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Authors

Smirti, Megan
Hansen, Mark

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Megan Smirti, Mark Hansen
University of California, Berkeley

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Megan Smirti[a]*, Mark Hansen[b]

[a]PhD Candidate
University of California, Berkeley, National Center of Excellence for Aviation Operations Research,
109 McLaughlin Hall, Berkeley, CA 94720-1720, USA
E-mail address: msmirti@berkeley.edu
*Corresponding Author
Telephone: 415-816-0925
Fax: 510-642-5687

[b]Professor of Civil and Environmental Engineering
University of California, Berkeley, National Center of Excellence for Aviation Operations Research,
114 McLaughlin Hall, Berkeley, CA 94720-1720, USA
E-mail address: mhansen@ce.berkeley.edu

Abstract

Aviation system planning, particularly fleet selection and adoption, is challenged by fuel price uncertainty. Fuel price uncertainty is due fuel and energy price fluctuations and a growing awareness of the environmental externalities related to transportation activities, particularly as they relate to climate change. To assist in aviation systems planning under such fuel price uncertainty and environmental regulation, this study takes a total logistic cost approach and evaluates three representative aircraft (narrow body, regional jet, and turboprop) for operating and passenger preference costs over a range of fuel prices. Homogenous fleets of each vehicle category are compared for operating and passenger costs over a range of fuel prices and route distances and the minimum cost fleet mix is determined. In general, as fuel prices increase, the turboprop offers a lower cost per seat over a wider range of distances when compared with both jet aircraft models. The inclusion of passenger costs along with operating costs decreases the fuel price - distance space where the turboprop exhibits the lower cost. This analysis shows that the lowest cost aircraft selection is highly sensitive to fuel prices and passenger costs, and points to the important balance between saving fuel and serving passengers. The conclusion that high fuel prices rationalize major changes in fleet composition despite higher passenger costs have implications for airlines and aircraft manufacturers when considering aircraft adoption and manufacturing strategies under future fuel price scenarios.

Keywords: Aircraft; Fuel; Operating Cost; Turboprop

1. Introduction

The market price for aviation fuel increased rapidly from 2004 to 2008. Figure 1 shows the wholesale cost of aviation fuel from the beginning of 2000 to mid-2009. To offset growing oil prices, airlines and manufacturers strive to continually improve their product through innovative technology and procedures. Such actions resulted in modest efficiency growth compared with the peaks of fuel fluctuations seen (ATA, 2008). Many major airlines announced capacity cuts during the first half of 2008, introducing the possibility that the current arrangement of interregional air transportation is not efficient in consideration of increasing fuel costs (Schlangenstein, 2008; BTS, 2003). After the summer of 2008 fuel price spike, fuel prices fell to lows seen in 2004 (EIA, 2009). Such volatility motivates a methodology that evaluates aviation system costs over a range of fuel prices.

