THE POTENTIAL OF TURBOPROPS TO REDUCE FUEL CONSUMPTION IN THE CHINESE AVIATION SYSTEM

Megan S. Ryerson, Xin Ge
Department of City and Regional Planning
Department of Electrical and Systems Engineering
University of Pennsylvania
mryerson@design.upenn.edu

ICRAT 2014
Agenda

• Introduction
• Data collection
• Turboprops in the current CAS network
  • Spatial trends for short-haul aviation
  • Regional jet and turboprop trade space
• Turboprops in the future CAS network
1. Introduction – Growth of the Chinese Aviation System

- The Chinese aviation system is in a period of rapid growth
- China’s civil aviation system grew at a rate of 17.6%/year, 1980 - 2009
  - Number of airports grew from 77 to 166 and annual traffic volume increasing from 3.43 million to 230 million
- The Civil Aviation Administration of China (CAAC) maintains a target of 244 airports across the country by 2020
- The CAAC plans for 80% of urban and suburban areas to be within a 100km (62 miles) of aviation service by 2020
- Plans also include strengthening hub-and-spoke networks across the country to meet the dual goals of improving the competitiveness and efficiency of domestic and international aviation.
1. Introduction – Reform of the Chinese Aviation System

• Consolidation
  → Strong national hubs + insufficient regional coverage

• Regional commuter airlines could fill this gap by partnering with China’s major carriers and serving the second-tier and emerging hubs (Shaw, 2009)
1. Introduction – Aircraft of the Short Haul Chinese Aviation System

<table>
<thead>
<tr>
<th>Domestic Traffic and Fleet Deployment Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily Passengers Each Way</td>
</tr>
<tr>
<td>------------------------------</td>
</tr>
<tr>
<td>&gt;600</td>
</tr>
<tr>
<td>500-600</td>
</tr>
<tr>
<td>400-500</td>
</tr>
<tr>
<td>300-400</td>
</tr>
<tr>
<td>200-300</td>
</tr>
<tr>
<td>100-200</td>
</tr>
<tr>
<td>&lt;100</td>
</tr>
</tbody>
</table>

- **Narrow Body Jet**
  - Fuel per seat: 7.9 gal
- **Regional Jet**
  - Fuel per seat: 19.0 gal
- **Turboprop**
  - Fuel per seat: 4.35 gal

Source: Civil Aviation Administration of China (CAAC)
1. Introduction – Short Haul Aircraft Comparison, Regional jet and Turboprop (Ryerson and Hansen, 2010).

### Graphs:

**Operating Cost per Passenger**
- Regional jet operating cost is 30-50% greater than turboprop.
- Regional jet operating cost is 50% or more greater than turboprop.

**Passenger + Operating Cost per Passenger**
- Market Densities (Passengers per day):
  - 125
  - 4000
- Above the curve: Regional Jet has minimum cost.
- Below the curve: Turboprop has minimum cost.
1. Introduction – Short Haul Aircraft Comparison, Narrow body jet and Turboprop (Ryerson and Hansen, 2010).
1. Introduction – Jet Fuel Price

![Figure 1. Fuel Prices in China and the US. Source: IndexMundi Data and National Development and Reform Commission Data.](image-url)
1. Introduction – International Climate Change

Overview

- China surpassed the US in 2007 in GHG emissions and ranked first on the Carbon Dioxide (CO₂) emissions country list
- Emissions of CO₂ have not slowed, as CO₂ emissions in China grew from 6.8 billion metric tons in 2007 to 8.3 billion metric tons in 2010
- Local pollutants are also a significant concern in China, as many major Chinese cities suffer from PM2.5 concentration much higher above World Health Organization standards

CAAC Action

- Reducing emissions is the major environmental goal for the aviation industry in the CAAC Twelfth Five-Year Plan (2011-2015).
- CAAC requires that airlines utilize energy efficient technologies to reduce fuel consumption in every stage and requires airports to be constructed and operated with new materials
- CAAC funding program In 2012 (approximately 49 million US dollars/year) to support airline and airport initiatives to reduce fuel consumption
1. Introduction – Research Question

• Given the existing short haul air transportation network, are there savings to be had from utilizing turboprops?

