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Metroplex Optimization Model Expansion and Analysis: The Airline Fleet, Route, and Schedule Optimization Model (AFRS-OM)

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EXECUTIVE SUMMARY

The Airline Transportation System (ATS) provides affordable, rapid, safe transportation to distant and/or remote destinations.

Airlines maximize profit by leveraging economies-of-scale to schedule passenger itineraries in time and space to meet the passenger demand for travel. The choice of routes served, schedule, and aircraft type used, determines the ability of the airlines to operate profitably. As passenger demand for air transportation service fluctuates, the airlines are obliged to continuously adjust their operations, resulting in dynamics in markets served, schedules, and aircraft used.

Estimates of the benefits of modernization efforts, such as the Airport Improvement Plan (AIP) and NextGen, are limited by existing analysis tools that assume a static airline service (i.e. fleet, route, and schedule) and do not consider the airline response to the introduction of additional capacity, new concepts-of-operations, and new technologies.

This report describes the Airline Fleet, Route, and Schedule Optimization Model (AFRS-OM) that is designed to provide insights into airline decision-making with regards to markets served, schedule of flights on these markets, the type of aircraft assigned to each scheduled flight, load factors, airfares, and airline profits. The main inputs to the model are hedged fuel prices, airport capacity limits, candidate markets. Embedded in the model are aircraft performance and associated cost factors, and willingness-to-pay (i.e. demand vs. airfare curves).

This model is based on the research of Le (2005) and Ferguson (2011). New features of the model described in this report include cumulative willingness-to-pay (i.e. demand) curves for 15 minute increments for U.S. domestic origin-destination pairs, and a model to adjust the willingness-to-pay curves that accounts for changes in hedged fuel prices and unemployment rates (a proxy for overall economic health). The model has been validated by comparing trends (i.e. growth or decay) with historic data and exhibits accuracy in the 10% to 15% range.

Case studies demonstrate the application of the model for analysis of the effects of increased capacity and changes in operating costs (e.g. fuel prices).

An *increase in capacity* at eight major airports (BOS, DFW, EWR, JFK, LGA, ORD, PHL, SFO) yields increases in the number of markets served and the flights per day. This is accompanied by a small increase in airline profits, and a slight decrease in airfares making air travel more affordable. Increases in airport capacity do, however, result in a slight reduction in airport/airspace slot efficiency, as airlines choose to use smaller aircraft.

An *increase in hedged fuel prices* at eight major airports (BOS, DFW, EWR, JFK, LGA, ORD, PHL, SFO) yields reductions in the number of markets served and the flights per day. This is accompanied by a marginal increase in airline profits, and an increase in airfares. An increase in fuel prices results in a reduction in airport/airspace slot efficiency as airlines choose to use smaller aircraft.

Although there are differences between airports (due to differences in the magnitude of travel demand and sensitivity to airfare), the system is more sensitive to changes in fuel prices than capacity. Further, the benefits of modernization in the form of increased capacity could be undermined by increases in hedged fuel prices.

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1 INTRODUCTION

The Airline Transportation System (ATS) provides affordable, rapid, safe transportation to passengers and cargo to distant and/or remote destinations. In terms of speed and cost for transportation of relatively small and lightweight items, this mode of transportation has unassailable advantages over other modes of transportation over long distances.

Airlines maximize profit by scheduling passenger itineraries in time and space to meet passenger demand for travel. To minimize costs and maximize the utilization of assets, airlines take advantages of economies-of-scale and schedule flights in a space-time network whereby passenger itineraries are satisfied by one or more flights, and the aircraft and crew are positioned to transport the next batch of passengers on the next leg of their itineraries. The choice of routes served, schedule, and aircraft type used directly determines the ability of the airlines to operate profitably. As passenger demand for air transportation service fluctuates, the airlines are obliged to continuously adjust their operations.

These airline decisions have broad implications on the overall structure of the ATS from an economic, social and political standpoint (Figure 1). The number of markets served determines the geographic availability of transportation (e.g. rural areas). The airfare determines the affordability of air travel. Airline profit determines the viability in operating an unsubsidized service. Aircraft size determines the efficiency in using airport/airspace slots to transport passengers.

