Airline Passenger Trip Reliability: Why NextGen May Not Improve Passenger Trip Delays

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INFORMS TSL - Asilomar
Organization

• Definitions & Terminology
1. Problem Statement
2. Model
3. Results
4. Conclusions
Definitions

Airline Passenger Transportation System

Passengers with Ticketed Travel Objectives → Airline Passenger Transportation System (APTS) → Passengers with Completed Travel

1. Quality (i.e. passenger safety)
2. Cost (i.e. total cost per passenger mile = airfare + terminal + ATC + …+ external costs)
3. Time (i.e. trip reliability)
Definitions

Trip Time & Reliability of APTS

• Trip Reliability = Passenger Trip Delays
  – Actual arrival time – Scheduled arrival time
  – Trip delays are a function of the number of passengers on itineraries in the time-space network of flights
Space-time Network

• Network is the manner in which airports are connected by flights
  – Network is a space-time network
  – Network determines the itineraries

• Two distinct types of networks
  – Point-to-point
  – Hub-and-Spoke
Itineraries and Flights

- **Itinerary** is the sequence of flights taken by a *given passenger* from Origin to Destination
  - Direct Itinerary
  - Connecting Itinerary

- By definition a given **flight** (in a hub-and-spoke network) will have passengers on board with different itineraries
Passenger Trip Reliability

• Reliability of APTS is measured by performance of itineraries (not flights)

• Itineraries disrupted by:
  – Delayed flights (includes Tarmac Delays, GDP/AFP/GS/MIT, ...)
  – Cancelled flights (includes mechanicals, tactical, ...)
  – Missed Connections
  – Over-booking
  – Diversions
Passenger Trip Performance Metrics

- **Itinerary Performance Metrics**
  1. Total Itinerary Delays
     - Cumulative delays
  2. % Itineraries Disrupted
     - Likelihood of a disruption
  3. Average Delay on Disrupted Itineraries
     - magnitude of delays

- **Passenger Trip Performance** = Itinerary Performance * # Passengers on each Itinerary
2007 Statistics

- Total Passenger Trip Delay = 30,000 years
- Percentage of Trips Disrupted = 22%
- Average Delay for a Disrupted Trip = 110 minutes

- Estimated Cost to Economy $16B (NEXTOR, 2010)
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NextGen & AIP

• Airport Improvement Plan (AIP)
  – Increase capacity at key nodes in network
  – Focused on airside capacity (runways, taxiways, ...)

• NextGen
  – Increase effective-capacity through productivity improvement
    • Super Density Operation (SDO)
    • Trajectory-based Operations (TBO) ...
### Observation 2007 - 2009

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Passenger Trip Delay (years)</td>
<td>29,873</td>
<td>26,605</td>
<td>16,957</td>
</tr>
<tr>
<td>Percentage of Passengers on Disrupted Trips</td>
<td>22%</td>
<td>20%</td>
<td>17%</td>
</tr>
<tr>
<td>Average Trip Delay for Disrupted Passengers (mins)</td>
<td>110</td>
<td>110</td>
<td>92</td>
</tr>
</tbody>
</table>

- Why did the % of Pax on Disrupted Trips and Average Delay not decrease proportionally?
- What phenomenon could be *nullifying* the effects of improved Flight Performance (i.e. reductions in Flight Delays and Cancellations)?
### Observation 2007 - 2009

Airline adaptations to market demand and fuel prices have shaped the “network structure”