• If short-haul, regional aircraft are to be deployed to serve growing low-density markets, what is the likelihood that these markets will be served by turboprops (given the existing deployment of turboprops)?
2. Data Collection

• OpenFlights Airport Database 2012
  • Data for 181 Chinese airports from OpenFlights, an open source resource for airport locational data
  • Fields: airport names, city names, country names, International Air Transport Association (IATA)/Federal Aviation Administration (FAA) codes, and latitudes and longitudes for all the airports

• Scheduled Flight Data
  • All intra-China scheduled arrival and departure operations for July 18, 2013 (the third Thursday of the month) are collected from masFlight
  • This dataset includes, among a host of variables, origin, destination, aircraft type, number of seats per operation, and market carrier for each flight.

• Aircraft Travel Time
  • Use the average cruise speed of turboprops (320 mi/hr) and regional jets (530 mi/hr) found empirically in the scheduled flight data

• Fuel Consumption Data and Model (Ryerson, 2010)
  \[ F_{tp} = 0.495 \times distance + 2.030 \times seats \]
  \[ F_{rj} = 2.392 \times distance + 3.488 \times seats \]
2. Data Collection – Status Quo Turboprop and Regional Jet Connections in China
2. Data Collection – Statistics of Turboprop and Regional Jet Flight Connections in China

<table>
<thead>
<tr>
<th>Hub</th>
<th>Airport Code</th>
<th>Number of Feeder Routes</th>
<th>Radius 75th Percentile</th>
<th>Radius Maximum</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Turboprops</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harbin</td>
<td>HRB</td>
<td>7</td>
<td>282 miles</td>
<td>342 miles</td>
<td>Northeast China</td>
</tr>
<tr>
<td>Xi’an</td>
<td>XIY</td>
<td>5</td>
<td>312 miles</td>
<td>313 miles</td>
<td>Northwest China</td>
</tr>
<tr>
<td>Taiyuan</td>
<td>TYN</td>
<td>4</td>
<td>276.5 miles</td>
<td>313 miles</td>
<td>North China</td>
</tr>
<tr>
<td>Zhengzhou</td>
<td>CGO</td>
<td>4</td>
<td>275 miles</td>
<td>289 miles</td>
<td>South Central China</td>
</tr>
<tr>
<td>Dalian</td>
<td>DLC</td>
<td>3</td>
<td>127 miles</td>
<td>192 miles</td>
<td>Northeast China</td>
</tr>
<tr>
<td>Hefei</td>
<td>HFE</td>
<td>3</td>
<td>275 miles</td>
<td>275 miles</td>
<td>East China</td>
</tr>
<tr>
<td><strong>Regional Jets</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urumqi</td>
<td>URC</td>
<td>56</td>
<td>408 miles</td>
<td>1,308 miles</td>
<td>Northwest China</td>
</tr>
<tr>
<td>Xi’an</td>
<td>XIY</td>
<td>32</td>
<td>690.5 miles</td>
<td>1,308 miles</td>
<td>Northwest China</td>
</tr>
<tr>
<td>Hohhot</td>
<td>HET</td>
<td>29</td>
<td>564 miles</td>
<td>1,255 miles</td>
<td>North China</td>
</tr>
<tr>
<td>Tianjin</td>
<td>TSN</td>
<td>28</td>
<td>574 miles</td>
<td>1,386 miles</td>
<td>North China</td>
</tr>
<tr>
<td>Guangzhou</td>
<td>CAN</td>
<td>22</td>
<td>709 miles</td>
<td>1,112 miles</td>
<td>Southern Central China</td>
</tr>
</tbody>
</table>
Research Question

• Given the existing short haul air transportation network, are there savings to be had from utilizing turboprops?