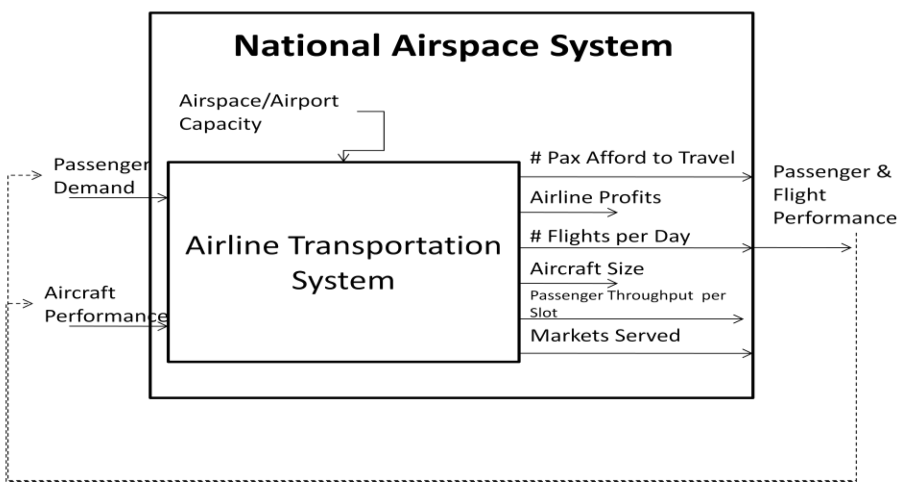

Figure 1: Understanding of the effects of modernization on the overall transportation system: economic, social, and political

Due to limitations in available land, funding, long investment and approval cycles, and political will, the capacity to support the demand at the largest metropolitan regions in a reliable manner has degraded over time. Recent reports have estimated the cost of poor reliability of the ATS for 2007 at \$32B (NEXTOR, 2010) and \$42B (Schumer Report, 2010).

Government and industry have partnered to develop plans to increase the capacity. The Airport Investment Plan (AIP, 2010) provides a roadmap for increasing airport infrastructure. NextGen, coordinated by the Joint Planning and Development Office (JPDO), has developed a roadmap to improve the productivity of the system by utilizing existing resources more effectively through new concepts-of-operations and technologies (JPDO, 2010).

Estimating the benefits of the overall modernization effort are limited by existing analysis tools that treat the airline service (i.e. fleet, route, and schedule) as static and do not consider the airline response to the introduction of additional capacity, new concepts-of-operations, and new technologies, on the economic, social and political decision-space (Figure 1).

This report describes the Airline Fleet, Route, and Schedule Optimization Model (AFRS-OM). The AFRS-OM is designed to provide insights into the airline decision-making with regards to markets served, schedule of flights on these markets, the type of aircraft assigned to each scheduled flight, load factors, airfares, and airline profits. The main inputs to the model are hedged fuel prices, airport capacity limits, and candidate markets. Embedded in the model are aircraft performance and associated cost factors and willingness-to-pay (i.e. demand vs. airfare curves).

This model is based on the research of Le (2005) and Ferguson (2011). New features of the model described in this paper include cumulative willingess-to-pay (i.e. demand) curves for 15 minute increments for most U.S. domestic origin-destination pairs, and model to adjust the willingness-to-pay curves to account for changes in hedged fuel prices and unemployment rates (a proxy for overall economic health). The model has been validated by comparing trends (i.e. growth or decay) with historic data and exhibits accuracy in the 10% to 15% range.

Case studies demonstrate the application of the model for analysis of the effects of increased capacity and changes in fuel prices. The highlights of the case-studies described in this report are shown in Table 1.