<table>
<thead>
<tr>
<th>Changes in Market and Industry</th>
<th>Effects on Airlines Passenger Transportation System</th>
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</table>
| Changes in passenger travel geographic demand, and changes in airlines networks (e.g. seasonal, consolidation/expansion of competing hubs, or consolidation, or consolidation/expansion of own network, availability of other modes of transportation) | • Changes is airports served in the hub-and-spoke network  
• Changes in % Passengers on Direct and Connecting Itineraries |
| Efforts to reduce airline costs and provide improve passenger quality of service | • Changes in time between banks (e.g. rolling banks, continuous banks) |
| Changes in travel demand in existing network | • Changes in Aircraft Size |
| Airlines adjust airfares and over-booking rates to meet revenue, profit, and market-share | • Changes in Load Factor |
| Reduced schedules or increased airport and airspace capacity and productivity (e.g. NextGen and SESAR) | • Improved flight delays (and cancellation rates) |
## Problem Statement

- What role do “network structural” changes have on Passenger Trip Delay
  1. Frequency of Service
     - e.g. reduced service to spokes
  2. Rolling-banks
     - e.g. increased time between arrival and departure banks
  3. Load Factors
     - e.g. up/down-gauging
     - e.g. improved yield management
  4. Shifting itineraries from Direct to Connecting
  5. Schedules (peak, off-peak)
     - e.g. flight delays and flight cancellations
Research Approach

• Build a model of the “physics” of:
  – Time-space network of flights
  – Itineraries
  – Flight Performance
  – Passenger trips

• Model configured for a “canonical” representation

• Adjust the parameters to evaluate sensitivity
Model Airline Passenger Transportation System (APTS)

Problem Statement

Model

Results

Conclusions

Model Airline Passenger Transportation System (APTS)

- # Airports served
- Type of Network (point-to-point, hub-and-spoke)
- Time-space Network (i.e. schedule)
- Frequency of Service
- Seats per Flight
- Load Factor
- Airport and Airspace Capacity (μ, σ)
- Total Passenger Trip Delay
- % Passenger Trips Disrupted
- Average Delay for Disrupted Trips

Airline Passenger Transportation System (APTS)
APTS System Structure

- **(1) Itinerary Structure**
  - # Airports in Hub-Spoke Network
  - % Direct/Connecting Itineraries
  - Time to Next Flight
  - # Flights
  - # Direct Itineraries
  - # Connecting Itineraries
  - # Passengers on Direct Itins
  - Candidate Itineraries for Rebooking
  - P(Delayed Flight), Average Delay for Delayed Flight
  - P(Cancelled Flight)

- **(2) Passengers Allocated to Itineraries, and Itineraries Assigned to Flights**
  - % Itineraries Served
  - Seats per Flight Load Factors
  - Total Passengers
  - Total Pax on Direct Itins
  - Total Pax on Connecting Itins
  - Direct Pax/Next Itin
  - Connecting Pax/Connecting Itin
  - Available Seats for Rebooking

- **(3) Itinerary Disruption**
  - P(Direct Itin Delayed)
  - P(Direct Itin Cancelled)
  - P(Connecting Itin Delayed)
  - P(Connecting Itin Cancelled)
  - P(Connecting Itin Missed_Connection)

- **(4) Passenger Trip Delays**
  - Total Pax Trip Delay
  - Total Direct Itin Pax Trip delay
  - Total Connecting Itin Pax Trip Del
  - % Pax On-Time
  - Average Disrupted Pax Trip Delay

Problem Statement | Model | Results | Conclusions
(1) Itinerary Structure
Single Bank, for a network with $N$ spokes

- Hub-and-spoke network servicing $N$ spoke airports
  - # Direct Itineraries = $2N$
  - # Connecting Itineraries = $N(N-1)$
  - % Direct Itineraries = $2N/(N(N-1)+2N) = 2/(N+1)$
  - Flights = $2N$
  - Aircraft = $N$

- Example: 50 spoke, hub-and-spoke network
  - 100 Direct itineraries
  - 2450 Connecting itineraries
  - 3.9% Direct itineraries
  - Flights = 100
  - Aircraft = 50
(2) Pax Allocation

