The Potential of Turboprops to Reduce Fuel Consumption in the Chinese Aviation System

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Abstract— **The Chinese aviation system is in a period of rapid growth, with significant growth in second tier and emerging cities. Lower density cities could be well served by regional aircraft, either regional jets or turboprops, which offer different qualities and a different future for Chinese aviation. Turboprops offer a high level of fuel efficiency compared with regional jets which may improve the cost economics for carriers and reduce the air quality and climate impacts of a growing aviation system in a region where air quality and greenhouse gas emissions are a serious concern. However, regional jets are known for their superior quality of service and faster travel speeds. We begin with a spatial analysis of existing US and Chinese short-haul aviation networks to explore the characteristics of routes served. We next explore the cost economics of utilizing turboprops on all short-haul aviation links in China. For the existing regional jet network we estimate the trade space of fuel and time for the replacement of regional jets with turboprops and find that most regional jet routes in China would generate savings if replaced with turboprops**.

Keyword s- China, Aviation, Turboprops, Fuel Consumption, Short-haul aviation

I. Introduction

The Chinese aviation system is in a period of rapid growth. In the 30 year period from 1980 to 2009, China's civil aviation system grew at a rate of 17.6% per year, with the number of airports growing from 77 to 166 and annual traffic volume increasing from 3.43 million to 230 million (Lin, 2012). The Civil Aviation Administration of China (CAAC), the aviation authority in the Ministry for Transport, maintains a target of 244 airports across the country by 2020 with the goal of expanding aviation coverage in their National Aviation Network Plan (CAAC, 2007). The CAAC aims to enlarge the aviation network such that 80% of urban and suburban areas are within a 100km (62 miles) of aviation service by 2020. As the eastern region of China is well covered with airports and aviation service, much of this growth will be in second tier and emerging western and southern cities. In growing the aviation services in these regions, the CAAC is looking to strengthen hub-and-spoke networks across the country to meet the dual goals of improving the competitiveness and efficiency of domestic and international aviation.

The aviation expansion into China's low-density areas follows years of reform in the Chinese Aviation System (CAS). In 2002, the state liberalized the CAS, a liberalization that was notably different compared with the free-market liberalization in the United States. Shaw (2009) notes that the Chinese liberalization led to airline consolidation leading to three major carriers serving three major (northeastern) hubs, and a protectionist strategy to reduce route overlap for the three major carriers. The goal of the three carriers – to be competitive internationally or to serve the large domestic population – remains, however, a debate (Lei and O'Connell, 2011). Lin (2012) finds that that the state focus on major national hubs and alliance partners for international travel leads to an underdeveloped system of regional and sub-regional hubs to support regional traffic. While the three major airlines focus on boosting domestic coverage, many areas with insufficient air service remain. Shaw (2009) discusses how regional commuter airlines could fill this gap by partnering with China's major carriers and serving the second-tier and emerging hubs that are not protected. This follows the practice of regional commuter carriers and major airlines partnering to serve low-density markets in the US.

Wang and Jin (2007) note that the physical and socioeconomic traits of the more remote emerging airport regions include challenging terrains along with high poverty and percentages of minority populations. These regions are uniquely positioned for service by regional commuter airlines utilizing short-haul aircraft, either turboprops or regional jets. These aircraft are smaller than traditional narrow body jet aircraft (generally 30-100 seats) which are widely used in China today (Shaw, 2009), offer lower ownership costs and operating costs per operation, and, because they necessitate shorter runways, are able to service some smaller and less developed airports. While aircraft in both of the short-haul aircraft categories share similarities, the adoption of short-haul aircraft in CAS expansion will have vast impacts on the economic and environmental impact of aviation. Firstly, turboprops necessitate shorter runways (1400m compared with 2000m for jets), offering the possibility of serving more challenging terrains; as a result, turboprops offer enhanced expansion opportunities. Secondly, turboprops are significantly more fuel efficient compared with regional jets; however, this fuel efficiency comes at the cost of passenger level of service (Ryerson and Hansen, 2010). Turboprops have a slower travel speed, and, in addition, are perceived as less comfortable compared with jets. In fact, Adler et al. (2005) find that the disutility of passenger travel on a turboprop can be up to \$40/passenger-trip. In addition, turboprops have a shorter range of travel (900-1300 miles) compared with regional jets (1400-2000 miles) and have smaller cargo holds, limiting their versatility to serve a network.

