DESIGN OF A SINGLE PILOT COCKPIT FOR AIRLINE OPERATIONS

Jonathan Graham, Chris Hopkins, Andrew Loeber, Soham Trivedi
Overview

- **Problem**: Poor financial performance in commercial aviation and predicted pilot shortage
- **Need**: System needed to reduce airline costs and hedge potential pilot shortages
- **How**: Single Pilot Cockpit system potentially reduces pilot labor need and airline labor cost
- **Our Job**: Analyze design alternative’s ability to meet system need within project scope and stakeholder win-win
- **Outcomes**: Recommend systems based on the derived feasibility of designing a Single Pilot Cockpit
Agenda

- Context
- Stakeholder Analysis
- Problem & Need
- Requirements
- Design Alternatives
- Simulation & Methodology
- Results
- Recommendation
Scope

- Large Commercial Air Transportation
  - Passenger and Cargo Carriers
  - Carriers With Operating Revenue > $20 Million
  - Domestic Operations
- US Airspace
  - National Airspace System (NAS)
  - ATC
  - FAA Regulatory Body
- Financial data adjusted for inflation to 2012 dollars
Large air carriers as a whole have had volatile financial performance

The year 2000 was the tipping point

30% of US Airlines filed for Chapter 11 between 2000-2010

[1] BTS Schedule P1.2

*Values are inflation adjusted to 2012 based on consumer price index
Projected growth in operating expense

Reducing operating expense relative to operating revenue is good for financial stability

[2] BTS Schedule P5.2

*Values are inflation adjusted to 2012 based on consumer price index
Large percentage of operating expense is composed of fuel and pilot labor costs

- Fuel costs are a variable cost
- Pilot labor costs are easier to control

[3] BTS Schedule P5.2

*Values are inflation adjusted to 2012 based on consumer price index
The number of pilots has been relatively static for the last decade

Pilot labor growth has been much greater in the past

Flight hour requirements and decreased retirement age impacting future pilot supply

6% Growth in commercial pilot labor projected from 2012-2022 using FAA forecasts for 2013-2033 [9]

~4,500 Air Transport Pilot licenses per year from 2004-2012 [5]

[4] BTS Schedule P10

*8.94% attrition rate and fixed licensure rate used to plot shortage curve in red [11]
Is a Single Pilot Cockpit the Next Step?
The Flight Deck

- Two pilots operate the aircraft
  - Pilot Flying
    - Flies the Aircraft
    - Confirms Callouts
  - Pilot Not Flying
    - Inspects/Manipulates Instruments
    - Performs Callouts
    - Interacts with ATC
    - Flies on Behalf of Pilot
- Both captain and co-pilot can take on each role during a flight
Cockpit Avionics

Mode Control Panel

Center Instrument Panel

1st Officer’s Instrument Panel

Avionics Downlink

Control Display Unit

Overhead Panel
Flight Procedures

- Procedures are followed to operate an aircraft
- Flight Crew Operating Manual (FCOM) BAE RJ100
  - Describes flight procedures
  - Official FAA approved document
- Identifies responsible entities for procedural tasks
  - Pilot Flying (PF)
  - Pilot Not Flying (PNF)
- Why do we care?
  - Used in analysis to show how workload is affected when alternatives change the operating procedures
A procedure is decomposed by tasks and physical/cognitive actions that are required to execute a task.

FCOM Codifies Procedures
- 63 Procedures
- 613 Total Tasks
- 737 Total Actions

Procedures are decomposed to identify potential reallocation of actions to a design alternative.
Example Procedure

**WINDSHEAR DETECTION PROCEDURE**

- **Pilot Flying**
  1. Sets thrust levers fully forward
  2. Presses TOGA buttons
  3. Follows flight guidance
  4. Orders “Windshear go thrust”

- **Pilot Not Flying**

- **Aircraft**
  5. Checks WS MAX thrust available
  6. Checks speed brake retracted
  7. Monitors flight path and speed

- **ATC**
  8. Reports encounter to ATC
### Action Frequencies

![Bar chart showing action frequencies.](image)

