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**Assessing the Role of Operating, Passenger, and Infrastructure Costs
in Fleet Planning under Fuel Price Uncertainty**

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Abstract — Aviation system planning is challenged by the rapid increase in fuel prices and uncertainty in air traffic management (ATM) charges. As airlines decrease capacity and decommission older aircraft and aviation navigation service providers ponder new ATM charging schemes, a critical question is: which aircraft provide air transportation service for the lowest cost? This study evaluates the introduction of a minimally utilized aircraft type in the United States, the 72-seat turboprop, compared with currently operated narrow body and regional jet aircraft. Homogenous fleets of these vehicles are compared for operating, passenger preference, and ATM costs over a range of fuel prices and the minimum cost fleet mix is determined. Findings include that the regional jet exhibits a higher cost per passenger than the turboprop for the entire fuel price and stage length space when operating costs are considered alone. When passenger costs are considered in addition to operating costs, there exists an equal cost per passenger curve between these two aircraft for fuel prices below \$4.00/gallon. When infrastructure costs are considered, the fuel price and stage length space where the turboprop offers a lower cost increases. The comparison of the turboprop with the narrow body shows that an equal cost curve exists under all cost combinations considered. With the introduction of ATM charging, the flat landing fee favors the narrow body, while variable ATM charges increase the space where the turboprop offers the lower cost. This analysis shows that aircraft fleet selection is highly sensitive to fuel prices, passenger costs, and ATM charging schemes.

Keywords- *Aviation, Fuel, Operating and Passenger Costs, Turboprop, Air Traffic Management Charges*

I. INTRODUCTION

Aviation system planning is challenged by fuel price uncertainty and future Air Traffic Management (ATM) charging mechanisms. During the first half of 2008, many major carriers announced capacity cuts. In the fourth quarter of 2008, American Airlines, the US carrier with the third most domestic enplanements, announced a 12 percent reduction in seat capacity and an 11 percent reduction of regional service capacity [1; 2]. Other major carriers, such as Continental and United Airlines, are following suit, with many faulting the soaring price of fuel. As airlines decrease capacity and decommission older aircraft, a critical unknown is which aircraft provide air transportation service for the lowest cost.

Since 2004, the cost of fuel has increased rapidly. Fig. 1 shows the cost of aviation commercial jet fuel, termed Jet A, and the cost index in cents per gallon. The cost index, as defined by the Air Transportation Association (ATA), is the price of Jet A indexed to 100 for the year 2000 [3]. To offset growing fuel prices, airlines and their manufacturers continually improve aircraft efficiency through innovative technology and procedures. This can be seen in the trends per Available Seat Mile (ASM) per gallon of fuel and Revenue Passengers Miles (RPM) per gallon of fuel, both which have been slowly increasing since late 2000 [3]. This growth, however, is modest compared with the large leap in fuel prices seen. It can be inferred from these statistics that airlines need a new strategy beyond incremental aircraft and operating improvement to adapt to the present-day fuel price uncertainty.



Figure 1. Fuel Cost Index and Price.

There is also uncertainty about future infrastructure financing. Currently in the United States, the predominant source of infrastructure charges is user fees: a percentage tax of each ticket sold on the aircraft and a fee based on aircraft weight [4]. There is concern that these variable fees are inefficient. This is because the fees do not fully recover the costs necessary to manage the air traffic system, and they do not send the correct signals to the airlines about how much it costs to provide air traffic management service to different aircraft types [5]. Reference [5] argues that such a financing scheme encourages small aircraft; small aircraft are charged less than large aircraft even though they do not have a proportionally lower demand on the en route air traffic control system.

While Robyn [5] argues for a more advanced financing scheme, many discuss how these fees should be planned to both capture revenue and use congested airports more efficiently. There are many mechanisms over which ATM fees can be collected. They can be weighted based, flat, or a variation on flat landing fees that vary depending on the peak period [4]. Ref [6] discusses airports that have implemented flat landing fees or minimum landing fees.

Currently the FAA is planning a robust financing system. This system will generate revenue that will grow in accordance with system funding needs [7]. The elimination of variable ticket tax charging for certain ATM activities is planned, along with increasing user charging for different aircraft types. However, it is uncertain exactly how the ticket tax will be replaced, and what will happen with the terminal related charges. The uncertainties in future financing schemes make forecasting the minimum cost fleet mix challenging. It is clear that certain aircraft are advantaged over other aircraft depending on the financing mechanism and fuel prices. To investigate this, a method that allows for fleet costs to be compared under a range of fuel prices and financing schemes is needed. This study presents a method for aircraft cost comparison under fuel price and infrastructure charging uncertainty. Empirical results are presented based on current aircraft in the fleet. Current, rather than future, fleet are used so aircraft costs could be based on realized data rather than estimated or forecasted performance values. While these empirical results will need updating with new generations of aircraft, this study provides a method through which such aircraft could be compared.

The objective of this study is to compare representative aircraft for their operating, passenger, and infrastructure costs over a range of fuel prices. Turboprops, noted for their low fuel consumption, will be compared with two widely deployed aircraft, a regional jet and a narrow body jet. The turboprop has an operating range up to 1000 miles, which will define the upper bound of the range considered for these three aircraft. Operating costs include fuel, crew, maintenance, and airport costs. Passenger costs include travel time costs (flying time differences and schedule penalties) and the disutility of flying on turboprops (relative to jets). Infrastructure costs include air traffic control costs and both weight based and flat landing fees. This study will explore these costs over a range of stage lengths (SL) and fuel prices (FP), to determine which aircraft models can serve which segments with the lowest cost.