Turboprops offer significant benefits at a cost, namely a cost to passengers in the form of reduced service quality and to airlines in the form of reduced flexibility. In the 1980s and 1990s, the relatively loud, uncomfortable turboprop with a limited operational range fell out of favor with the introduction of regional jets (Johnston, 1995; Mozdzanowska and Hansman, 2004). Recent improvements to passenger level of service and operating range, coupled with fuel price increases are leading a surge of interest in new turboprop models. New turboprops are currently in service for North American carriers such as Alaska Airlines/Horizon Air, Canada's *Porter Airlines*, along with other carriers worldwide. In 2008, turboprops were 4 percent of the domestic seat capacity provided by US carriers. While this is a small percent, it is very robust; in fact, turboprops saw a reduction in total seat capacity offered in 2008 of 6% compared with 2007, a minimal decline compared with the 11% seat capacity reduction from 2007-2008 seen by narrow body aircraft. Because turboprops consume fuel at a relatively low rate, the Government Accountability Office (GAO, 2009) concludes that the market for turboprops is small but stable compared with other jet aircraft, a finding empirically confirmed by Ryerson and Hansen (2010). Aircraft manufacturer plans also signal a renewed interest in turboprops. As of 2013, five aircraft manufacturers in as many different countries – China, India, Korea, Canada, and Italy – maintain serious plans to develop and market 90-seat turboprops; such a move will boost turboprop seat capacity and also increase the competitiveness of turboprops with regional jets. Also signaling a growing market for turboprops is the increased competition in the engine market, with General Electric designing a turboprop engine to contend with the established Pratt & Whitney model.

While turboprops may be close to shedding their perception as aircraft with low quality of service and flexibility, their perception as unsafe aircraft lingers, particularly in China. Two crashes of the Xian MA-60 turboprop, the model favored in China and manufactured by Chinese manufacturer Xi'an Aircraft Industrial Corporation, occurred on the same day in the summer of 2013. In the immediate aftermath, the civil aviation authorities of Indonesia and Myanmar grounded their fleets of the MA-60 (Dennis, 2013). There are instances of turboprop crashes worldwide, including a high profile crash in Buffalo, New York in 2009. Turboprops are not necessarily unsafe aircraft, however, they are generally operated by inexperienced crew and pilot error is a frequency cause for such crashes (Ryerson and Hansen, 2010).

Turboprops present challenges compared with regional jets: institutional challenges such that the operating crew are well-trained, and passenger preference challenges because of their perceived discomfort. However, the significantly lower cost of operation reduces the break-even point needed to provide such services. This lower cost allows airlines to serve more destinations and complete their hub networks, increasing their market dominance and allowing them to charge higher fares (Morrison and Winston, 1990. Much of this savings comes in the form of reduced fuel costs. In addition to financial health, turboprops present an opportunity for the CAS because of their potential to reduce aviation fuel consumption, a major initiative of both public and private entities worldwide. The consumption of fuel has significant economic and environmental implications. The cost of fuel plays a large role in the economic health of the airline industry worldwide. Because of the skyrocketing cost of fuel, fuel in 2012 fuel was 33% percent of operating cost for US-based carriers compared with 9% in 2004 (BTS, 2013). This percentage is likely larger in China, as fuel costs are greater in China compared with the US. Figure 1 shows US and Chinese jet fuel prices (IndexMundi, 2013; National Development and Reform Commission, 2013). Currently, Chinese jet fuel prices are set by the National Development and Reform Commission. While both follow the same trend, Chinese prices are higher, making fuel consumption an even greater cost concern for airlines in China.

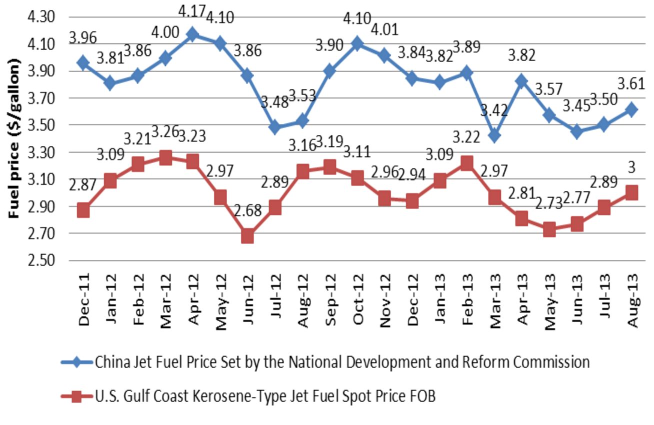

Figure 1. Fuel Prices in China and the US.