• If short-haul, regional aircraft are to be deployed to serve growing low-density markets, what is the likelihood that these markets will be served by turboprops (given the existing deployment of turboprops)?
3. Existing Network Regional Jet and Turboprop Trade Space

• Replacing regional jet operations with turboprops would come at a cost: flight times would increase (increasing the cost faced by passengers) while fuel consumed by each flight would decrease.

• Estimating the trade-off between these two costs requires a value of time.

• Instead of imputing this value of time directly, we calculate a “break-even” value of time that would make the passenger cost (time) and the fuel cost equal.

• We do this because of difficulties estimating value of time overall, and particularly in the developing world.
3. VoT in China

• Walker et al. (2010), in a case study of commute mode in Chengdu, China estimate the VoT for local commute travel to be 12 yuan/hour (which is about 80% of the average income rate, and about $2.00)

• Liu (2006), in a study using survey data from transportation users in Shanghai in 2001, finds the value of “In-vehicle time” and “Out-of-vehicle time” to be 15.1 yuan per hour and 20.2 yuan per hour, respectively (with the mean wage across the sample at 21.7 yuan per hour)

• Sample population is of local travelers and not air travelers, who are likely to have higher values of time
3. Regional Jet and Turboprop Trade Space

\( \bar{V} \hat{o} \bar{T} \alpha \rho \) represents the value of the savings, in $/hour-seat, from switching flights of a distance less than the p-th percentile of all flights from regional jets to turboprops at fuel price \( \alpha \)

\[
\bar{V} \hat{o} \bar{T} \alpha \rho = \frac{\sum_i \alpha \left( \hat{F}_i^{rj} - \hat{F}_i^{tp} \right) I_i(\rho)}{\sum_i \left( \hat{T}T_i^{tp} - \hat{T}T_i^{rj} \right) I_i(\rho)}
\]

\( \hat{F}_i^k \) is the estimated fuel consumed in gallons for flight \( i \) on aircraft \( k \)

\( \hat{T}T_i^k \) is the estimated travel time for flight \( i \) on aircraft \( k \)

\( \alpha \) is the price of fuel in $/gallon, to be considered parametrically from $3.00/gallon to $5.00/gallon

\( I_i(\rho) \) is an indicator function if the distance of flight \( i \) is less than the p-percentile distance across all flights
3. Regional Jet and Turboprop Trade Space

\( \overline{VoT_{\alpha\rho}} \) represents the value of the savings, in $/hour-seat, from switching flights of a distance less than the p-th percentile of all flights from regional jets to turboprops at fuel price \( \alpha \)

\[
\overline{VoT_{\alpha\rho}} = \frac{\sum_i \alpha \left( \overline{F_{i}^{r,j}} - \overline{F_{i}^{t,p}} \right) I_i(\rho)}{\sum_i \left( \overline{TT_{i}^{t,p}} - \overline{TT_{i}^{r,j}} \right) I_i(\rho)}
\]

\( \overline{F_{i}^{k}} \) is the estimated fuel consumed in gallons for flight \( i \) on aircraft \( k \)

\( \overline{TT_{i}^{k}} \) is the estimated travel time for flight \( i \) on aircraft \( k \)

\( \alpha \) is the price of fuel in $/gallon, to be considered parametrically from $3.00/gallon to $5.00/gallon

\( I_i(\rho) \) is an indicator function if the distance of flight \( i \) is less than the p-percentile distance across all flights

A switch to turboprops is justified if \( \overline{VoT_{\alpha\rho}} > VoT \), where VoT is the average value of passenger time for intra-China aviation
Regional Jet Routes (576 Miles or Less)
Regional Jet Connections in China on 07/18/2013
3. Break-even Value of Time

- A switch to turboprops is justified if $V_{oT\alpha p} > V_o T$, where $V_o T$ is the average value of passenger time for intra-China aviation.

- When $V_{oT\alpha p} > V_o T$, the savings per passenger from switching to turboprops is more than the value of passenger value of time.