Metrics	Effect of Increase +$1/gallon	Effect of Increase in +4 ops/hour
Flights per Day	-1.4%	0.05%
Markets Served	-1.1%	Unchanged
Pax Trips per Day	-8.7%	+0.05%
Average Airfare ($)	+$34	+0.006%
Airline Profits ($M)	+3.2%	+0.12%
Average Aircraft Size (Seats per Aircraft)	-7.5%	+0.024%
Daily Fuel Burn (M gallons)	-8.3%	+0.014%

Table 1: Percent change due to increase in capacity at airports and increase in hedged fuel price

An *increase in capacity* at eight major airports (BOS, DFW, EWR, JFK, LGA, ORD, PHL, SFO)) yields increases in the number of markets served and the flights per day. This is accompanied by a small increase in airline profits, a slight decrease in airfares, and a slight reduction in runway slot efficiency through use of smaller aircraft.

An *increase in hedged fuel prices* at eight major airports (BOS, DFW, EWR, JFK, LGA, ORD, PHL, SFO) yields reductions in the number of markets served and the flights per day. This is accompanied by a marginal increase in airline profits, an increase in airfares, and slight reduction in runway slot efficiency through use of smaller aircraft.

Although there are differences between individual airports (due to differences in the magnitude of travel demand and sensitivity to airfare), on aggregate the ATS is more sensitive to changes in fuel prices than capacity increases. Further, the benefits of modernization on geographic access (i.e. markets served) and economic access (i.e. affordability of travel) could be undermined by increases in hedged fuel prices. In both cases, capacity increase and fuel price increase, the efficiency of the air transportation system is degraded by the use of smaller aircraft.

The remainder of this report is organized as follows: Section 2 provides a detailed description of the AFRS-OM. Section 3 describes validation and limitations of the model. Section 4 describes a case-study of metroplex airports. Appendix A includes a Flight Delay Cost model.

2 AIRLINE FLEET, ROUTE AND SCHEDULE OPTIMZATION MODEL (AFRS-OM)

The AFRS-OM is a multi-commodity model to optimize the domestic non-stop airline service to an airport in the presence of travel demand with associated sensitivity to airfares, a fleet mix with associated aircraft performance characteristics, and limitations of capacity at the focus airport (Le, 2006; Ferguson, 2011).

The main ouputs of the model are;

- markets served
- schedule of flights on these markets
- the type of aircraft assigned to each scheduled flight
- load factors
- airfares
- airline profits, revenues, and costs
- total fuel burn

The main inputs to the model are:

- hedged fuel prices
- airport capacity limits (adjusted for international flights with bi-lateral agreements and reserved general aviation slots)
- candidate markets

Embedded in the model are detailed models of:

- aircraft performance and associated cost factors
- willingness-to-pay (i.e. demand vs. airfare curves) for domestic U.S. origin-destination pairs
- effect of hedged fuel prices and unemployment (a proxy of economic health) on the willingess-to-pay-curves