There is significant uncertainty, however, regarding fuel prices going forward. Ma and Oxley (2010) address tentative moves by the Chinese government towards energy market deregulation, which may bring down energy prices. Deregulation faces significant barriers and challenges, however, surrounding the future of energy regulation and resulting prices in China with uncertainty (Ma et al., 2009). Despite the uncertainty, Ma et al. (2009) emphasize the need for energy pricing reform in China, particularly in the response of prices to demand, because of the need to manage transportation system congestion and environmental emissions.

The consumption of fuel leads to environmental externalities in the form of local and global pollutants, both of which have reached large levels in China. Regarding global Greenhouse Gas (GHG) emissions, China surpassed the US in 2007 and ranked first on the Carbon Dioxide (CO_2) emissions country list. Emissions of CO_2 have not slowed, as CO_2 emissions in China grew from 6.8 billion metric tons in 2007 to 8.3 billion metric tons in 2010, accounting for 26.4% of global 2010 CO_2 emissions (United Nations Statistics Division, 2013). Emissions from aircraft are particularly significant, as GHG emissions at altitude can be particularly harmful in terms of an increased warming effect (Williams at al., 2002). Aircraft also emit local pollutants such as CO, NO_x, and PM during their ground taxi procedures, which have a strong impact on human health (Chester and Horvath, 2009). Local pollutants are a significant concern in China, as many major Chinese cities suffer from PM2.5 concentration much higher above World Health Organization standards (Tan, 2013). The small particles generated from burning fossil fuels contribute to significant number of fatal respiratory diseases and premature deaths (Winter, 2013).

While the aviation industry continually seeks improvements in fuel efficiency, this share is expected to increase as other transport modes shift away from carbon-based fuels. Such an action will further increase the pressure on the aviation sector to reduce GHG emissions (Yang et al., 2009). Additionally, aviation in the European Union is now included in emissions trading, effectively increasing the cost of fuel; as environmental concern intensifies, so does the threat of fuel price increases from a mix of market forces and environmental charges.

The severity of environmental issues in aviation prompted action from the Chinese government and the aviation industry. The CAAC identified reducing emissions as the major environmental goal for the aviation industry in their Twelfth Five-Year Plan covering the years 2011 to 2015. The CAAC requires that airlines utilize energy efficient technologies to reduce fuel consumption in every stage. The recommended technologies include winglets on aircraft, upgraded aircraft engines, and replacing Auxiliary Power Units (APUs), which run on fuel, with ground devices that run on electricity (CAAC, 2011). CAAC also requires airports to be constructed and operated with new materials and renewable energy to mitigate environmental pollution. To help airlines and airports adopt CAAC-recommended technologies, the CAAC document titled "CAAC Energy Conservation and Emission Reduction Funding Program Guidelines" (CAAC, 2013) outlines environmental initiatives supported by a CAAC funding program. In 2012, 254 projects received 300 million yuan (approximately 49 million US dollars assuming a conversion factor of 6.12 yuan/1 USD) to support their projects (Wang, 2013). These projects will lead to reductions in fuel consumption and environmental emissions, yet the gains are expected to be modest compared with changes in aircraft types, confirmed empirically by Ryerson and Hansen (2013). In addition, Ryerson et al. (2013) find that the benefit pool for surface emissions can be overestimated because airlines have already streamlined their surface operation, leading surface-based initiatives to smaller potentials than expected.