Previous studies have worked to model and compare operating costs for airlines. These studies have employed models to look for the lowest operating cost aircraft types for different segments or routes. Reference [8] develops comparative aircraft cost models that divide operating costs into fixed and variable costs. Using cost models developed in this manner, with fixed components and components that vary with distance and users, aircraft costs are compared [8]. When discussing an efficient airline market, Ref. [8] qualitatively discusses fleet assignment based on passenger preferences but stops short of developing an integrated model. In a similar study, the operating cost of different aircraft for commuter service is evaluated and a parametric analysis of operating cost versus stage length is performed to determine percent difference contour curves for comparing aircraft costs [9].

In a move to include passenger costs, a function to maximize net benefit by trading off user costs and operating costs is developed [10]. The function developed depends on flight frequencies, number of travelers, 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, as discussed in Ref. [11].

The importance of considering a total cost function rather than individual cost components is demonstrated by Ref. [12] and Ref. [13]. Reference [12] develops an operating cost model for jet aircraft in which size is endogenous, in that cost has a fixed cost and a marginal cost of serving an additional passenger. It is found that airlines could decrease operating costs by using larger aircraft than were currently in operation during the study period. Such findings are balanced with the conclusions of Ref. [13]. 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. Therefore the findings of Ref. [12] and Ref. [13] point to the importance of balancing airline operating cost and passenger costs when determining optimal fleet mix and scheduling.

The remainder of this paper is organized as follows: Section II introduces the three aircraft to be compared; Section III derives the key relationships based on stage length (up to 1000 miles) for fuel consumption and flying time. These cost relationships will then be combined to achieve a single cost model equation, and this equation will be used to compare the operating costs of the different aircraft under different fuel prices. As it is shown that the turboprop achieves low operating costs over a large range of stage lengths and fuel prices, passenger preferences for jet aircraft and faster flying times are introduced to determine the reality of replacing a jet fleet with turboprops (§IV). Finally, air traffic control costs and the impacts of differing landing fees are included (§V). The study concludes in Section VI with a discussion of how fuel price uncertainty impacts minimum cost fleet composition.

II. METHODOLOGY

This study identifies three aircraft models and compares their operating, passenger preference, and infrastructure costs: turboprops, regional jets, and narrow body aircraft. Specific aircraft are chosen to represent the three categories of models. The specific aircraft are chosen for a combination of their large presence in the market (for the jet aircraft) and the availability of data. Details of these aircraft are shown below in Table 1. All details are for the most common configuration [14, 15, 16, 17] and monetary values are in present day dollars.

TABLE I. DETAILS OF REPRESENTATIVE AIRCRAFT.

Aircraft Category	Aircraft Details		
	<i>Turboprop</i>	<i>Regional Jet</i>	<i>Narrow Body</i>
Aircraft Model	ATR 72-200	ERJ 145	B737-400
Manufacturer	EADS & Alenia Aeronautica	Embraer	The Boeing Company
Number of Seats	72	44	137
Maximum Takeoff Weight (lb)	50,265	44,070	149,710
Aircraft Cost per Unit (millions)	17.5	19.7 (Converted from 2002 dollars using CPI)	36.4 (Converted from 2002 dollars using CPI)
Runway Length Requirement	1,408 m	1,951 m	2,012 m

The following section develops the key cost relationships dependent on stage length.

III. KEY COST MODELS

This section introduces and develops the various cost model components. For each aircraft type, two key relationships are identified: fuel consumption and flying time. The fuel burn allows for the important calculation of fuel expenses per flight over a range of stage lengths (SL). Flying time to operate over a certain stage length allows for the calculation of crew and maintenance costs. In §IV, a flying time relation also allows for the inclusion of passenger value of time into the comparative cost analysis. Both flying time and fuel burn are linearly related to stage length. When these quantities are multiplied by the factors discussed in this section, the final cost model results.

A. Fuel Consumption

Fuel consumption for the three aircraft over fixed stage lengths is reported by the European Environmental Agency (EEA). Reference [18] uses aircraft characteristics, such as number of engines and fuel type, and estimates fuel consumption for a stage length by using standard values for thrust at different stages of flight. A standard Landing Take-Off (LTO) Cycle is also assumed. The EEA calculates fuel consumption from the entire gate-to-gate operation for a flight of a defined stage length. Using this data, individual relationships between fuel consumption and stage length are developed for each aircraft model. The form of the linear model is shown in (1), with fuel burn (FB) in pounds of fuel (lbs) and SL in miles. The model results are shown in the upper portion of Table 2.

$$FB = \alpha + \beta * SL \quad (1)$$

B. Flying Time

For the jet aircraft, data to develop a relationship between flying time and SL was collected from the US Department of Transportation Form 41, summarized by aircraft model. For each aircraft model there are carrier-specific reports on average SL per flight, total block time (the time to complete a gate-to-gate operation) operated in a day, and the number of departures that aircraft completes in a day. To extract SL (the independent variable) and block hours (BH) (the dependent variable) for an individual flight from this data, BH operated in a day were divided the number of departures (D) completed in a day. Average SL in Form 41 is used as the independent variable. The flying times for the turboprop are reported by the EEA for a range of stage lengths; these observations are used in lieu of Form 41 due to low observation count in Form 41. A relationship in the form of (1) was estimated for each aircraft model individually, with flying time (FT) as the dependent variable. Results are in the lower portion of Table 2.

TABLE II. FUEL CONSUMPTION-DISTANCE AND FLYING TIME-DISTANCE RELATIONSHIPS.