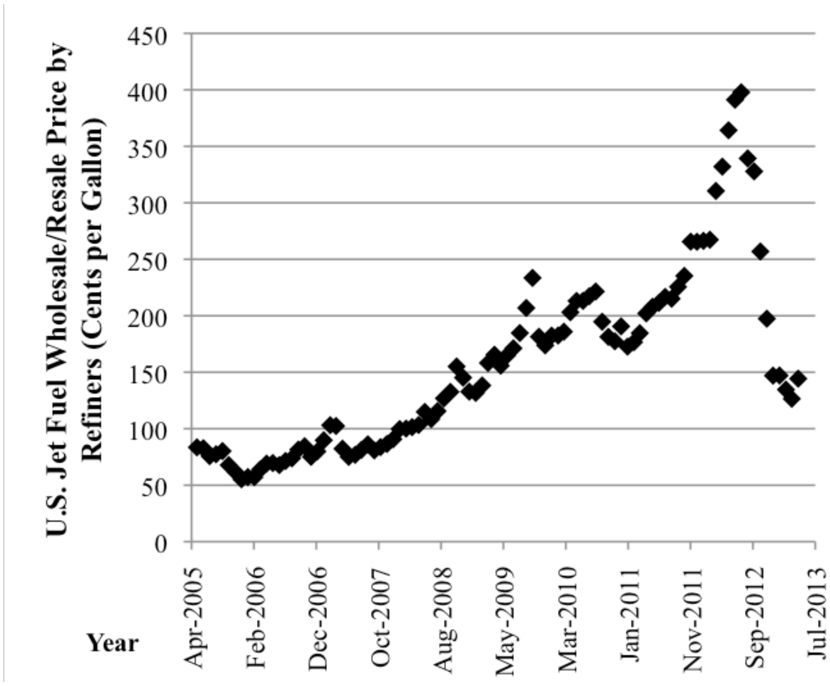


FIGURE 1 U.S. Jet Fuel Wholesale/Resale Price by Refiners, in Cents per Gallon, 2000-2009.

In addition to fuel price fluctuations, cost uncertainties arise due to the emission of greenhouse gases (GHG), the gases which cause climate change. Transportation plays a major role in GHG considerations because the use of all transportation fuels increases levels of GHG. In the United States, the transportation sector is responsible for 27 percent of all GHG emissions, making it the second largest end use sector after electric power generation. Aviation accounts for 10 percent of transportation emissions, or about 3 percent of total (EPA, 2008), but this share is expected to increase as other transport modes shift away from carbon-based fuels (Yang et al., 2009). State, federal, and international initiatives are encouraging aviation to reduce GHG emissions through a variety of policy initiatives. Many of these involve market mechanisms that would effectively increase the price of fuel. At an international level, for example, ICAO is investigating an open emission trading system for aviation and the European Commission has announced a legislative proposal for the inclusion of aviation in the European Union Emissions Trading Scheme (Wit et al., 2004; Scheelhaase and Grimme, 2007). The evolution and impacts of GHG reduction policy thus add further uncertainty about the future price of fuel.

In light of the wide range of future fuel price scenarios, it is important to understand how fuel price affects the comparative advantage of alternative air transport technologies and vehicles. For example, while recent years have witnessed a shift away from turboprops toward regional jets, it may be that, since turboprops are more fuel efficient, increasing fuel prices could reverse this trend. This would have important implications for airport planning as well as airframe manufacturer strategy. The objective of this study is therefore to compare representative aircraft for their operating costs and passenger costs over a range of fuel prices. The range of fuel prices reflects uncertainties about future market conditions as well as environmental policy choices.

This study compares the operating and passenger cost of turboprops, noted for their low fuel consumption, with two widely deployed aircraft, a regional jet and a narrow body jet. Operating costs include fuel, crew, maintenance, and airport costs. Passenger costs include travel time costs (flying time differences and schedule penalties) and the perceived disutility of flying on turboprops (relative to jets). By combining passenger and operating costs in a single function, this study takes a total logistic cost approach. This allows vehicles with different cost structures and service attributes to be compared. This study will perform these comparisons over wide ranges of distances and fuel prices to identify the combinations of values of these parameters at which the different aircraft models can serve segments with the lowest cost.

The remainder of this paper is organized as follows: Section 2 reviews existing aircraft cost comparison studies and methodologies. Section 3 introduces the three aircraft to be compared and derives key relationships based on stage length for fuel consumption and flying time. These cost relationships are then combined to achieve a single operating cost model equation, and this equation is used to compare the operating costs of the different aircraft under different fuel prices (§4). Passenger preferences for jet aircraft, short in-vehicle time, and frequent service are introduced to determine the balance of operating cost and passenger costs aircraft exhibit (§5). The potential market penetration of turboprops in the under-1000 mile market is evaluated in Section 6. The study concludes in Section 7 with a discussion of how fuel price uncertainty impacts minimum cost fleet composition.