The focus on environmental pollutants brings fuel savings to the forefront of future CAS planning. However, despite the significant potential of turboprops to reduce fuel consumption and to manage fuel cost fluctuations, the use of turboprops for short-haul aviation travel is not included in the CAAC guidelines nor is investment in low-emission aircraft supported by the CAAC funding. Towards informing guidelines on aircraft investments in addition to modifying operations, we seek to understand the potential role of turboprops in the CAS in the present aviation network and in the future planned aviation network. We are interested in the spatial distribution of networks best served by turboprops as well as the potential benefit of turboprops, towards providing guidelines for including turboprops in a state-based energy conservation plan. To do so, we collect information on existing and future short-haul air travel in China. We investigate statistics and spatial patterns to understand Chinese short-haul, lower density aviation today. The spatial analysis and supporting empirical models are used to estimate the gains and losses from transitioning the existing regional jet fleet with a fleet of turboprops.

II. DATA COLLECTION

To support our analysis, we collect Chinese airport data and scheduled flight data as well as travel time and fuel consumption data related to regional jets and turboprops.

A. OpenFlights Airport Database 2012

We collect latitudes and longitudes for 181 Chinese airports from OpenFlights, an open source resource for airport locational data. The data includes airport names, city names, country names, International Air Transport Association (IATA)/Federal Aviation Administration (FAA) codes, and latitudes and longitudes for all the airports.

B. Scheduled Flight Data

All intra-China scheduled arrival and departure operations for July 18, 2013 (the third Thursday of the month, a common aviation planning day) are collected from masFlight, an aviation data company. From this data, we restrict our analysis to flights on aircraft that are less than 180 seats. This dataset includes, among a host of variables, origin, destination, aircraft type, number of seats per operation, and market carrier for each flight.

C. Aircraft Travel Time

Towards modeling travel time, we use the average cruise speed of turboprops (320 mi/hr) and regional jets (530 mi/hr) found empirically in the scheduled flight data. Throughout the analysis we will be most interested in the relative travel times rather than the absolute travel times; for this reason, we use the average cruise speeds and not traditional models of block time (such as in Ryerson and Hansen, 2010). This also avoids any distortions to block time because of airport congestion or airline practices.

D. Fuel Consumption Data and Model

To capture fuel consumption for the different aircraft types, we utilize two fuel consumption models estimated by Ryerson (2010). The fuel consumption models are a function of the two variables which are the key drivers of fuel consumption (*F*), distance and seats. The estimated models for turboprops and jets are shown in (*1*), with all coefficients significant at the 1% level. The data utilized in the model is based on US fuel consumption from the Bureau of Transportation Statistics, due to data availability. While the model formulation is simple, Ryerson and Hansen (2013) find that models of aviation cost can be well captured by simple models that assume a Leontief production process (the inputs are entered in fixed proportions) compared with more complex models allowing for input interaction. As fuel is a large component of operating cost, we generalize this result to the fuel consumption models.

$$\begin{aligned} F_{tp} &= 0.495 * distance + 2.030 * seats \\ F_{rj} &= 2.392 * distance + 3.488 * seats \end{aligned} \tag{1}$$

It is clear from the relative values of the coefficients in (*1*) that turboprops burn less fuel per seat and per mile compared with jet aircraft.

III. TURBOPROPS AND THE CURRENT CAS NETWORK

In this section we explore the role of turboprops in the current Chinese aviation network. We begin by exploring the short-haul Chinese air transportation network.

A. Spatial Trends for Short-haul Aviation

We begin by exploring the flows of regional jets and turboprops based on our scheduled flight data. We create geodetic two-point line features from an array of start and end points to visualize the flight routes (matching the OpenFlights airport dataset with the scheduled flight data) between origins and destinations in ArcMap 10. The resulting flowlines are color-coded according to the two aircraft types. We begin with Figure 2 which includes all 655 flights on regional jets and 70 with turboprops.

This map shows the dominance of regional jets over turboprops in the Chinese short haul aviation market. Regional jets knit eastern China together, connecting smaller cities with hubs and providing direct service between secondary cities. They are particularly prevalent in Western China. The top five regional jet hubs with the largest number of feeder routes are Urumqi (Northwestern China), Xi'an (Central China), Hohhot (North Central China), Tianjin (Northeast China), and Guangzhou (Southeast China). Overall, there are seven airlines operating 655 flights on regional jets including two of the major Chinese carriers, China Southern Airlines (CZ) and China Eastern Airlines (MU), along with the regional carriers Shandong Airlines (SC), Tianjin Airlines (GS), Shanghai Airlines (FM), China Express Airlines (G5) and Northeast Airlines (NS).