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<th>Conclusions</th>
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</thead>
<tbody>
<tr>
<td>• # Direct Passengers =</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seats per Flight * Load Factor * % Pax on Direct Itineraries * Itineraries per Flight (=1) * # Direct Itineraries</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• # Connecting Passengers =</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seats per Flight * Load Factor * (1-% Pax on Direct Itineraries) * Itineraries per Flight (=N) * # Connecting Itineraries</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Multiple Itineraries on a Flight
### (3) Itinerary Disruption

<table>
<thead>
<tr>
<th>Itinerary Type</th>
<th>Type of Itinerary Disruption</th>
<th>Probability of Itinerary Disruption</th>
<th>Magnitude of Disruption (Average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>Delayed</td>
<td>Based on Probability of Delayed Flight (typical 0.3)</td>
<td>$10 \times e \times (\text{Probability of Delay Flight} \times 6)$. (Typical 60 mins)</td>
</tr>
<tr>
<td></td>
<td>Cancelled</td>
<td>$0.004 \times (\text{Probability of Delay Flight} \times 6.67)$. (Typical 0.02)</td>
<td>$(0.0483 \times e \times (5.8902 \times \text{Load Factor})) \times \text{Time to Next Flight}$. Based on Availability of Seats on subsequent flights and Time to next flight (average = 300 mins)</td>
</tr>
<tr>
<td>Connecting</td>
<td>Delayed</td>
<td>Based on Probability of Delayed Flight (typical 0.3)</td>
<td>$10 \times e \times (\text{Probability of Delay Flight} \times 6)$. (Typical 60 mins)</td>
</tr>
<tr>
<td></td>
<td>Cancelled</td>
<td>$2 \times 0.004 \times (\text{Probability of Delay Flight} \times 6.67)$. Twice probability of Cancelled Flight (typical 2 * 0.02)</td>
<td>$(0.0483 \times e \times (5.8902 \times \text{Load Factor})) \times \text{Time to Next Flight}$. Based on Availability of Seats on subsequent flights and Time to next flight (average = 645 mins)</td>
</tr>
<tr>
<td></td>
<td>Missed Connection</td>
<td>0.1 \times \text{Probability of Delayed Flight}. A function of connecting times and airline policies regarding holding flights (typical 0.03)</td>
<td>$(0.0483 \times e \times (5.8902 \times \text{Load Factor})) \times \text{Time to Next Flight}$. Based on Availability of Seats on subsequent flights and Time to next flight (average = 645 mins)</td>
</tr>
</tbody>
</table>

Ball et al, 2004/6/7; Tien, Churchill, 2009; Subramanian, 2007; Bratu & Barnhart, 2005; Zhu, 2007; Wang & Sherry, 2006; Le, 2007
(4) APTS Performance

- Total Passenger Trip Delay =
  - $\sum \text{PTD}\_\text{DDF} + \text{PTD}\_\text{DCF} + \text{PTD}\_\text{CDF} + \text{PTD}\_\text{CCF} + \text{PTD}\_\text{CMC}$

- % Passengers on Disrupted Trips =
  - Total Pax on Disrupted Itineraries / Total Passengers

- Average Delay for Disrupted Trips =
  - Total Pax Trip Delay / # Disrupted Passengers
### Results (50 spoke Hub-and-Spoke)

<table>
<thead>
<tr>
<th>Factors</th>
<th>Impact of Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Passenger Trip Delay</strong></td>
<td><strong>Percentage Passengers Disrupted</strong></td>
</tr>
<tr>
<td>Proportion of Passengers on Connecting Itineraries increases</td>
<td>Linear increase (+34 days for every 10% shift from Direct to Connecting)</td>
</tr>
<tr>
<td>Load Factor</td>
<td>Non-linear Increase (natural log exponent 0.2)</td>
</tr>
<tr>
<td>Time to Next Flight</td>
<td>Linear Increase (+23 days for every 60 minute increase in Time to Next Flight)</td>
</tr>
<tr>
<td>Flight On-Time Performance</td>
<td>Non-linear increase (natural log exponent 0.34 exponent)</td>
</tr>
</tbody>
</table>
### 50 spoke Hub-and-Spoke

