Runway 21L

Approach Plate:
Runway 21L
Detroit Airport

Airport Diagram

Typical ILS Landing Process

Runway 21L, Detroit Airport

Ref: AirNav.com. [http://204.108.4.16/d-tpp/0610/00119I21L.PDF](http://204.108.4.16/d-tpp/0610/00119I21L.PDF), EC1, AL-119 (FAA 2007)
Data Analysis Process to Estimate: IAT, IAD and ROT pdf’s

<table>
<thead>
<tr>
<th>Aircraft Type</th>
<th>Threshold</th>
<th>Leave Runway</th>
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<td>Heavy</td>
<td>10:23:14</td>
<td>10:24:04</td>
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<tr>
<td>Large</td>
<td>10:26:16</td>
<td>10:27:12</td>
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Col. Clint Haynie, USA PhD., 2002
Yue Xie, PhD. 2005
### ILS* Separation Standards (nmi)

- Current standards provide *separation Minima* for aircraft pairs

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<th>ILS Approach</th>
<th>In-Trail Threshold Separation</th>
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<tr>
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<table>
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<th>B757</th>
<th>Heavy</th>
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<tr>
<td>Heavy</td>
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<td>3</td>
<td>4</td>
<td>4</td>
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1) Ref: FAA 7110.65 Separation Rules For Arrivals and departures

- Standards should be fully respected
- In practice, this is not always the case

* Instrument Landing System
1. Simultaneous Runway Occupancy (SRO)
   - Can be avoided by go-around procedure
   \[ P\{\text{SRO}\} = P\{LTI_{k,k+1} < ROT_k \& k \text{ lands}\} \]

(Throughput, Risk_{WV}, Risk_{SRO}) = f(LTI, ROT, WV strength/position)
2. Wake Vortex (WV) hazard

- Depends on follow-lead aircraft pair type
- Meteorological condition
- Strength and position of the WV and position of the following aircraft
ROT vs. IAT to find Simultaneous Runway Occupancy (SRO) Probability: est to be ~ 2 / 1000

- Detroit Metropolitan Airport (DTW)
- Freq \((IAT < ROT) \sim= 0.0016\) in peak periods and \(0.0007\) overall (including non-peak periods - 1870 total samples)
- IMC: \(1 / 669 = 0.0015\) in peak periods
- Correlation coefficient = 0.15 \[Babak, Shortle and Sherry, 2006\]
It does Not Have to Be this Way

Changes in FAA Procedures, Airport Slot Controls and New Avionics Will Improve BOTH Safety and Capacity
Variance Reduction of \( LTI \) (B. Jeddi, GMU PhD 08)

\( LTI \sim \text{LogNormal}(40; 4.1, 0.45) \)
\( \text{Mean}= 104.2, \text{Std}=49, \text{mode}= 87 \)

\( ROT \sim 0.59 \text{Beta}(11.8, 27.9) + 0.41 \text{Beta}(9.0, 16.6) \)

LTI of 3 nm pairs
\( \text{Mean}= 104 \text{ sec} \)
\( \text{Std}=% \text{ of } 30 \text{ sec} \)

- 30% Std reduction: \( P\{\text{SRO}\}=0.0014 \)
- 50% Std reduction: \( P\{\text{SRO}\}=0.0002 \)

Current \( P\{\text{SRO}\} \)
0.007
Risk vs. Throughput (B. Jeddi, GMU PhD 08)

Risk is the other side of the throughput coin!
Variance Reduction Effect  (B. Jedd, GMU PhD 08)

Effect of LTI Variance Reduction on Throughput Curve

Percentages are of the Original LTI Standard Deviation

3 nm pairs

4 nm pairs

3.6
Weaknesses of Current Standard

1. Many landings fall below given minimum
   • For example, for 3 nm separation pairs, at DFW 26% under 3.0 nm and 7.5% under 2.5 nm (Ballin 1996)
   • Why are they violated so frequently? Well designed?!
   • Are standards too conservative?