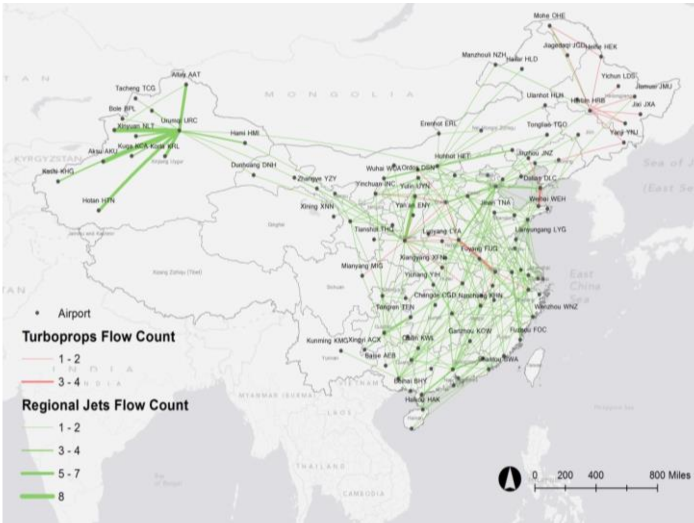

Figure 2. Flight Connections in China.

Compared with regional jet service, turboprops exhibit more spatial concentration and a narrow range of distances. Turboprops are concentrated in Northeast China, as well as the intersection of North China, Northwest China, and South Central China. The turboprop flights in Northeast China are operated by Okay Airways. The main hub of Okay Airways is Tianjin Binhai International Airport in North China. Okay Airways does not operate turboprops from the hub, but rather operates turboprops in Northeast China from Harbin with seven feeder routes into nearby second-tier cities. The operator of turboprop flights in Central China is Joy Air, a subsidiary of China Eastern Airlines. The turboprop network in central China consists of several hubs with a few feeder routes. The current turboprop hubs there include Xi'an (Joy Air's . with five feeder routes), Taiyuan (4 feeder routes), and Zhengzhou (4 feeder routes). The three hubs are also inter-connected by turboprops. While there are multiple operators of turboprops, all the turboprops in China are Xian MA-60 manufactured by Xi'an Aircraft Industrial Corporation.

Figure 2 illustrates that turboprop flights serve a narrow range of very short-haul flights while regional jets serve both very short haul flights and longer haul flights (such as between Western and Central China). To explore the difference in catchment areas of the aircraft types in the current Chinese network, we identity the key hubs of turboprops and regional jets and calculate the 75th and maximum distance flight from that hub. Table 1 includes results for both turboprops and regional jets; because of the large number of regional jet routes, the top five hubs based on the number of feeder routes are displayed. The ranges of turboprops routes are significantly less those of regional jets. Generalizing the 75th percentile and the maximum distance turboprop flights from each turboprop hub into catchment areas (Figure 3), we see that much of Northeastern and Eastern China falls in the catchment area of the turboprop hubs.

Table 1. Statistics of Turboprop and Regional Jet Flight Connections in China.

Hub	Apt Code	# Route	Radius 75th Perc (Miles)	Radius Max (Miles)	Region China
Turboprops					
Harbin	HRB	7	282	342	NE
Xi’an	XIY	5	312	313	NE
Taiyuan	TYN	4	276.5	313	North
Zhengzhou	CGO	4	275	289	South
Dalian	DLC	3	127	192	NE
Hefei	HFE	3	275	275	East
Regional Jets					
Urumqi	URC	56	408	1,308	NW
Xi’an	XIY	32	690.5	1,308	NW
Hohhot	HET	29	564	1,255	North
Tianjin	TSN	28	574	1,386	North
Guangzhou	CAN	22	709	1,112	S