- We find that the break-even VoTs are at the upper bound of US VoTs or greater.

- A switch to turboprops is easily justified for all flight distances covered by regional jets, offering a significant potential to save fuel.

- $V_{oT\alpha p}$ decreases with increasing $\rho$, as it is less attractive to switch a regional jet with a turboprop over longer distances.

- $V_{oT\alpha p}$ increases with fuel price, as regional jets are less fuel efficient than turboprops.

<table>
<thead>
<tr>
<th>Distance percentile</th>
<th>Fuel Price ($/gal)</th>
<th>Seat-by-Seat Replacement ($/hour)</th>
<th>Full Aircraft Replacement ($/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.00</td>
<td>4.00</td>
<td>5.00</td>
</tr>
<tr>
<td>25%</td>
<td>77.4</td>
<td>103.2</td>
<td>129.1</td>
</tr>
<tr>
<td>50%</td>
<td>71.4</td>
<td>95.2</td>
<td>119.0</td>
</tr>
<tr>
<td>75%</td>
<td>67.9</td>
<td>90.5</td>
<td>113.1</td>
</tr>
<tr>
<td>100%</td>
<td>64.2</td>
<td>85.6</td>
<td>107.0</td>
</tr>
</tbody>
</table>
Research Question

• Given the existing short haul air transportation network, are there savings to be had from utilizing turboprops?

• If short-haul, regional aircraft are to be deployed to serve growing low-density markets, what is the likelihood that these markets will be served by turboprops (given the existing deployment of turboprops)?
4. Future of Aviation in China

• Newly emerging airports and routes provide a unique opportunity to expand the short-haul aviation network

• We consider the potential for turboprops to play a role in an expanded network with these newly emerging markets

• Utilizing CAAC development plans, we explore the spatial patterns of the future CAS and, using a binary logit model, predict the market share of turboprops on the future routes
Emerging Airport Hubs and Spokes
(Based on the 12th 5-Year Plan by ACCA)

One-way flights per day on turboprops
- 1 - 2
- 3 - 4

One-way flights per day on regional jets
- 1 - 2
- 3 - 4
- 5 - 7
- 8

Existing Turboprop Hubs
Regional Hubs
Secondary Hubs
Emerging Spokes
Other Airports

Scale: 0 - 800 Miles
4. Future of Aviation in China - Binary Logit Model

The binary logit model predicts the probability that a route is served with aircraft type \( k \).

\[
P(k) = \frac{e^{V_k}}{\sum_{j \in K} e^{V_j}}
\]

\[
V_k = \beta_{tt} tt_k + I_k(rj) \sum_d \beta_d D_d
\]

\( P(k) \) is the probability that, for a single flight on aircraft type \( k \), \( V_k > V_j \) \( \forall j \in K \)
\( V_k \) is the deterministic utility function for aircraft \( k \)
\( tt_k \) is the travel time on aircraft \( k \)
\( D_d \) is a binary variable designating the density measure for the route, where \( d \in \{LL, MM, LM, LH, MH\} \). HH is the base case.
\( I_k(rj) \) is an indicator function which is 1 if the observation is for a regional jet and 0 otherwise
4. Future of Aviation in China - Binary Logit Estimation Results

- Coefficient of travel time is negative as expected

- Compared with regional jets serving high density regions, the utility of using a RJ for travel between airports in low density regions is less than the utility of using turboprops

- The density pairings with significant coefficient estimates (all negative) are LL, LH, and MH, showcasing that turboprops have a higher utility than regional jets when serving at least one region of low density/medium density