The structure and components of the model are are summarized in

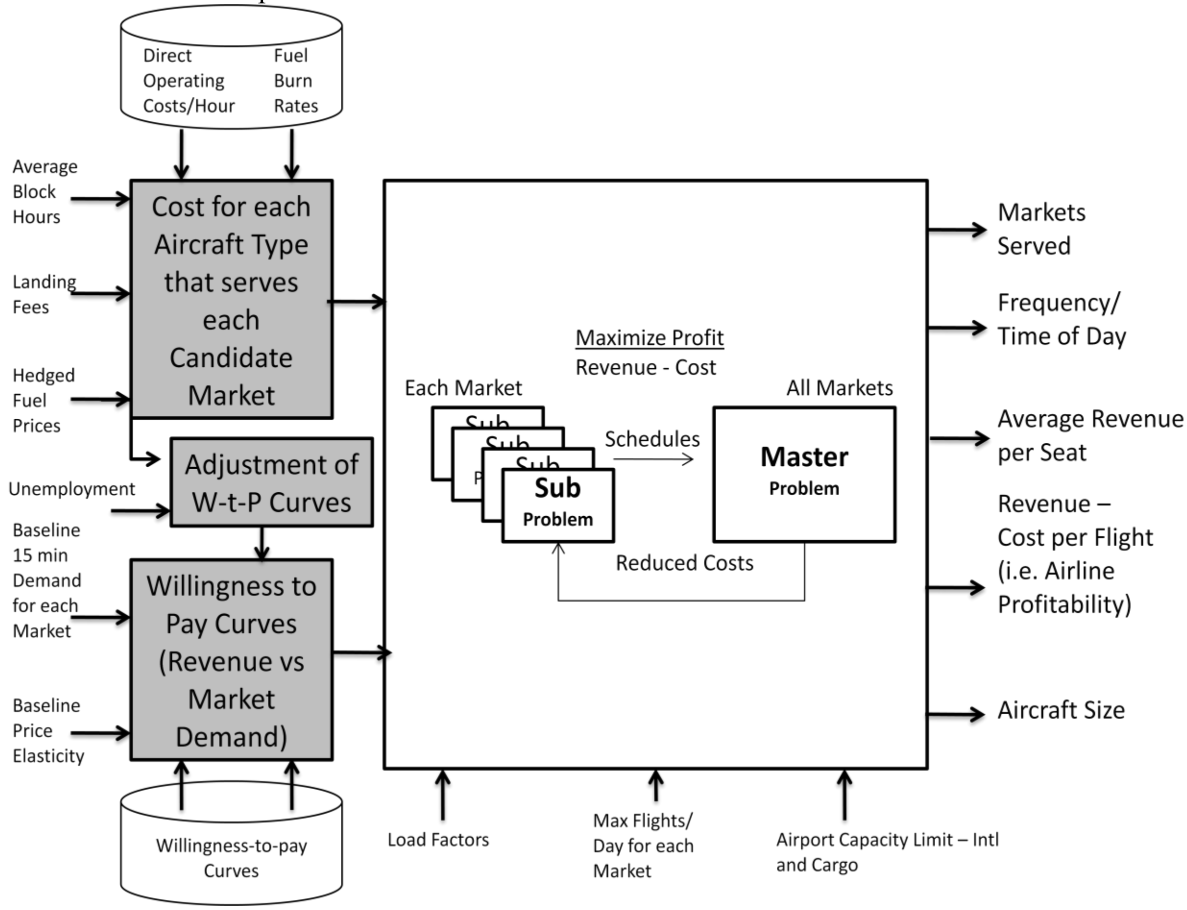

Figure 2. The optimization model includes a master problem and sub-problem. The sub-problem selects the most desirable schedule and fleet for individual origin-destination pairs (e.g. Atlanta to Boston) for each 15 minute period of the day. The preferred schedules for each origin-destination pair are submitted to the master problem that selects the most profitable flights for each 15 minute period. The shadow price information (i.e. value of an additional flight within any 15 minute time period) are fed back to the sub-problem for adjustment of the schedule and fleet for each individual origin-destination pair. The sub-problem/master problem iteration continues until the "stable" criteria are satisfied.

The model includes detailed models of aircraft performance and associated cost factors, "baseline" willingess-to-pay curves for domestic U.S. origin-destination pairs, and a model that adjusts the baseline willingness-to-pay curves for changes in hedged fuel prices and unemployment. Each of these components and the format of the inputs and outputs are described in the following sections.