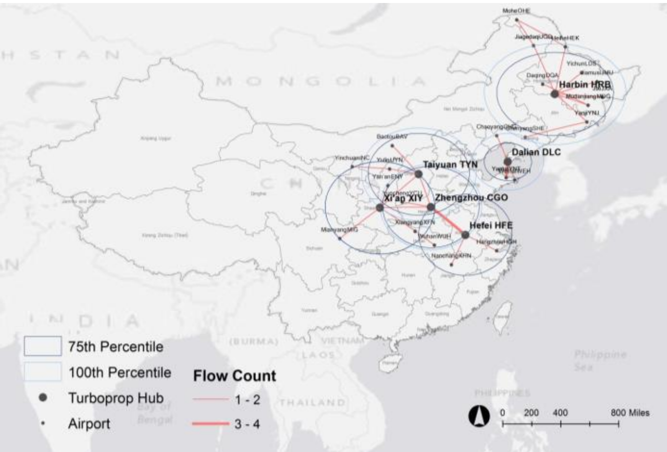

Figure 3. Turboprop Flight Connections in China and Catchment Areas.

B. Regional Jet and Turboprop Trade Space

Figure 3 indicates turboprops could be more widely deployed. Towards exploring their potential, we estimate the benefits and costs of the system if regional jet routes were replaced with turboprops.

1) Distance-based Aircraft Replacement

We begin by spatially depicting regional jet routes that could be replaced by turboprops. Figure 4 shows the regional jet routes that would be replaced if we limited the replacement to flights of a distance less than the 25th percentile of regional jet flight distances across the network ((a) 266 miles); the 50th percentile ((b) 402); the 75th percentile ((c) 576); and all flights ((d) 1,308 miles). The small gap between the 50th and 75th percentile of regional jet flight distances indicates that there are many flights in the under 600-mile category for regional jets. The 75th percentile of flight distances for regional jets, 600 miles, is well within the technical range of the MA-60 turboprop, but the maximum distance regional jet route is not. We see from Figure 4(a) that if our strategy is to place turboprops on the shortest regional jet flight routes first, the flights will be spatially distributed across the country. Within this spatial distribution we see many hubs emerge with connections less than 266 miles, particularly in the Northwest, the Southeast, and the Northeast. As we increase the distance threshold for replacement, we see these hubs increase in intensity as far as the number of connections to be served by turboprops. This indicates that the deployment of turboprops might be well suited to be a state-led strategy targeted at airlines, allowing them to redefine their hub connections with lower emissions turboprops.

2) Fuel and Time Trade-offs

Certainly, 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. To estimate this trade-off we monetize time and fuel to explore the distance-fuel price trade space between regional jets and turboprops. The monetization of fuel is straightforward, as fuel price is published and shown in Figure 1. The monetization of time is more nebulous, and requires a Value of Time (VoT) metric. VoT in transportation is typically estimated through discrete choice models that capture how a decision maker trades time, cost, and other attributes. VoT is then the marginal rate of substitution between the time and cost inputs.

Estimates of VoT exist in the US-based air traveler literature. Using a combination of revealed and stated preference surveys for air transportation users, Adler et al. (2005) use a mixed logit model to estimate the value of flying time, schedule delay, and on-time performance assuming all non-fixed parameters are normally distributed. Adler finds that the value of time for in-vehicle time for a business traveler is \$69.70/hour and for a leisure traveler it is \$31.20/hour. Ball et al. (2010) use a value of time of \$37.6/hour for a study of US aviation delay for the Federal Aviation Administration.