Aircraft Model	Aircraft Category			
	<i>Alpha</i> (standard error)	<i>Beta</i> (standard error)	<i>Adjusted R-Squared</i>	<i>Observations</i>
Fuel Consumption				
Narrow Body	2.7*10 ² (20.7)	2.1 (0.022)	0.999	7
Regional Jet	1.9*10 ² (7.6)	1.9 (0.010)	0.999	6
Turboprop	4.5*10 ¹ (0.19)	6.5*10 ⁻¹ (1.5*10 ⁻⁴)	0.999	7
Block Time				
Narrow Body	6.7*10 ⁻¹ (0.071)	2.0*10 ⁻³ (6.8*10 ⁻⁵)	0.973	25
Regional Jet	7.4*10 ⁻¹ (0.069)	1.883*10 ⁻³ (1.3*10 ⁻⁴)	0.942	14
Turboprop	3.1*10 ⁻¹ (0.0021)	4.9*10 ⁻³ (2.2E-06)	0.999	7

C. Operating Costs

The operating costs considered in this study include crew cost, aircraft fuel cost, and flight equipment maintenance. Not considered are aircraft rental costs and equipment depreciation, due to high variability and low observation counts in Form 41 and the desire to exclude ownership issues in this study at this stage.

1) Fuel Consumption Costs

For each aircraft, the fuel consumption model is multiplied by fuel prices FP (\$/gallon) to achieve a direct relationship between fuel cost and stage length.

2) Crew

Flight crew costs per block hour are available from Form 41. Form 41 reports these statistics for all carriers operating an aircraft type. To achieve a single value for crew costs, the carrier average for each aircraft model is used. A shortcoming to using the carrier average is that it is sensitive to different carrier operating procedures. If legacy and low-cost airlines operate the same aircraft, the average will be skewed downward compared with a scenario where all operators are legacy airlines. In the data, there is only one low-cost carrier present, and that is for the ERJ145 Regional Jet; it is then possible that the Regional Jet carrier average for crew costs is skewed downward.

Total crew cost is obtained by multiplying the block time by the crew cost. Cabin crew, while not typically included in cost analyses, were included in this study because the aircraft necessitate different number of cabin crew. While one cabin crew would be sufficient for the regional jet, a minimum of two is necessary on the other aircraft types (and two per aircraft type are assumed). Cabin crew costs are fixed at \$20/hour. Crew costs are shown in Table 3.

3) Maintenance

Maintenance cost per block hour is available from Form 41, and therefore exhibits the same sensitivities discussed previously. Similarly to crew costs, the average maintenance cost per block hour for all airlines operating an aircraft model was used as the maintenance costs. Costs were direct maintenance plus maintenance burden costs. Direct maintenance is labor and materials. Maintenance burden costs are overhead, such as maintenance administration, planning, and supervising [19]. These values are in Table 3.

TABLE III. OPERATING COST COMPONENTS.

Cost Category	Aircraft Category		
	<i>Turboprop</i>	<i>Regional Jet</i>	<i>Narrow Body</i>
Crew Cost including Flight and Cabin (\$/Block hour) (CC)	233	294	602
Maintenance (\$/Block Hour) (MT)	553	352	721

4) Operating Cost Equations

By combining all cost factors evaluated above, operating cost equations can be derived for all aircraft models. Evaluating operating cost per passenger will allow for a direct cost comparison. These aircraft have a range in size between 44 seats (regional jet) and 137 seats (narrow body). Assuming the load factor for each aircraft is 75.6 percent [20], the equations for operating cost per passenger are shown in the latter part of Table 4.

TABLE IV. OPERATING COST FUNCTIONS PER OPERATION AND PER PASSENGER FOR AIRCRAFT CATEGORIES.

Aircraft Model	Aircraft Category			
	Fuel Price (FP) Coefficient	SL*FP Coefficient	Stage Length (SL) Coefficient	Constant
Per Operation				
Narrow Body	$2.7*10^2$	2.1	2.6	$8.8*10^2$
Regional Jet	$1.9*10^2$	1.9	1.2	$4.8*10^2$
Turboprop	$4.5*10^1$	$6.5*10^{-1}$	3.8	$2.4*10^2$
Per Passenger				
Narrow Body	2.5	$2.0*10^{-2}$	$2.5*10^{-2}$	8.4
Regional Jet	5.6	$5.7*10^{-2}$	$3.6*10^{-2}$	$1.4*10^1$
Turboprop	$8.1*10^{-1}$	$1.2*10^{-2}$	$7.0*10^{-2}$	4.4

When costs are considered on a per operation basis, the turboprop exhibits a lower fixed cost and a lower cost that varies with fuel consumption than the jet aircraft. However, the cost that varies with distance alone is higher for the turboprop, due to the higher variable travel time. The two jet aircraft have similar costs, yet their constants are different due to the difference in cost components and fixed travel time.

When costs are considered on a per passenger basis the regional jet has consistently higher values than the narrow body. The lower capacity means costs are spread among few passengers. The cost segment which varies 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. The following section will explore how these differences translate into vehicle fleet selection based on operating cost.

D. Operating Cost Analysis

The following section utilizes the operating cost functions to compare the costs of the three aircraft models over a range of distances and fuel prices. Such an analysis will develop guidelines for deploying a homogenous vehicle fleet. Vehicles are compared using contour curves representing a percent difference in operating cost per passenger. Such a procedure allows for simple identification of the combinations of fuel price and distance for which a given aircraft has a cost advantage.