### % Actions by Pilot

![Pie chart showing percentage of actions by pilot.](image)
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<table>
<thead>
<tr>
<th>Stakeholder Group</th>
<th>Primary Objectives</th>
<th>Tension with SPC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Regulatory Agencies</strong></td>
<td>• Maximize:</td>
<td>A SPC would inherently introduce new risks and decrease overall flight safety, leading regulatory agencies to withhold their approval</td>
</tr>
<tr>
<td>(FAA, DoT)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Flight safety</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Consumer protection</td>
<td></td>
</tr>
<tr>
<td><strong>Aviation Workforce</strong></td>
<td>• Maintain:</td>
<td></td>
</tr>
<tr>
<td>(Pilots, Pilots’ Unions, ATC, ATC Unions)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Job Stability</td>
<td>View SPC as a major potential threat to job stability, leading to a high risk of pushback</td>
</tr>
<tr>
<td></td>
<td>• Wage Stability</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Safety level</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Workload</td>
<td></td>
</tr>
<tr>
<td><strong>Customer Base</strong></td>
<td>• Minimize:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Travel time</td>
<td>May have reservations about flying in a plane with only one pilot, leading them to avoid flying with an airline that uses SPC</td>
</tr>
<tr>
<td></td>
<td>• Flight risk</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Ticket expenses</td>
<td></td>
</tr>
<tr>
<td><strong>Aviation Industry</strong></td>
<td>• Maintain:</td>
<td></td>
</tr>
<tr>
<td>(Air Carriers, Management, Manufactures, Insurance, &amp; Airports)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Consistent revenues</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Customer base</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Market predictability</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Low risk profile</td>
<td>Want to increase profitability through sales/service, but don’t want to increase expenses commit to long term investments without noticeable return</td>
</tr>
</tbody>
</table>
Stakeholder Interactions

ALPA/ Pilot Unions
- Bargaining Services for Pilots
- Pay Dues & Voice Concerns

Pilots
- Want Wage Decrease
- Pay Dues & Voice Concerns

FAA
- Collectively Bargain
- Certification & Licensure
- Employ Controllers
- Regulate & Certify

Air Traffic Controllers
- Pay Dues & Voice Concerns
- Collective Bargaining for ATC

Airports
- Provide ATC

Commercial Air Carriers/Airline Management
- Provide Insurance
- Improve Safety & Regulate

Aviation Insurance Agencies
- Provide Insurance

Aviation Manufacturers
- Sell/Lease Aircrafts
- Push For Higher Earnings
- Balance Operation Costs

Airline Investors
- Demand Lower Fares & Better Service
- Demand Increased Safety

Passengers
- Destabilizing
- Stabilizing
- Neutral

Support SPC
- Reserved about SPC
- Oppose SPC
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Problem Statement

- Rising operating expense contributes to financial instability in commercial aviation
  - Profitability is difficult to achieve
- Pilot labor shortage predicted
GAP Analysis

Operating Revenue to Operating Expense Ratio

*Values are inflation adjusted to 2012 based on consumer price index

*BTS Schedule P5.2
Airlines will continue to have volatile financial performance if operating costs continue to grow
- Variable costs like fuel driving operating expense
- Labor expense can be controlled more effectively

A single pilot cockpit is needed to decrease labor expense and mitigate the effects of a pilot shortage
<table>
<thead>
<tr>
<th>Organization</th>
<th>Tension to be Mitigated</th>
<th>Benefit to Slow Phase-In</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulatory Agencies</td>
<td>Fear of elevated risk caused by removing a pilot</td>
<td>Allows regulatory agencies to observe the effects of implementing a SPC and collect reliability data without the worry of deploying an uncertain system and dealing with damage control.</td>
</tr>
<tr>
<td>Aviation Workforce</td>
<td>Fear of labor downsizing</td>
<td>The resultant decline in pilot labor demand can be spread out over several decades, meaning that job stability can remain relatively stable, and pilots can adapt to using a new system. A SPC system can also potentially reduce a pilot’s workload.</td>
</tr>
<tr>
<td>Customer Base</td>
<td>Fear of boarding a plane being flown by a single pilot</td>
<td>Fliers with concerns about the safety of a SPC will be allowed more time to acclimate to the new technology. Also, the majority viewpoint will shift due to changing generational attitudes regarding automation in general.</td>
</tr>
<tr>
<td>Aviation Industry</td>
<td>Fear of costs/changes needed to adapt to new system</td>
<td>Airports and aircraft manufacturers will be given additional time to adapt their operations, products, and business plans to the current phase of SPC deployment, keeping them from wasting resources on developing unutilized solutions.</td>
</tr>
</tbody>
</table>
Win-Win Analysis

- Majority of stakeholders involved have serious conflicts with moving to a single-pilot system