2. Review of Aircraft Cost Comparison Studies and Methodologies

Several previous studies modeled and compared operating costs for airlines. These studies employ models to look for aircraft with the lowest operating costs as a function of segment characteristics such as stage length and market density. Douglas and Miller (1975) develop comparative aircraft cost models that divide operating costs which vary per user into fixed and variable costs. Using cost models developed in this manner, with fixed components and components that vary with distance and traffic, aircraft costs are compared. When discussing an efficient airline market, Douglas and Miller (1975) qualitatively discuss fleet assignment based on passenger preferences but stop short of developing an integrated passenger and operating cost model. In a similar study, Oster and McKey (1984), compared the operating costs of different commuter aircraft and performed a parametric analysis of operating cost versus stage length is performed.

The importance of considering a total logistic cost function with passenger and operating cost rather than individual cost components is demonstrated in two studies by Wei and Hansen (2003; 2005). Wei and Hansen (2003) develop a translog cost model for jet aircraft operating cost. It is found that airlines could decrease operating costs by upgauging from the sizes they typically employed during the study period. Such findings are balanced with the conclusions of a second study by Wei and Hansen (2005). Using a nested logit model, the study finds that an airline's market share experiences greater increases from increasing vehicle frequency rather than aircraft size. These findings point to the importance of balancing airline operating cost and passenger preference costs when choosing fleet mix and determining flight schedules.

Viton (1986) addresses this trade off by formulating and maximizing a net benefit function to maximize net benefit that includes both user costs and operating costs. The function depends on flight frequency, traffic level, and fare. When optimized, user benefit of increased frequency and the use of higher service quality aircraft are balanced by the marginal cost incurred to the carrier. The model is then used to empirically assign distinct aircraft types to travel corridors, using standard values for stage length, value of time, and fuel prices. Beyond aviation, total cost studies, considering a combination of operating passenger, and infrastructure costs have a long history in urban transportation (Meyer and Miller, 1984). This study includes both operating and passenger costs in the same function in a manner similar to Viton (1986), while allowing both fuel price and distance to vary parametrically.

In this study, we interpret fuel price to derive from both GHG reduction policies and market conditions. GHG emissions are strongly correlated with fuel burn; this is the rationale for policy proposals such as carbon taxes, which translate directly into changes in the price of fuel (Brueckner and Zhang, 2009). Other policy proposals, such as cap-and-trade, can also be portrayed as fuel price increases. An emissions cap is essentially a resource constraint imposed on the production process, and it is well known that such constraints can be represented through shadow prices on the associated resources (Plaut, 1998). There are other mechanisms through which aircraft flights affect climate, such as contrail formation, that are not related to fuel burn (Waitz et al., 2004). These are not considered in our analysis.

The motivation behind considering GHG regulation through the lens of a fuel price increase stems from the varied methods to calculate GHG emissions and the political challenges related to defining the emission owner. The methods developed to calculate GHG emissions from aircraft operations span from basic to detailed. The Environmental Protection Agency (EPA) performed a GHG inventory aviation in which they multiplied the jet fuel sold in the United States, the jet fuel carbon coefficient from the Energy Information Agency, and the percent of fuel combusted (99 percent) (EPA, 2008). More detailed methodologies for calculating GHG emissions include those of the Federal Aviation Administration (FAA), the European Environmental Agency (EEA), and the German Research Labs; each have developed systems to calculate GHG emissions from flight trajectories moving through the airspace (Kim et al., 2007; EEA, 2006; Scheelhaase and Grimme, 2007). Other calculation methods involve political consideration of the GHG emission owner such as the San Diego County Regional Airport Authority’s (2008) separation of aircraft emissions below 3,000 feet and above in their inventory. This study develops a method to evaluate GHG regulation in the form of fuel taxes without explicitly calculating GHG emissions.

3. Model Formulation

Let the total logistics cost per passenger to serve a segment with aircraft type □ be (travel time.