Fig. 1 presents the contour curves 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 10 percent higher and lower operating cost compared with the turboprop, respectively. The narrow body has a 10 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, such as existed as recently as 2007 and 2009, the situation is dramatically different, with the narrow body jet less expensive than the turboprop for stage lengths greater than 300 miles. As anticipated, the turboprop is very cost competitive at over short distances because of the lower fixed and higher variable costs with distance.

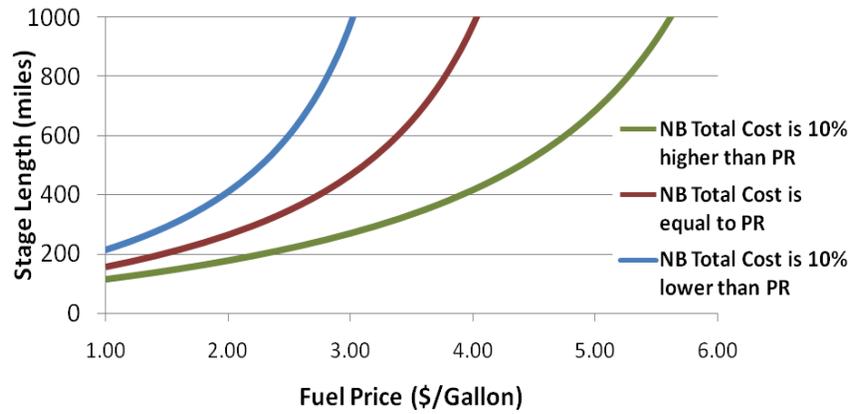


Figure 2. Percent Difference Operating Cost per Passenger Contour Curve for Regional Jet and Turboprop, and Regional Jet and Narrow Body Comparison.

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. In other words, the turboprop exhibits a lower cost per passenger for all stage length and fuel price combinations considered.

Based on these results, turboprops have a lower operating cost per seat for fuel prices prevailing as of summer 2008 when compared with the narrow body. When compared with the regional jet, the turboprop has a lower operating cost per seat for fuel price and distance combinations considered. However, there are additional factors beyond operating cost to be considered when comparing aircraft economics; the following section will include passenger time valuation and differences in willingness to pay for service on different aircraft types.

IV. PASSENGER COSTS

Passenger related costs include passenger willingness to pay (WTP) for certain aircraft models, for reduced flying time, and for travel close to their desired schedule (the value of frequency). As the introduction of frequency involves assumptions regarding schedule and seat preservation, the first two costs noted, the disutility for turboprops and flying time will be considered first with frequency added in latter part of this section.

A. 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, to produce a cost per time-passenger. The willingness to pay not to travel on a turboprop, in units of cost per operation-passenger, incorporates the perceived negatives of flying on a turboprop including increased passenger noise and potential safety concerns. Estimates for the passenger disutility of traveling on a turboprop and the cost of travel time can be found in [21]. In the data collected for that study, it was found that business travelers are 43% of the population with the remaining 57% non-business. The value of flying time and disutility for turboprop travel were estimated separately for both groups using a mixed logit model. By taking the weighted average of these values, we arrive at \$47.75/hour-passenger for travel time, and \$29.17/operation-passenger for the disutility of turboprop service.

B. Operating and Passenger Cost Equations

The disutility of flying a turboprop and the cost of passenger flying time are now combined with the operating cost equations. The cost of flying time is multiplied by the flying time equations defined. Passenger and operating cost per operation and total cost per passenger equations are defined in Table 5.

TABLE V. OPERATING AND PASSENGER COST FUNCTIONS PER OPERATION AND PER PASSENGER FOR AIRCRAFT CATEGORIES.

Aircraft Model	Aircraft Category			
	Fuel Burn (FP) Coefficient	SL*FP Coefficient	Stage Length (SL) Coefficient	Constant
Per Operation				
Narrow Body	2.7×10^2	2.1	1.3×10^1	4.2×10^3
Regional Jet	1.9×10^2	1.9	4.2	1.7×10^3
Turboprop	4.5×10^1	6.5×10^{-1}	1.7×10^1	2.6×10^3
Per Passenger				
Narrow Body	2.5	2.0×10^{-2}	1.2×10^{-1}	4.0×10^1
Regional Jet	5.6	5.7×10^{-2}	1.3×10^{-1}	5.0×10^1
Turboprop	8.1×10^{-1}	1.2×10^{-2}	3.0×10^{-1}	4.8×10^1

C. Parametric Passenger and Operating Cost Analysis

Similarly to the contour plot in Fig. 2, Fig. 3 displays percent different contours for operating and passenger cost for the two aircraft comparison pairs. When passenger costs are introduced, a zero percent difference contour emerges between the regional jet and turboprop (Fig. 3) in the stage length – fuel price space between \$1.5/gallon and 100 miles and \$3.50/gallon and 1000 miles. At \$3/gallon, the regional jet has a lower cost for stage lengths greater than 400 miles, but the at summer 2008 fuel prices, regional jets have a higher total cost per passenger for all stage lengths up 1000 miles. In short, the 2007-2008 run-up in fuel prices completely altered the competitive balance between regional jets and turboprops in the under-1000 mile market.

Figure 4 presents a similar analysis for narrow body jet and turboprops. Narrow body jets have a lower total cost per passenger than the turboprop for all stage lengths and fuel prices up to \$8.00/gallon. The zero percent contour curve does not extend to stage lengths over 100 miles until fuel prices are almost double current day levels. It is clear from the operating and total cost fleet comparisons that the comparative advantage of narrow body jets over turboprops is strongly dependent on the monetization of passenger costs. Considering total cost, narrow body jets have a lower total cost per passenger compared to turboprops under a wide range of fuel prices and stage lengths, including current day fuel prices. 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.