- However, these issues can be mitigated by extending the phase-in process
  - Helps to minimize safety concerns brought on by major systemic change
  - Decreases financial risk
  - Gradual labor downsizing

<table>
<thead>
<tr>
<th>Today</th>
<th>5 Years</th>
<th>10 Years</th>
<th>15 Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two Pilot Cockpit</td>
<td>Two Pilot Cockpit with Alternative</td>
<td>Evaluation of Alternative</td>
<td>Single Pilot Cockpit</td>
</tr>
</tbody>
</table>
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<td>The single pilot cockpit system shall meet ARP4761 Level B assurance of 1 failure per million flight hours.</td>
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<td>M.3</td>
<td>The single pilot cockpit system shall decrease yearly pilot labor operating expense.</td>
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<tr>
<td>M.4</td>
<td>The single pilot cockpit system shall have a total aircraft lifecycle cost no greater than $153.9 million dollars.</td>
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Design Alternatives

1. Two Pilot Cockpit (No Change)
2. Single Pilot with No Support
3. Single Pilot with Onboard Support System
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<table>
<thead>
<tr>
<th>Procedure Simulation</th>
<th>Reliability Modeling</th>
<th>Business Case</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Assumptions</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Human Processor Model approximate operator actions in cockpit under normal flight conditions
- Events are independent of each other
- Normal flight conditions and expert skill level
- Assume alternatives follow contemporary avionics costs
- RJ100 FCOM is representative of similar operating manuals compiled by commercial airlines
- Assume procedures in operating manual are complete representation of flight
- Additional company specific pilot tasks not included

[12] Liu, Feyen, Tsimhoni: Queuing Network Model Human Processor
Input data derived from RJ100 Flight Crew Operating Manual (FCOM)

Convert FCOM and classify procedures based on ontology
- Procedures are changed for each alternative
- One procedure model for each alternative

Each alternative’s procedural model is translated into an XML representation
- XML is parsed into simulation
Java program
- Input procedural model for each alternative
- Output Alternative Processing Time (APT)

Simulation based on Model Human Processor
- Network of perceptual, cognitive, and motor sub-networks
- Each process associated with capacity and process time
- Model combines concepts from ACT-R, GOMS, and Fitt’s Law
- Additional block added for alternative processing time where applicable

[12] Liu & Wu: Modeling Psychological Refractory Period (PRP) and Practice Effect on PRP with Queuing Networks and Reinforcement Learning Algorithms
Inside the Simulation

[12] Liu & Wu: Modeling Psychological Refractory Period (PRP) and Practice Effect on PRP with Queuing Networks and Reinforcement Learning Algorithms
### Simulation

<table>
<thead>
<tr>
<th>Perception</th>
<th>Cognition</th>
<th>Motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eyes</td>
<td>VSen</td>
<td>Eyes</td>
</tr>
<tr>
<td>Ears</td>
<td>ASen</td>
<td>Ears</td>
</tr>
<tr>
<td>ASen</td>
<td>CE</td>
<td>ASen</td>
</tr>
<tr>
<td></td>
<td>SMA</td>
<td></td>
</tr>
<tr>
<td></td>
<td>M1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BG</td>
<td></td>
</tr>
<tr>
<td>50ms</td>
<td>Exp(70ms)</td>
<td>A+Bexp(-aN)</td>
</tr>
<tr>
<td>10ms</td>
<td>180ms</td>
<td>kLog(D/S+0.5)</td>
</tr>
<tr>
<td>50ms</td>
<td>70ms</td>
<td>10ms</td>
</tr>
</tbody>
</table>

\[
APT = \sum_{i=1}^{j} \sum_{k=1}^{l} \sum_{m=1}^{n} (\text{Perception} + \text{Cognition} + \text{Motor})_{jln}
\]

\[
APT = \text{alternative processing time}
\]

\[
\text{Task} = k..l \quad \text{Procedure} = i..j \quad \text{Action} = m..n
\]

### Replications

\[
\text{Replications} \geq \left( \frac{Z_{0.025} \ast S_0}{\varepsilon} \right)^2
\]

\[
\text{Workload} = \frac{\text{time required}}{\text{time available}} = \frac{\text{Alternative Procedure}_{i..j}}{\text{Two Pilot Procedure}_{k..l}}
\]

\[
H_0: APT_{\text{Alternative}} = APT_{\text{Control}}
\]

\[
H_1: APT_{\text{Alternative}} > APT_{\text{Control}}
\]

\[
\text{reject iff } p < 0.05
\]