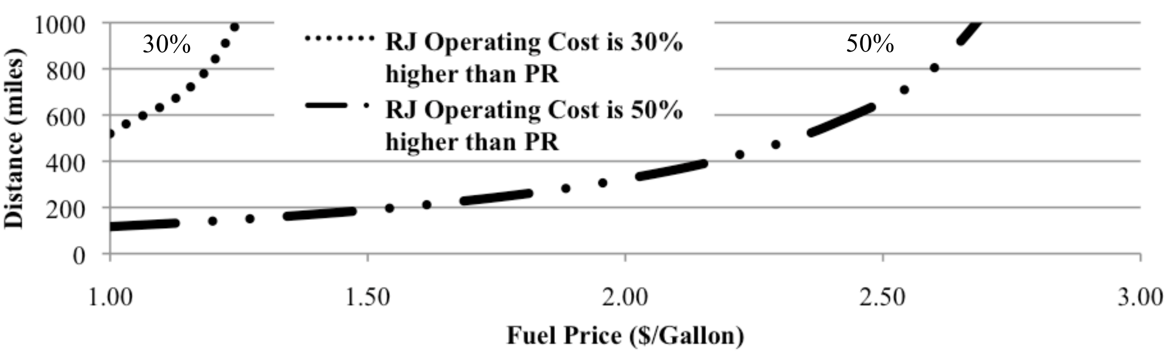
When costs are considered on a per passenger basis the regional jet has consistently higher values than the narrow body. The lower seat capacity of the regional jet means costs are spread among fewer passengers. The costs that vary with distance alone is still highest for the turboprop, and therefore, while all other costs are lower, distance appears to be the factor which will constrain the region for which turboprops can offer lower costs. Section 5 explores how these differences translate into the minimum cost homogenous vehicle fleet based on operating cost.

4. Parametric Operating Cost Comparison

We use the operating cost functions in Table 5 to compare the costs of the three aircraft models over a range of distances and fuel prices. Difference in operating cost per passenger for two pairs of aircraft, the regional jet and the turboprop and the narrow body and the turboprop, are compared using contour curves representing a percent difference in operating cost. The calculations of percent difference in operating cost are done for varying distance and fuel price. Such a procedure allows for simple identification of the combinations of fuel price and distance for which a given aircraft has a cost advantage. In each chart, the middle dashed line represents the two aircraft being compared having an equal operating cost per passenger. The region under the middle dashed line represents the fuel price-stage length region where a turboprop has a lower cost per passenger; the region above the middle dashed line represents the fuel price-stage length region where the jet aircraft being compared has a lower cost per passenger. The percentage labels are based on the jet aircraft in comparison to the turboprop: 20% means the jet has a 20% higher operating cost than the turboprop, while -20% means the jet has a 20% lower operating cost than the turboprop.

A fuel price and distance combination (for distances under 1000 miles) for which the regional jet has a lower or equal operating cost per passenger compared with the turboprop does not exist because the regional jet has a higher operating cost per passenger than the turboprop for all fuel prices and stage lengths. Therefore, Figure 2 shows a contour plot for the regional jet and turboprop comparison with two curves, one for where the regional jet has a 50% higher operating cost per passenger than the turboprop, and the other for 30% higher. This is an atypical chart, due to the fact the regional jet consistently has a higher operating cost per passenger. This is due to the higher per passenger fuel consumption and block time for the regional jet as seen in Tables 2 and 3.

Figure 2 shows a contour plot for the narrow body and turboprop comparison. In this comparison, there are fuel price and distance combinations for which the two aircraft models have an equal operating cost. This equal operating cost curve exists in the sub-1000 mile distance region for fuel prices up to $4.00/gallon. The curves above and below the zero percent difference curve represent the narrow body holding a 20 percent higher and lower operating cost compared with the turboprop, respectively. The narrow body has a 20 percent higher operating cost per passenger than the turboprop for all stage lengths up to 1000 miles when the fuel price equals levels seen in the summer of 2008, $4.30/gallon. At a price of $2.00/gallon, the situation is dramatically different, with the narrow body jet having a lower cost per passenger than the turboprop for stage lengths greater than 300 miles. As anticipated, the turboprop is very cost competitive over short distances because of the lower fixed and higher variable costs with distance.