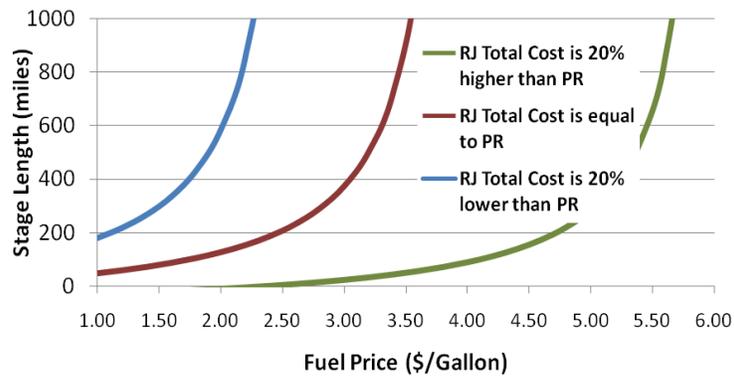


Figure 3. Percent Difference Operating and Passenger Cost per Passenger Contour Curve for Regional Jet and Turboprop.

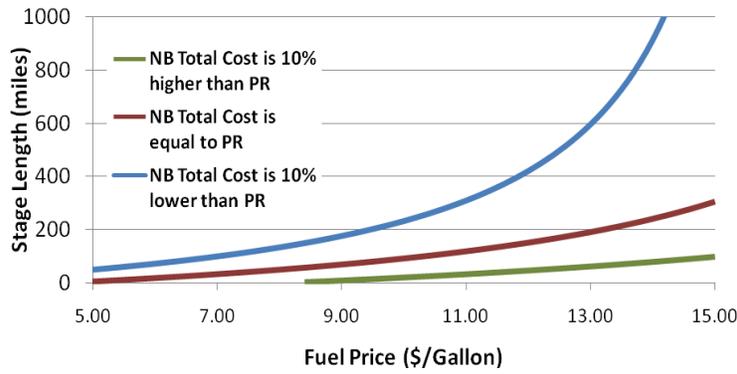


Figure 4. Percent Difference Operating and Passenger Cost per Passenger Contour Curve for Narrow Body and Turboprop Comparison.

D. Cost of Schedule Delay

As passengers place a value on the ability to choose a flight time, the frequency of service should be incorporated into passenger costs. The inclusion of frequency is motivated by the wide range of seat capacity among the three representative aircraft. 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 assignment. To capture the impact of providing more frequent service, a relationship between frequency and schedule delay must be identified. Reference [22] reviews a relationship developed by Ref. [23] 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 (2) shows the Schedule Delay ($SD(i, j)$) function in hours [17, 18]. The function is based on a route with origin i and destination j . Flight frequency $FQ(i, j)$ (3) is determined by the Market Density (MD), or the number of passengers wishing to depart from a given origin and destination in a day, the number of Seats (S) on an aircraft model, and the load factor (LF).

$$SD(i, j) = \frac{5.7}{FQ(i, j)} \quad (2)$$

$$FQ(i, j) = \frac{MD}{S * LF} \quad (3)$$

It should be noted that other representations of schedule delay functions exist. Using pre-regulation data, Ref. [4] discusses a similar relationship which is less sensitive to high and low market densities than (2). However, for market densities between the highest and lowest, the estimates produced by both methods were very similar; therefore (2) will be the one used for this analysis. As the result of (2) does not depend on stage length or fuel price, the new cost equations only differ from those previously defined by a constant. Because the constant term varies with market density, those densities which will be explored in the analysis below are displayed.

The zero percent different contour curves between aircraft pairs after the introduction of frequency delay are evaluated for a range of market densities in Fig. 5 and Fig. 6. The area under each curve represents the stage length – fuel price space where the turboprop has the lower cost per passenger.

As market density increases the stage length – fuel price space where the turboprop offers a lower cost per passenger increases. Because the regional jet has a smaller seat capacity, its use necessitates more frequency service than the turboprop. At lower market densities, the frequency delay incurred by the regional jet is lower due to this more frequent service. As market density increases, the discrepancy in frequency delay is decreased, and the difference is overtaken by the higher operating cost of the regional jet. The highest fuel price in Fig. 5 is \$3.50, which indicates that even after the introduction of frequency delay, the regional jet still offers a higher cost per passenger at current day fuel prices.

The narrow body jet and the turboprop (Fig. 6) exhibit a reverse relationship regarding market densities and cost per passenger than the regional jet and turboprop. Because the narrow body has almost twice the seats of a turboprop, it serves the same market density with less frequent service, increasing the frequency delayed incurred from using this aircraft. As market density increases, the cost impact of frequency delay decreases, and the stage length – fuel price space where a turboprop offers a lower cost per passenger shrinks and tends toward higher fuel prices. Most of the market density curves begin at fuel prices of \$4.60 to \$7.60/gallon. At the highest fuel price shown, \$14.80/gallon, the curves terminate at stage lengths between 400 and 600. For a wide range of fuel prices and stage lengths, narrow body exhibits a lower cost per seat despite higher frequency delays.