2. Minima are not directly operational
   • Controllers add some buffer spacing to assure the minimum (Lebron 1987, Vandavenne 1992, …)
   • These standards do not directly incorporate uncertainty
Summary on Capacity

• 40 Arrival per Runway per Hour is current Safety Maximum
• 32 Arrivals per Runway per Hour is ONSET of Queuing Delays
  • Using Current (OLD) Technology
  • Using Current (OUTDATED) ATC Procedures
• FAA has Refused to Mandate New Technology and Procedures to Reduce the Variability in IAT to Increase BOTH Safety and Capacity
What would happen if schedules at major airports were Capped at Safe, Predictable Runway Capacity and allocated by a Market mechanism?

- What markets would be served?
- How would airline schedules change?
  - Frequency
  - Equipment (#seats per aircraft)
- How would passenger demand change?
  - At airport
  - On routes
- How would airfares change?
  - What would happen to airline profit margins?
- How would airport and network delays be altered?
Modeling Approach and Assumptions

- Port Authority of NY&NJ has the ability to Determine and Set an Optimum Schedule to:
  - Operate at Competitive Profit Margins
  - Maximize Passenger Throughput
  - Ensure an Airline Operating Profit (Max, 90%, 80%)
- All Current Origin and Destination Markets are Considered
  - 67 Scheduled Daily Serviced Markets
- Current Market Price Elasticity Remains Constant
NY LGA Has 67 Daily Markets

Average daily frequencies of LGA nonstop markets (ASPM Q2, 2005)
Airline Competitive Scheduling: Modeling Framework

Auction IMC Rate:
32 Slots/Hr

Demand-Price Elasticity

Network Flow Optimization Problem

Delay Network Simulation

ASPM, BTS databases

Flight schedules
Fleet mix
Average fare
Flight delays

(Le, 2006)
Model Estimate of Airline Response to an All Weather Predictable Schedule Restriction

- 20% Fewer Scheduled Flights
- Increased Passenger Throughput
- Same Airfares
- Loss of 3 Unprofitable Markets
- 70% Less Delay
Annual Passenger Enplanements Predicted to be Lost: FAA Forecast to 2025

Annual Projected Enplanements Foregone Because of Airport Capacity Constraints

Optimistic: All Planned Airport Improvements Occur

All available landing slots fully utilized regardless of congestion

FAA 2005 TAF & 2004 Benchmark
Economic Optimum Slot Allocation is at 80 - 90% Max Capacity

Donohue and Shaver, forthcoming spring 2008
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IS NextGen addressing the Problem?

- ADS-B (out), 4-D trajectories, RNP-0.1
  - Good but NOT ENOUGH
- Aircraft Gauge, Schedule Synchronization and Network Load Balancing will Be Required
  - Annual Combinatorial Clock Slot Auctions?
- Aircraft Separation in Terminal Airspace and on the Runways MUST be REDUCED by X3!
  - Closely Spaced, Fully-coupled Autopilot Formation Landings with 2 – Lane Runways?
- Closely Spaced Airports need to be Cross-linked with Runway Independent Air Transport
  - New Generation of Heavy Lift Helicopters?
The Predicted Growth in Aviation Demand is based on *Passenger Demand* NOT Aircraft Operations

- Larger Aircraft will be required to meet X2 or X3 demand
- Business Jet and VLJ Air Taxi Service will emerge to compete with Commercial aviation due to current System Failure
  - May not be able to put the Geni back in the Bottle
  - Environmental Implications?
- New Aircraft (e.g. B 787) should be Environmentally Friendly (Emissions/pasenger/mi.?)
  - US airlines are not currently ordering them due to poor financial position
- New Public Policy will be needed to Deal with these Complex Adaptive System Problems
  - NextGen System not addressing these issues
Center for Air Transportation System Research
Publications and Information

- Other Useful Web Sites
  - http://catsr.ite.gmu.edu
  - http://mytravelrights.com