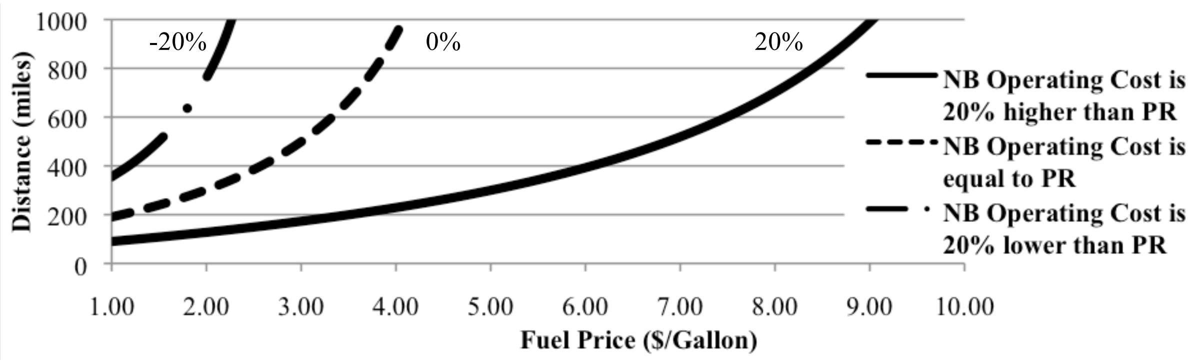


FIGURE 2 Percent Difference Operating Cost per Passenger Contour Curve for Regional Jet and Turboprop Comparison and Narrow Body and Turboprop Comparison.

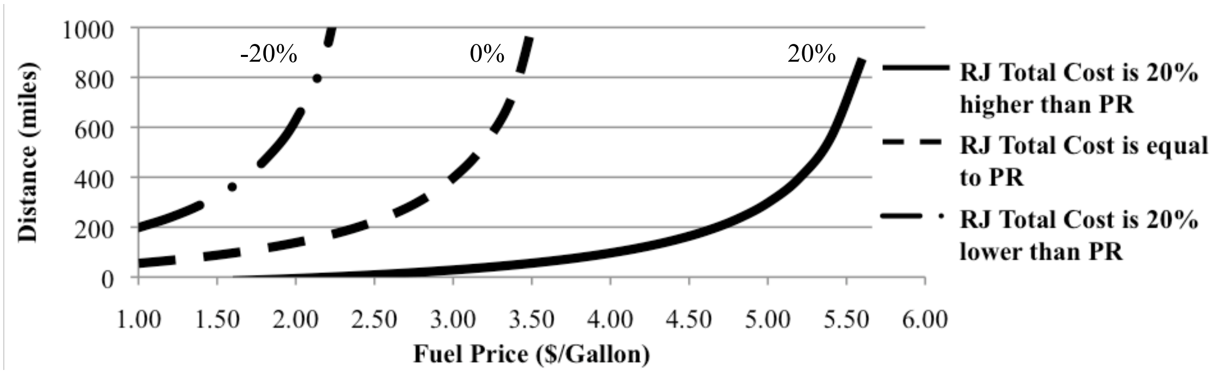
There are additional factors beyond operating cost to be considered when comparing aircraft economics; to this end, Section 5 will include passenger time valuation and differences in willingness to pay for service on different aircraft type.

5. Passenger Cost Model

We now consider the passenger cost component of the total logistics function,□, described in Section 3.

6.1 Cost of Flying Time and Turboprop Disutility

The cost of flying time for each aircraft type is the flying time function multiplied by a passenger value of time, y dependent on the monetization of passenger costs. Considering this total logistic cost, narrow body jets have a lower cost per passenger compared to turboprops under a wide range of fuel prices and distances. When only operating costs are considered, narrow body jets have a higher operating cost per passenger when compared with turboprops for fuel costs above $4.00/gallon.