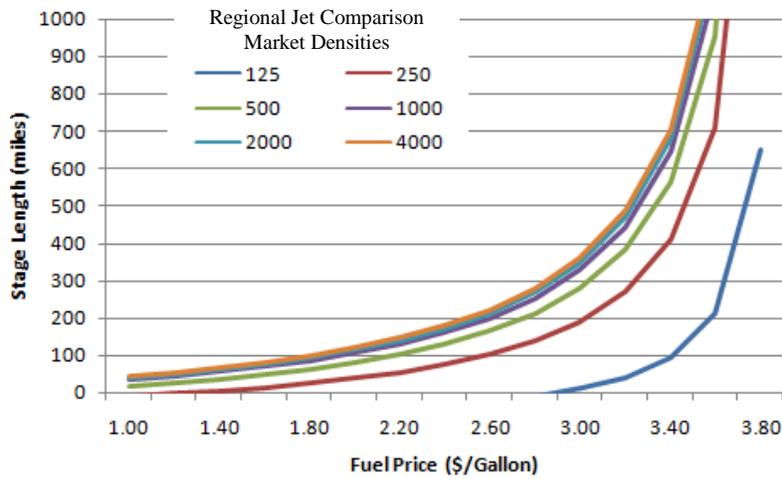


Figure 5. Percent Difference Operating and Passenger Cost per Passenger Contour Curve for Regional Jet and Turboprop for Varying Market Densities.

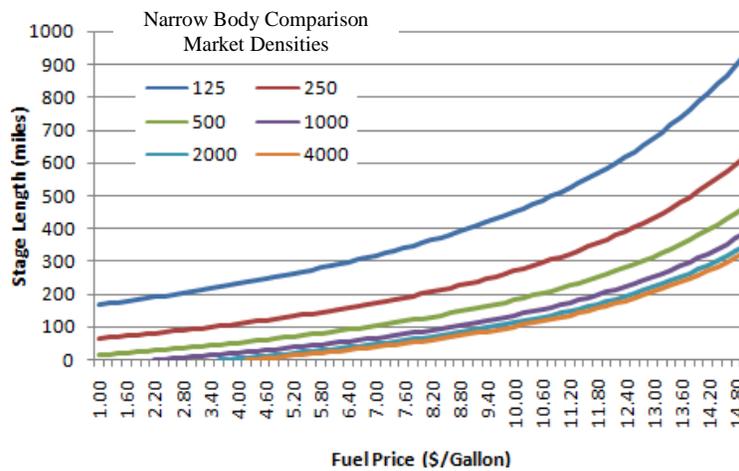


Figure 6. Percent Difference Operating Cost per Passenger Contour Curve for Narrow Body Comparison and Turboprop for Varying Market Densities.

V. AIR NAVIATION INFRASTRUCTURE COSTS

This study will cover two categories of air navigation infrastructure costs: en route and terminal.

As discussed in [4], en route air traffic navigation charges are included to capture the value of providing air traffic management services in the en route airspace. In the United States, these are captured by a passenger ticket tax. Such a fee could also be collected as a fixed sum. Both methods of en route air navigation fee collection will be evaluated.

Landing fees are fees levied by an airport on an arriving aircraft to capture the value of providing service in the terminal airspace. Landing fees incorporate a charge for using the airfield. They can be weight based, flat, or a variation on flat landing fees that vary depending on the peak period [4]. In the United States, terminal area air navigation fees are generally collected as part of the landing fee, and the funds go toward funding services and facilities to both arriving and departing aircraft, including landing and traffic control aids (see [4] for a detailed description).

The following section will investigate the minimum cost fleet composition under the two infrastructure charging scenarios. One scenario represents the current charging scheme in the United States, and the second represents a future scenario used to capture more of the costs to provide ATM services. The first scenario is a weight based landing fee and a ticket tax per ticket; the second is a fixed landing fee and a fixed charge for en route navigation.

A. Weight-Based Landing Fee, Variable Ticket Tax

The most common landing fee is levied in proportion to aircraft weight [4]. The determination of landing fees varies airport to airport; in this study, fees are based on Maximum Takeoff Weight (MTOW) and are charged the current landing fee at San Francisco International Airport (\$3.01/1000 lbs) for illustrative purposes [26].

The current ticket tax in the United States is set at 7.5% [24] of each ticket. The basis for the passenger ticket price used in this study will be the operating costs per passenger found in §III.C. The ticket tax charges can be seen in Table VI.

TABLE VI. PASSENGER TICKET TAXES PER TICKET.

Aircraft Model	Aircraft Category			
	Fuel Price (FP) Coefficient	SL*FP Coefficient	Stage Length (SL) Coefficient	Constant
Narrow Body	$1.9*10^{-1}$	$2.0*10^{-3}$	$1.9*10^{-3}$	$6.3*10^{-1}$
Regional Jet	$4.2*10^{-1}$	$4.3*10^{-3}$	$2.7*10^{-3}$	1.1
Turboprop	$6.1*10^{-2}$	$8.8*10^{-4}$	$5.2*10^{-3}$	$3.3*10^{-1}$

The resulting operating, passenger, and infrastructure (total) cost functions are shown in Table VII.

TABLE VII. TOTAL COST FUNCTIONS PER OPERATION AND PER PASSENGER FOR AIRCRAFT CATEGORIES, WITH VARIABLE INFRASTRUCTURE CHARGES.