[12] Liu, Feyen, Tsimhoni: Queuing Network Model Human Processor
<table>
<thead>
<tr>
<th>Alternative</th>
<th>Procedures &amp; Tasks</th>
<th>Additional Processing Node</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Pilot No Support</td>
<td>$P_1\ldots P_n$</td>
<td>None</td>
<td>Processing Time</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$T_1m\ldots T_{nm}$</td>
<td></td>
<td>Workload</td>
<td></td>
</tr>
<tr>
<td>Two Pilot</td>
<td>$P_1\ldots P_n$</td>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$T_1o\ldots T_{no}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Pilot With Onboard</td>
<td>$P_1\ldots P_n$</td>
<td>$\text{Exp}(1/X)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>System</td>
<td>$T_1p\ldots T_{np}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Simple reliability block diagram used to establish comparative reliability between cockpit elements and major accidents

- Major accidents as defined by NTSB
- Major accidents per million flight hours ~ MTBF
- Assume that cockpit reliability is critical to aircraft and can be isolated from other subsystems
- Assume there is an emergency land capability in the event of pilot incapacitation

- Don’t know the reliability of the system, but assists in reliability requirements development
\[
R_P(t, R_{1,n}) = 1 - \prod_{i=1}^{n} (1 - R_i)
\]

\[
R_z(t, R_{1,n}) = \prod_{i=1}^{n} R_i = \exp \left( \frac{-t}{\sum_{i=1}^{n} R_i} \right)
\]
<table>
<thead>
<tr>
<th>Alternative</th>
<th>Cockpit Failure Rate (per flight hour)</th>
<th>Aircraft Failure Rate (per flight hour)</th>
<th>Target System Reliability (@1 Million Flight Hours)</th>
<th>Required Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Pilot No Support</td>
<td>( \lambda_c = (100k^{-1}, 10m^{-1}) )</td>
<td>( \lambda_A = (100k^{-1}, 10m^{-1}) )</td>
<td>0.8674</td>
<td>( R_s = R_A R_{P1} )</td>
</tr>
<tr>
<td>Two Pilot</td>
<td>( \lambda_c = (100k^{-1}, 10m^{-1}) )</td>
<td>( \lambda_A = (100k^{-1}, 10m^{-1}) )</td>
<td>0.8674</td>
<td>( R_s = [1-(1-R_{P1})(1-R_{P2})] R_A )</td>
</tr>
<tr>
<td>Single Pilot With Onboard Support System</td>
<td>( \lambda_c = (100k^{-1}, 10m^{-1}) )</td>
<td>( \lambda_A = (100k^{-1}, 10m^{-1}) )</td>
<td>0.8674</td>
<td>( R_s = [1-(1-R_{alt})(1-R_P)] R_A )</td>
</tr>
</tbody>
</table>

Model an aircraft lifecycle cost (25 years) for each alternative and calculate net savings (if any)

Limited aircraft costs to:
- Maintenance data collected for Boeing 737s
- Average pilot labor costs used with an escalation rate
- Fuel too variable for our analysis
- Salvage value of aircraft considered at end of life
Cost Formulas

\[ ALC = C_{Alt} + C_{Pilot_0} \sum_{t=1}^{N} \left( \frac{1 + e}{1 + d} \right)^t + \sum_{t=1}^{N} \frac{C_{Maintenance}}{(1 + d)^t} - \sum_{t=1}^{N} \frac{C_{Residual}}{(1 + d)^t} \]

\[ Net \ Savings = \sum_{t=1}^{N} \frac{S_t}{(1 + d)^t} - \sum_{t=1}^{N} \frac{\Delta I_t}{(1 + d)^t} \]

\( d = \text{discount rate} \quad e = \text{escalation rate} \quad S_t = \text{Savings in year } t \quad \Delta I_t = \text{Additional investment} \)
### Procedure Simulation
### Reliability Modeling
### Business Case
### Design of Experiment