<table>
<thead>
<tr>
<th>Scenario</th>
<th>% Passengers on Direct</th>
<th>% Load Factor (Seats Adjusted)</th>
<th>% Delayed &amp; Cancelled Flights</th>
<th>Time between Banks</th>
<th>Change in Total Pax Trip Delay</th>
<th>Change in % Pax Disrupted</th>
<th>Change in Average Disrupted Pax Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>50%</td>
<td>80%</td>
<td>30% / 2%</td>
<td>120 mins</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Consolidating flights to hubs resulting in shift to Connecting Itineraries</td>
<td>45%</td>
<td>80%</td>
<td>30% / 2%</td>
<td>120 mins</td>
<td>Increase 6%</td>
<td>Decrease 1.7%</td>
<td>Increase 4.5%</td>
</tr>
<tr>
<td>Downguaging and/or Improved Revenue Management resulting in Increased Load Factor</td>
<td>50%</td>
<td>88%</td>
<td>30% / 2%</td>
<td>120 mins</td>
<td>Increase 32%</td>
<td>No Change</td>
<td>Increase 43%</td>
</tr>
<tr>
<td>Reduced Frequency and/or Rolling Banks resulting in longer Time to Next Flight</td>
<td>50%</td>
<td>80%</td>
<td>30% / 2%</td>
<td>180 mins</td>
<td>Increase 37%</td>
<td>No Change</td>
<td>Increase 36%</td>
</tr>
<tr>
<td>ATC/Airport Capacity decrease or Peaking congested Schedules resulting in improved Flight On-time Performance</td>
<td>50%</td>
<td>80%</td>
<td>25% / 1.8%</td>
<td>120 mins</td>
<td>Decrease 16%</td>
<td>Decrease 18%</td>
<td>Decrease 12%</td>
</tr>
<tr>
<td>All of the above scenarios combined</td>
<td>45%</td>
<td>88%</td>
<td>25% / 1.8%</td>
<td>180 mins</td>
<td>Increase 55%</td>
<td>Decrease 19%</td>
<td>Increase 92%</td>
</tr>
</tbody>
</table>
Conclusions

• Model demonstrates role of “network structure’ on Passenger Trip Delays
  – network structure can nullify/amplify effects of improved flight performance
## Conclusions - Airline Decisions

- Airlines obliged to continuously adjust their operations
- In many cases enterprise actions are **not** congruent with the goal of maximizing the reliability of passenger trips
  - Revenue Management (Cross, 1997) and Demand-Driven Dispatch (Berge et. al, 1993) → longer delays for rebooked pax
    - increased load factors
    - increased time between flights
- Increased time between banks improves on-time flight performance and reduces likelihood of missed connection, but increases time-to-next flight
Conclusions - NextGen

• Implications:
  – NextGen benefits case of *improved flight operations* subject to “network structure”

• Example (under certain circumstances)
  – 10% increase in load factor can nullify the benefits of a 5% improvement in flight on-time performance
Conclusions – NextGen Benefits Analysis

- Implications:
  - NAS-wide simulations tools simulate the operation of up to 60,000 flights per day.
  - Passenger itineraries not considered
  - Lost economic productivity under-reported
    - passenger trip delays due to delayed flights only account for approximately 45% of the total passenger trip delays.
  - Careful book-keeping must be done to capture underlying factors (load factors, bank structure, ...)

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CENTER FOR AIR TRANSPORTATION SYSTEMS RESEARCH
Conclusions

• Implications:
  – Consumer Protection initiatives need to consider “network structure”
    • Cancelling passengers on Direct Itinerary different than cancelling passengers on Connecting Itinerary (e.g. Tarmac delay)
    • One-size-fits-all-rule not compatible with complex shades of grey system