Aircraft Model	Aircraft Category			
	FP Coeff.	SL*FP Coeff.	SL Coeff.	Const.
Per Operation				
Narrow Body	$2.8*10^2$	2.3	$1.3*10^1$	$5.6*10^3$
Regional Jet	$2.0*10^2$	2.1	4.3	$1.9*10^3$
Turboprop	$4.8*10^1$	$7.0*10^{-1}$	$1.7*10^1$	$3.1*10^3$
Per Passenger				
Narrow Body	2.7	$2.2*10^{-2}$	$1.2*10^{-1}$	$5.4*10^1$
Regional Jet	6.0	$6.1*10^{-2}$	$1.3*10^{-1}$	$5.7*10^1$
Turboprop	$8.7*10^{-1}$	$1.3*10^{-2}$	$3.1*10^{-1}$	$5.6*10^1$

B. Flat Landing Fee, Fixed En Route Navigation Charge

A flat landing fee would also be levied per arrival, but instead of varying with weight, the fee would be equal for all aircraft. The rationalization for this kind of landing fee, as described in Ref. [25], is that an operation precludes another operation. The values from the variable fee scenario for the narrow body will be used for all aircraft types in the fixed fee scenario. The per operation and per passenger equations can be seen in Table 8; note the narrow body values are the same as in Table 7.

TABLE VIII. TOTAL COST FUNCTIONS PER OPERATION AND PER PASSENGER FOR AIRCRAFT CATEGORIES, WITH FIXED INFRASTRUCTURE CHARGES.

Aircraft Model	Aircraft Category			
	FP Coeff.	SL*FP Coeff.	SL Coeff.	Const.
Per Operation				
Narrow Body	$2.8*10^2$	2.3	$1.3*10^1$	$5.6*10^3$
Regional Jet	$2.1*10^2$	2.1	4.4	$2.2*10^3$
Turboprop	$6.5*10^1$	$8.0*10^{-1}$	$1.7*10^1$	$3.4*10^3$
Per Passenger				
Narrow Body	2.7	$2.2*10^{-2}$	$1.2*10^{-1}$	$5.4*10^1$
Regional Jet	6.2	$6.1*10^{-2}$	$1.3*10^{-1}$	$5.8*10^1$
Turboprop	1.2	$1.5*10^{-2}$	$3.1*10^{-1}$	$5.7*10^1$

In Table 8, the values for the regional jet and the turboprop are mostly higher than those in Table 7, reflecting a higher charge borne by fewer passengers for these aircraft in a fixed fee scenario.

The following section determines the fuel price and stage length break even cost curves for the aircraft comparison pairs under the two infrastructure charging schemes.

C. Parametric Total Cost Analysis

To begin the aircraft comparison, a relatively low market density of 125 passengers per day for one way non-stop service will be assumed. The zero percent difference contour curves for a 125 passenger per day market density between aircraft pairs after the introduction of the two possible infrastructure charging schemes is shown in Fig. 7 and Fig. 8.

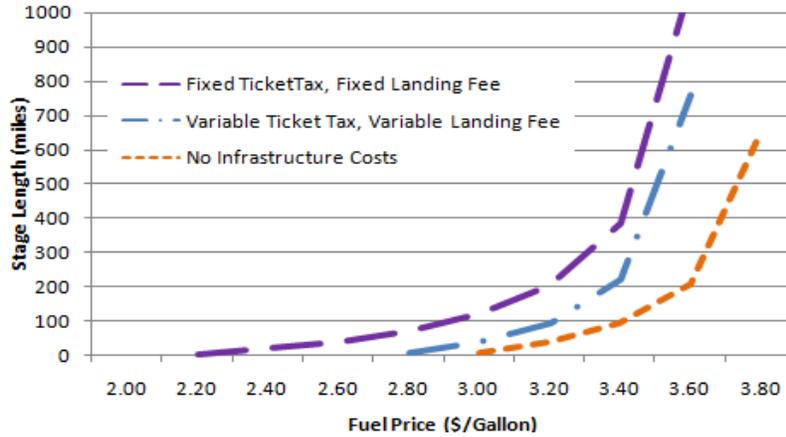


Figure 7. Percent Difference Total Cost per Passenger Contour Curve for Regional Jet and Turboprop for a Market Density of 125 passengers.

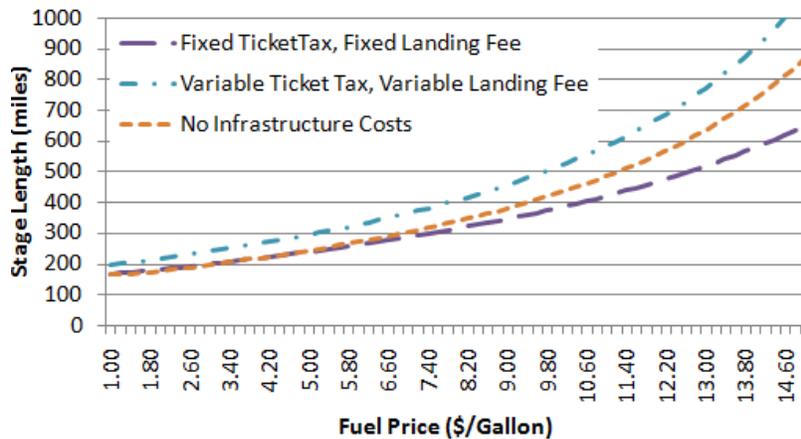


Figure 8. Percent Difference Total Cost per Passenger Contour Curve for Narrow Body and Turboprop for a Market Density of 125 passengers.

Again, the area under each curve represents the stage length – fuel price space where the turboprop has the lower cost per passenger. Figure 7, the regional jet and turboprop comparisons, shows that both infrastructure charging schemes increase the fuel price – stage length space where the turboprop offers a lower cost per passenger. When infrastructure costs are variable, the turboprop gains an advantage due to similar landing fees due to similar aircraft weights (Table 1). When infrastructure costs are fixed, the turboprop has the largest region where it exhibits the lowest cost. Due to the greater capacity of the turboprop, costs can be spread among more passengers and the importance of decreased schedule delay on the regional jet is diminished.