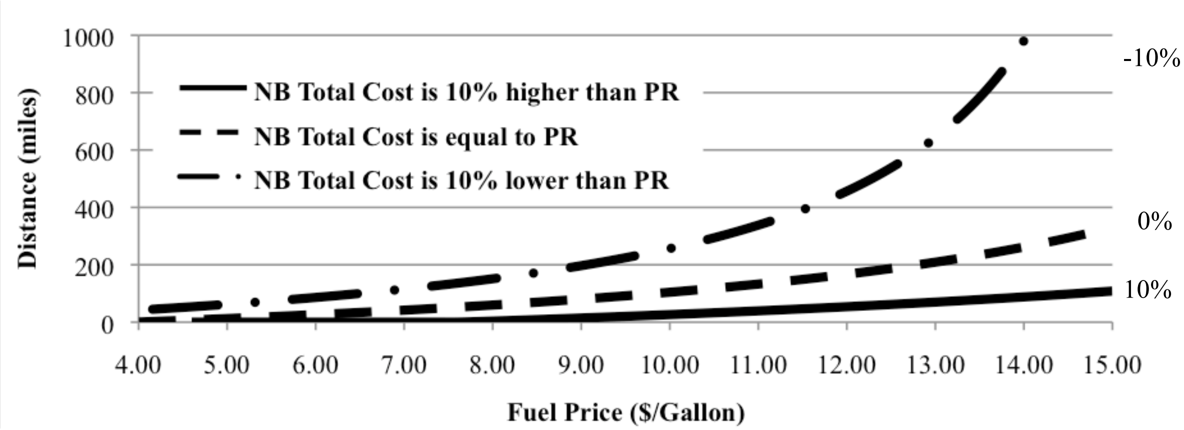


FIGURE 3 Percent Difference in Total Cost per Passenger Contour Curve for Regional Jet and Turboprop and Narrow Body and Turboprop Comparison.

6.4 Value of Frequency

The inclusion of frequency highlights the difference in operating aircraft with a wide range of seat capacities. The range of seating capacities means that a fixed number of passengers can be served by a different number of flights depending on the fleet selection. Passengers place value on the difference between desired arrival time and actual arrival time, and the frequency of service is included into passenger costs. The value of the difference between a passenger's desired arrival time and actual arrival time, termed schedule delay, was estimated by Adler et al. (2005). Passenger value of frequency was captured through passenger WTP for flights of varying flight times around the desired time. Delays in either direction (early or late) were considered to be equally onerous.

To capture the impact of providing more frequent service, a relationship between frequency and schedule delay must be identified. Abrahams (1983) reviews a relationship developed by Eriksen (1978) for schedule delay based on flight frequency. The equation was estimated to account for schedule peaking and does not assume that flights are uniformly distributed in time. Equation (13) shows the schedule delay function, termed □(·) in section 3, in hours developed by (Eriksen, 1978). The function is based on a route with origin i and destination j. The equation for flight frequency (12) is determined by rison between the turboprop and narrow body, at fuel prices under $2.00/gallon, the fraction of passengers which could be carried on a turboprop with less total cost per passenger than the narrow body is 20 percent. As fuel prices increase, the fraction increases slowly, ultimately reaching 80 percent at $14/gallon.