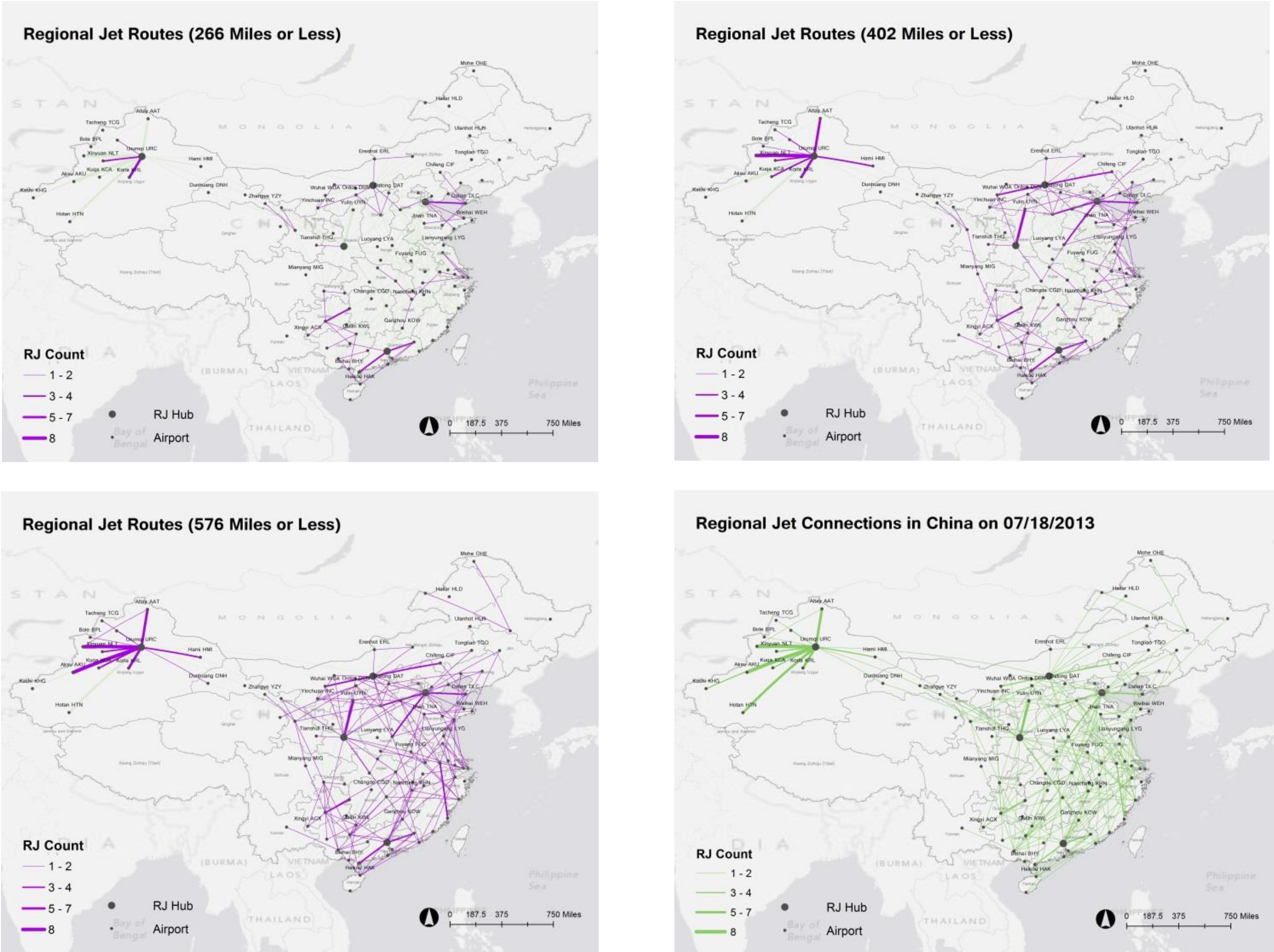

Figure 4(a-d). Candidate Regional Jet Routes for Replacement.

There is less understanding of VoT in developing countries. In presenting a methodology to estimate VoT for developing countries, Walker et al. (2010), in a case study of commute mode in Chengdu, China, notes the dearth of estimates of VoT for Chinese travel. The authors 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). In a study using survey data from transportation users in Shanghai in 2001, Liu (2006) 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). These values are consistent across the two studies, however, the sample population is of local travelers and not air travelers, who are likely to have higher values of time.

Towards gaining more insight into Chinese VoTs, we explore spatial and temporal trends in the wage rate. In 2011, the per capita personal income in China was $3,560, and Shanghai had the maximum average income for a province at $6,622.90 (National Bureau of Statistics of China, 2013). Comparatively the average income in the US was $41,560 in 2011 (University of New Mexico, 2013). If the US VoT for air travelers is $37.60/hour, we can estimate that a commensurate VoT for China based on the wage rate is $3.22/hour on average and $6.00/hour for the maximum income province of Shanghai. There is, however, a significant wage gap in China as well as rapid income growth. While personal income in the US increased 32% from 2002 to 2011, per capita personal discretionary income in China increased 183% during the same time period. From 2002 to 2011, the standard deviation of per capita annual discretionary income by province in China also increased from $328.94 to $876.27, reflecting an expanding income disparity between regions in China. In 2011, the highest average annual discretionary income by province was $5,920 in Shanghai on the east coast, and the lowest was $2,449.1 in Gansu in the west inland, highlighting the spatial differences in economic conditions.