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>t Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel Time</td>
<td>-0.0904***</td>
<td>-5.46</td>
</tr>
<tr>
<td>Low Density/Low Density</td>
<td>-2.0615**</td>
<td>-1.97</td>
</tr>
<tr>
<td>Low Density/Medium Density</td>
<td>-0.3327</td>
<td>-0.29</td>
</tr>
<tr>
<td>Low Density/High Density</td>
<td>-1.1673**</td>
<td>-2.07</td>
</tr>
<tr>
<td>Medium Density/Medium Density</td>
<td>-0.6095</td>
<td>-0.52</td>
</tr>
<tr>
<td>Medium Density/High Density</td>
<td>-1.0125*</td>
<td>-1.66</td>
</tr>
</tbody>
</table>
Potential Turboprop Connections
(Based on the 12th 5-Year Plan by ACCA)

Potential Turboprop Connections
Probability - Choosing Turboprop

- 25.01% - 38.18%
- 15.01% - 25%
- 10.01% - 15%

Current one-way flights per day on turboprops
- 1 - 2
- 3 - 4
5. Conclusions

• In this study we focus on a segment of the Chinese aviation system that is on the precipice of expansion: the short-haul aviation system.

• We find a large role for turboprops in the CAS, motivating the inclusion of turboprops in the state-led initiatives to support aviation sustainability.

• We find that this role is not confined to one area of the country, but rather is dispersed. This is true for both the replacement of regional jets by turboprops and the deployment of turboprops on emerging routes.
Megan S. Ryerson, Ph.D.
Assistant Professor
Department of City and Regional Planning
Department of Electrical and Systems Engineering
University of Pennsylvania
mryerson@design.upenn.edu

Xin Ge
Master of City Planning ‘14
Department of City and Regional Planning
University of Pennsylvania
veronicaxge@gmail.com
<table>
<thead>
<tr>
<th>Spoke</th>
<th>Hub</th>
<th>Distance (Miles)</th>
<th>Probability - Turboprop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shihezi</td>
<td>Urumqi</td>
<td>71</td>
<td>38.2%</td>
</tr>
<tr>
<td>Daqing</td>
<td>Harbin</td>
<td>88</td>
<td>35.5%</td>
</tr>
<tr>
<td>Baise</td>
<td>Nanning</td>
<td>108</td>
<td>32.5%</td>
</tr>
<tr>
<td>Huaian</td>
<td>Nanjing</td>
<td>139</td>
<td>28.0%</td>
</tr>
<tr>
<td>Huaian</td>
<td>Hefei</td>
<td>174</td>
<td>23%</td>
</tr>
<tr>
<td>Shihezi</td>
<td>Korla</td>
<td>179</td>
<td>22.9%</td>
</tr>
<tr>
<td>Huaian</td>
<td>Qingdao</td>
<td>185</td>
<td>22.2%</td>
</tr>
<tr>
<td>Baise</td>
<td>Guiyang</td>
<td>194</td>
<td>21.1%</td>
</tr>
<tr>
<td>Hengyang</td>
<td>Guilin</td>
<td>195</td>
<td>21.0%</td>
</tr>
<tr>
<td>Jiuhuashan</td>
<td>Wuhan</td>
<td>206</td>
<td>19.8%</td>
</tr>
<tr>
<td>Daqing</td>
<td>Changchun</td>
<td>210</td>
<td>19.4%</td>
</tr>
<tr>
<td>Jiuhuashan</td>
<td>Shanghai</td>
<td>218</td>
<td>18.6%</td>
</tr>
<tr>
<td>Huaian</td>
<td>Jinan</td>
<td>237</td>
<td>16.7%</td>
</tr>
<tr>
<td>Daocheng</td>
<td>Chengdu</td>
<td>249</td>
<td>15.6%</td>
</tr>
<tr>
<td>Baise</td>
<td>Kunming</td>
<td>279</td>
<td>13.1%</td>
</tr>
<tr>
<td>Hengyang</td>
<td>Wuhan</td>
<td>285</td>
<td>12.6%</td>
</tr>
<tr>
<td>Hengyang</td>
<td>Shenzhen</td>
<td>302</td>
<td>11.4%</td>
</tr>
<tr>
<td>Huaian</td>
<td>Zhengzhou</td>
<td>308</td>
<td>11%</td>
</tr>
</tbody>
</table>
3. Income Disparity in China