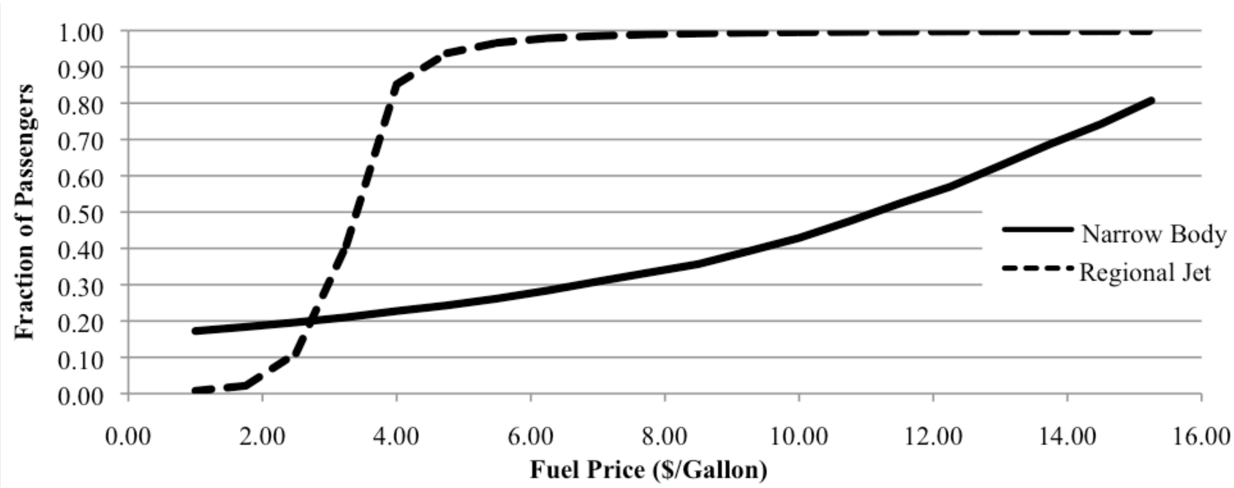


FIGURE 5 Potential Fraction of Passengers Served by a Turboprop with the Lowest Comparative Total Cost Per Passenger Compared with a Regional Jet and a Narrow Body.

Beyond the aircraft pair comparisons shown in Figure 5, a comparison between the three aircraft (Figure 6) gives an overall picture of the fraction of passengers that can be served on a turboprop at the minimum total cost per passenger. This fraction begins at 1 percent for a fuel price of $2.00/gallon, increases to 10 percent at a fuel price of $4.00/gallon, and reaches 80% at $15.00/gallon. An assumed future carbon tax of $1/gallon can be added to these base fuel prices to understand the change in percent of passengers carried for the least cost on a turboprop. As the slope between $3.00/gallon and $5.50/gallon is the steepest slope in Figure 6, carbon taxes instituted on fuel prices in this range yield the largest percent increases in turboprops offering the lowest cost. For example, for fuel prices of $4.00/gallon plus a $1/gallon carbon tax, the percent of passengers carried for the least cost on a turboprop would jump from 10 to 20 percent. If fuel prices were to double from their summer 2008 highs and reach 8.60 and a $1/gallon tax was added, 40 percent of passengers would be carried for a lower total cost on turboprops compared with 35 percent before the tax.

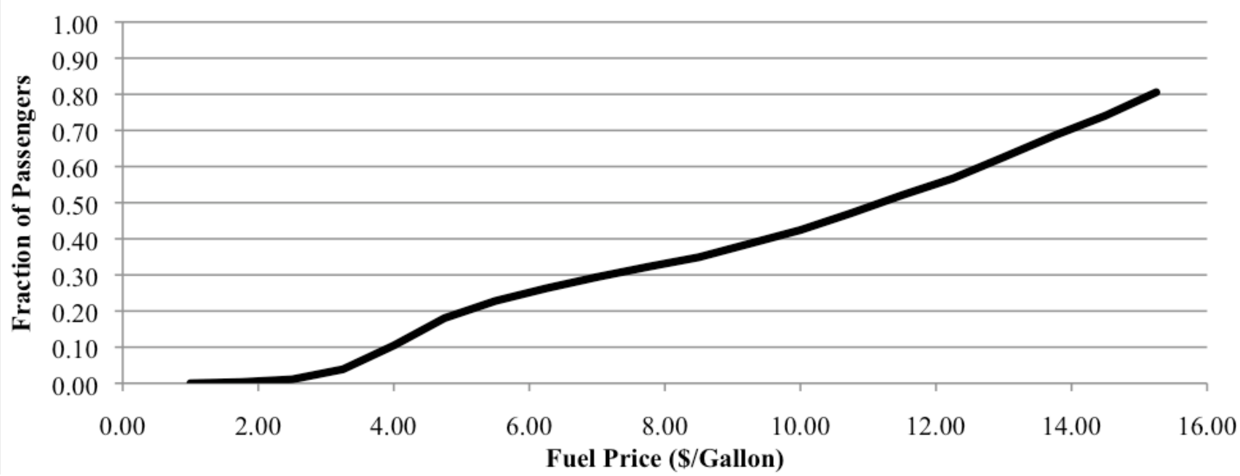


FIGURE 6 Potential Fraction of Passengers Served on a Turboprop for the Lowest Comparative Total Cost Per Passenger.