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Alternative Cost</th>
<th>Pilot Cost</th>
<th>Maintenance Cost</th>
<th>Residual Cost</th>
<th>Interest</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Pilot No Support</td>
<td>$0</td>
<td>$141,927</td>
<td>$9.127M</td>
<td>$8M-$9M</td>
<td>d=1%-10%</td>
<td>Total Lifecycle Cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Net Savings</td>
</tr>
<tr>
<td>Two Pilot</td>
<td>$0</td>
<td>$269,126</td>
<td>$9.127M</td>
<td>$8M-$9M</td>
<td>d=1%-10%</td>
<td></td>
</tr>
<tr>
<td>Single Pilot With Onboard Support</td>
<td>($100K,$4.38M)</td>
<td>$141,927</td>
<td>$9.127M</td>
<td>$8M-$9M</td>
<td>d=1%-10%</td>
<td></td>
</tr>
</tbody>
</table>
Value Hierarchy

- Single Pilot Utility
  - Alternative Processing Time
  - Workload Risk
  - Reliability
  - Technology Readiness Level
  - Maintenance
    - Training
    - Liability
    - Usability
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Procedure Simulation

- Predicted reduced processing times due to reduction in procedures
- Both single pilot cockpit designs on average have procedure times smaller than the two pilot cockpit p<0.0001
- Time pilot spends performing tasks for operating procedures is reduced
Procedure Simulation

Procedure Processing Time Distributions

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Mean (s)</th>
<th>Median (s)</th>
<th>Standard Deviation (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two Pilot (No Change)</td>
<td>20.868</td>
<td>14.193</td>
<td>20.926</td>
</tr>
<tr>
<td>Single Pilot</td>
<td>12.703</td>
<td>9.386</td>
<td>13.770</td>
</tr>
<tr>
<td>Single Pilot with Onboard Support</td>
<td>16.909</td>
<td>11.894</td>
<td>18.637</td>
</tr>
</tbody>
</table>
Procedure Simulation

- Single pilot had smallest processing time p<0.0001
- The single pilot incurred a significant increase in workload: 4.17 +/- 1.77
- Single pilot with onboard support had a reduction in workload: 0.75 +/- 0.13
Reliability Analysis

- Single pilot would not be achievable to maintain required reliability
  - Approximately 1 failure every 23 million flight hours

- Single pilot with onboard support would be feasible as long as an emergency auto-landing feature could be integrated into the system
  - Avionics would have to be certified above 1 in 1 million flight hour failure
- Single pilot would support up to a $4.38M per-aircraft savings
- Savings could be allocated to procedure support system acquisition or other operating costs
- Single pilot cockpit decreases aircraft operating costs
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## Requirements

<table>
<thead>
<tr>
<th>Requirement ID</th>
<th>Description</th>
<th>Alternatives Satisfying Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>M.1</td>
<td>The single pilot cockpit system shall reduce or maintain the baseline pilot flying procedure working time of 20.87±3.7s</td>
<td>✓</td>
</tr>
<tr>
<td>M.2</td>
<td>The single pilot cockpit system shall meet ARP4761 Level B assurance of 1 failure per million flight hours.</td>
<td>n/a</td>
</tr>
<tr>
<td>M.3</td>
<td>The single pilot cockpit system shall decrease yearly pilot labor operating expense.</td>
<td>X</td>
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<td>M.4</td>
<td>The single pilot cockpit system shall have a total aircraft lifecycle cost no greater than $153.9 million dollars.</td>
<td>X</td>
</tr>
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</table>
Recommendation

- Utility Ranking:
  1. Two Pilot Cockpit
  2. Single Pilot with Onboard Support
  3. Single Pilot

- A single pilot has cost reductions but workload and safety bounds overall utility
  - Safety mechanism for pilot would give alternative increased utility (and cost)

- A single pilot with onboard support has marginally equivalent utility to the two pilot cockpit but has cost savings
  - Larger cost savings from unexplored areas could lower costs making utility ranking highest
Recommendation

- Recommend keeping two pilot cockpit and evolve alternative system per the win-win scenario
- Procedure Support system to be phased in and evaluated for the eventual change to the single pilot cockpit pending further future analysis
Further Research

- Extend procedure simulation to a live pilot simulator to validate and/or recalibrate models
  - Tie in ATC procedures to test their workloads
  - Incorporate dynamics feedback loop
- Conduct focus groups with stakeholders to validate win-win scenario
- Begin development of Single Pilot with Onboard Support requirements baseline
Questions?
Sources

[5] WSJ Airlines Face Acute Shortage of Pilots  
http://online.wsj.com/news/articles/SB10001424052970203937004578079391643223634#articleTabs%3DArticle
[12] Liu & Wu: Modeling Psychological Refractory Period (PRP) and Practice Effect on PRP with Queuing Networks and Reinforcement Learning Algorithms