Figure 8 compares the narrow body and turboprop under varying infrastructure charges. When the infrastructure costs are variable, there is a larger region where the turboprop offers a lower cost compared with the curve before infrastructure costs are introduced. The turboprop has an advantage due to its lighter weight and smaller capacity. When infrastructure costs are fixed, there is a smaller region where the turboprop offers a lower cost compared with the narrow body, compared to the curve representing the cost comparison without infrastructure. Here the narrow body has the advantage, as there are more passengers who can share the fixed costs.

The next market density for comparison will be a relatively high market density of 2000 passengers per day.

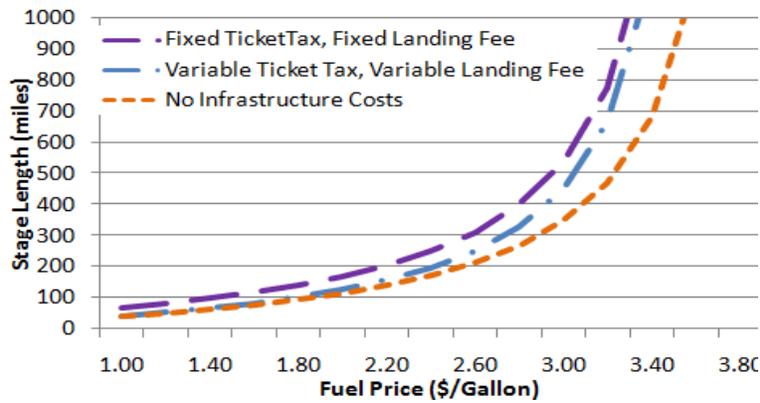


Figure 9. Percent Difference Total Cost per Passenger Contour Curve for Regional Jet and Turboprop for Varying Market Densities.

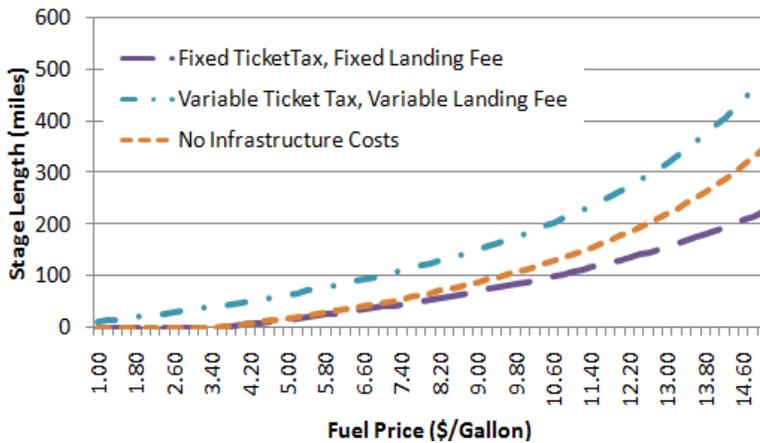


Figure 10. Percent Difference Total Cost per Passenger Contour Curve for Narrow Body and Turboprop for Varying Market Densities.

As seen in §IV.D, high market densities diminish the importance of schedule delay in the aircraft cost functions. The comparisons before infrastructure costs show that while the regional jet exhibited efficiencies at lower market densities, the break even curve terminated within a range of \$0.80. Therefore, as exhibited in the comparison of Fig. 7 and Fig. 9, the higher density makes little difference for the regional jet and the turboprop.

The higher density significantly decreases the region where the turboprop offers a lower cost when compared with the narrow body (Fig. 10). The region where the turboprop offers a lower cost per passenger compared with the narrow body decreases with increasing market density due to the diminishing importance of schedule delay. The curves are shifted toward the x-axis significantly, diminishing the region where the turboprop offers the lower cost per passenger.

VI. CONCLUSION

This analysis shows that the determination of least-cost aircraft stage lengths of 1000 miles or less is highly sensitive to fuel prices and passenger costs. It was shown that during a fuel price spike such as that seen in the summer of 2008, regional jets generally have a higher total cost per passenger than turboprops, and narrow body jets have lower operating costs per passenger. In contrast, at fuel prices seen one year earlier, in the summer of 2007, there are many routes for which the regional jet has a lower cost per passenger. For certain stage lengths, it is only the recent jump in fuel prices that have made the turboprop a more attractive option over regional jets.

The findings of this study help further our understanding of future infrastructure funding schemes. The FAA can use these results and perform other vehicle comparisons to understand how airlines may respond to their infrastructure changes with fleet changes. In general, the FAA could expect that moves toward a fixed infrastructure charges would favor larger jets, as well as a move toward turboprops. If infrastructure charges are left as variable, the move toward larger jets may not occur, especially in the absence of a fuel price increase, because smaller jets would continue to have an advantage under variable charging schemes.

An interesting conclusion from this study is that low fuel prices send inefficient fleet selection signals to airlines. At fuel prices below \$3.00-\$4.00/gallon, airlines are encouraged to adopt less fuel efficient aircraft (regional jets) in order to keep passenger costs low. Low fuel prices also incentivize manufacturers to make aircraft that are less efficient but offer smaller recurring infrastructure charges and offer higher levels of passenger service. This practice is beneficial for airline costs but runs counter to other policy

priorities such as reducing the environmental impact of aviation and fuel conservation. Results of this study indicate that high fuel prices rationalize the adoption of fuel efficient aircraft, 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.

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