In short, establishing a VoT that is both credible and inclusive is a challenge, particularly in China. For this reason, we design a metric titled the *break-even VoT*. This is the VoT for which the fuel savings and increased travel time incurred if a turboprop is used in place of a regional jet are equal. The break-even VoT indicates the maximum VoT for which turboprops are still an economically viable option. In short, if VoT for Chinese travelers is greater than the calculated metric, regional jet operations should not be replaced with turboprops. The metric, termed $\widehat{VoT_{\alpha\rho}}$, is formulated as a function of the fuel consumption and travel time of a flight:

$$\widehat{VoT_{\alpha\rho}} = \frac{\sum_i \alpha\left(\widehat{F_i^{rj}} - \widehat{F_i^{tp}}\right) I_i(\rho)}{\sum_i \left(\widehat{TT_i^{tp}} - \widehat{TT_i^{rj}}\right) I_i(\rho)} \qquad (2)$$

Where

$\widehat{F_i^k}$ is the estimated fuel consumed in gallons for flight *i* on aircraft *k* (turboprop, regional jet $\ni k$) using the equations estimated in (*1*) and the scheduled flight data

$\widehat{TT_i^k}$ is the estimated travel time for flight *i* on aircraft *k* estimated using the average cruise speed for aircraft type *k* and the travel distance for flight *i* in the scheduled flight data

α is the price of fuel in \$/gallon, to be considered parametrically from \$3.00/gallon to \$5.00/gallon, consistent with recent historical Chinese jet fuel prices

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

The aircraft replacement algorithm is done in two ways. First, we do a seat by seat replacement such that we estimate $\widehat{F_i^k}\ \forall k$ as a function of the number of seats for flight *i* (the number of seats per flight is reported in the scheduled data). By assuming aircraft size is continuous we allow for the notion of direct aircraft size replacement. Second, we assume all turboprops have 50 seats, and, if flight *i* is on a regional jet with more than 50 seats, we replace it with two turboprops. This is a conservative, estimate that provides an upper bound (or, a lower bound break-even VoT) for analysis.

The quantity $\widehat{VoT_{\alpha\rho}}$ presented in Tables 2a&b 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 α. A switch to turboprops is justified if $\widehat{VoT_{\alpha\rho}} > VoT$, where VOT is the average value of passenger time for intra-China aviation. When $\widehat{VoT_{\alpha\rho}} > VoT$, the savings per passenger from switching to turboprops is more than the value of passenger value of time. Overall, 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. We note that $\widehat{VoT_{\alpha\rho}}$ decreases with increasing ρ, as it is less attractive to switch a regional jet with a turboprop over longer distances. $\widehat{VOT_{\alpha\rho}}$ also increases with fuel price, as regional jets are less fuel efficient than turboprops.

Table 2a. Break-even VoT with Seat-by-Seat Replacement.

	Fuel Price (\$/gal)	Seat-by-Seat Replacement (\$/hour)		
		3.00	**4.00**	**5.00**
Distance percentile	25%	77.4	103.2	129.1
	50%	71.4	95.2	119.0
	75%	67.9	90.5	113.1
	100%	64.2	85.6	107.0

Table 2b. Break-even VoT with Full Aircraft Replacement.

	Fuel Price (\$/gal)	Full Aircraft Replacement (\$/hour)		
		3.00	**4.00**	**5.00**
Distance percentile	25%	66.3	88.4	110.5
	50%	58.2	77.6	97.0
	75%	53.4	71.2	89.0
	100%	48.6	64.8	81.1

IV. Conclusion

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. Our study motivates the inclusions of turboprops in the state-led initiatives to support aviation sustainability. In defining new metrics for analysis, such as the break-even VoT, and in exploring the spatial patterns of the current and future short-haul CAS, we find a large role for turboprops in the CAS. More specifically, 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. After years of growing the aviation system in the east, the CAAC has made Western and Southern China a priority. Because of the potential of turboprops to serve these areas with lower fuel costs and reduced environmental impact at a high enough level to well balance the increase in travel time for passengers, supporting the deployment of turboprops directly through the sustainability fund is a move of support for the emerging aviation markets of China.

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