6. Conclusions

This analysis shows that the determination of minimum cost aircraft operations over distances of 1000 miles or less is highly sensitive to fuel prices and passenger costs. The following section reviews conclusions from the vehicle comparisons, turboprop market penetration potential, and environmental concerns and consequences.

The results of this study show that the popularity of regional jets is due to their relatively low passenger costs when compared with the turboprop. Passengers value the faster flying time, the ability to fly on a jet aircraft, and also the potential for more frequency service. The balance between operating and passenger costs is what makes the regional jet a lower cost aircraft for many stage lengths up to a fuel price of about \$3.50/gallon. At fuel prices seen before and after the 2008 spike, there are many routes for which the regional jet has a lower cost per passenger. For certain stage lengths, it is only the fuel prices spike that made the turboprop a more attractive option over regional jets. The market penetration analysis indicates that at fuel prices just under \$4.00/gallon, 90 percent of passengers can be served on a turboprop for a lower total cost per passenger compared with a regional jet. As fuel prices seen in 2008 were above \$4.00/gallon, we can expect that if fuel prices return to their 2008 highs to see turboprops replacing regional jets over all distances up to 1000 miles.

The cost comparison curve between narrow body jets and turboprops experiences a large shift with the introduction of passenger costs. When operating costs alone are considered, an equal operating cost curve exists (in the sub-1000 mile distance region) for fuel prices up to \$4.00/gallon. As anticipated, the turboprop is very cost competitive over short distances because of the lower fixed and higher variable costs with distance. However, with the introduction of passenger costs, the turboprop loses the advantage over the narrow body aircraft; this advantage is however minimized at low market densities as smaller aircraft are able to serve a low density market with decreased schedule delay, decreasing passenger costs. The market penetration analysis indicates that at fuel prices of \$4.00/gallon, just over 20 percent of passengers can be served on a turboprop for a lower total cost per passenger compared with a narrow body. However, at a fuel price of \$11.00/gallon, the share of passengers served on a turboprop at a lower cost than a narrow body reaches 50 percent, indicating that fuel prices would have to nearly triple beyond their 2008 highs to realize such a high market penetration for turboprops.

The difference observed in the minimum cost aircraft category with the incorporation of passenger costs points to the importance of considering multiple costs when evaluating aircraft types. Aircraft adoption and deployment decisions are made for a variety of reasons. However, as displayed in the results of this study, high fuel costs can overshadow the importance of all passenger costs; the inclusion of other fuel consumption based costs, such as environmental costs, would tip the advantage to the turboprop in both cases.

Results of this study indicate that high fuel prices rationalize major changes in fleet composition despite higher passenger costs. Such a finding allows for the consideration of additional taxes, such as carbon taxes, to encourage airline low-emissions fleet selection to consider environmental and fuel preservation. At fuel prices below $3.00-$4.00/gallon, airlines are encouraged to adopt regional jets which are less fuel efficient in order to keep passenger costs low. This practice can be beneficial for airline costs but runs counter to other policy priorities such as reducing the environmental impact of aviation and fuel conservation.

This study evaluated aircraft currently operated in the US and also presented a method to evaluate aircraft types under fuel price and environmental regulation uncertainty. As this study details specific aircraft, it represents a snapshot of time rather than an evolving fleet. Aircraft advancements, from incremental upgrades to major changes such as the use of alternative fuels for power, will alter the relationship between aircraft categories and is an area for future research. Another area of future research is the incorporation of increased passenger heterogeneity which could alter the impact of passenger preference costs.

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