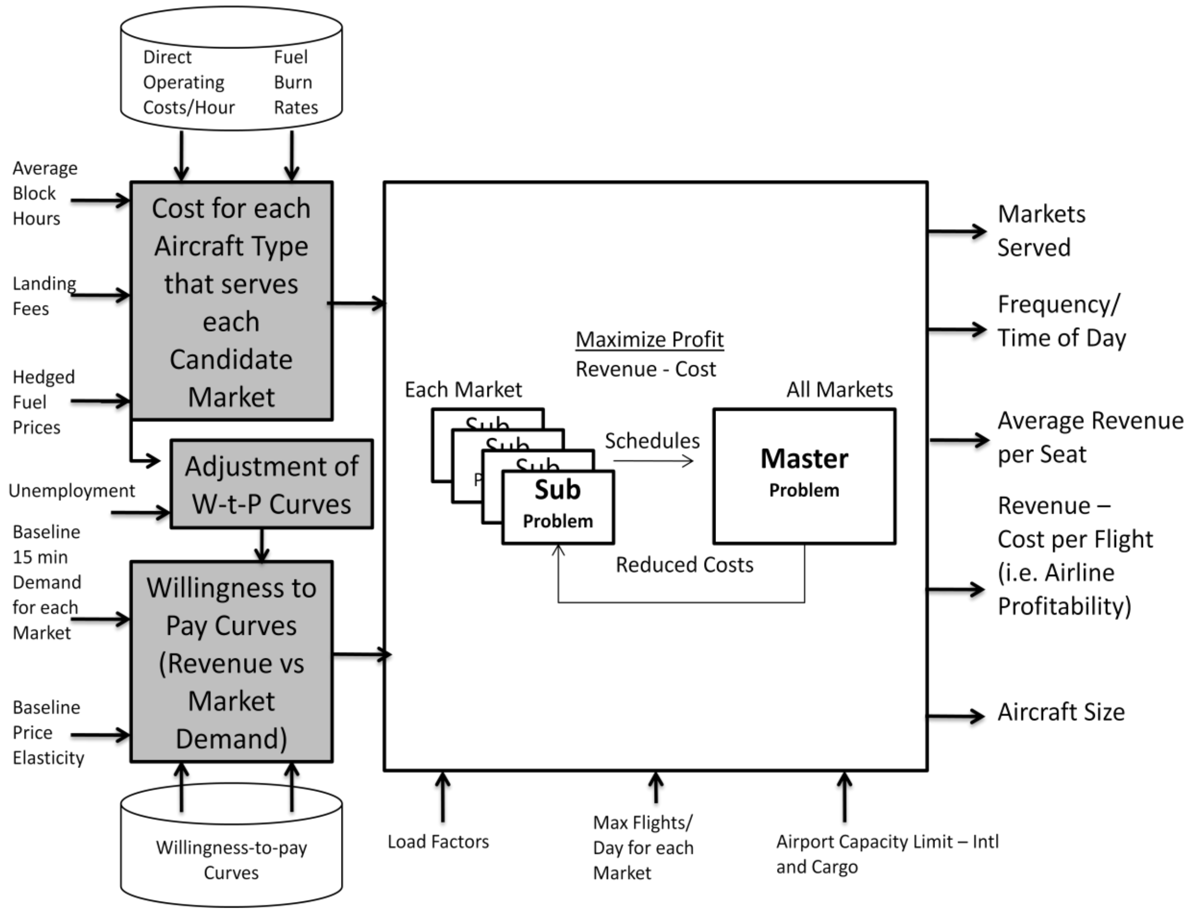

Figure 2: Structure and components of the AFSR-OM

2.1 Master Problem

The master problem is formulated as a set packing problem for the candidate market schedules generated by the sub-problem. The optimization is constrained by airport capacity, with no more than one schedule chosen per market. The objective function maximizes total profit for the airport's schedule.

The optimization formulation is as follows:

$$max \sum_{j \in S} Z_j y_j$$

subject to:

$$\sum_{j \in S} a_{ij} y_j \leq C_i - I_i^{\alpha} \quad \forall_i \in T \tag{1}$$

$$\sum_{j \in S} d_{ij} y_j \leq C_i - I_i^d \quad \forall_i \in T \tag{2}$$

$$\sum_{j \in S(m)} y_j \leq 1 \quad \forall m \in M \tag{3}$$

$$y \in B^{|S|}$$

where:
Z_j = Profit from schedule j
y_j = Decision variable (0,1) on whether schedule j is selected
a_{ij} = Decision variable (0,1) on arrival for time i and schedule j
d_{ij} = Decision variable (0,1) on departure for time i and schedule j
I_j = average number of international or cargo arrivals (a) or departures (d) for time i

τ = Set of 15 minute time windows in the day
S = Set of schedules submitted to master problem from sub problems
S(m) = Set of schedules for market m
M = Set of possible markets for schedule
Constraint #1 and #2 ensure that there are no more flights in a single 15-minute bin than the arrival and departure capacity available to handle these flights, respectively. Capacity is defined to be airport capacity minus the portion of that capacity used by other flights (e.g. international and general aviaton).
Constraint #3 guarantees that at most only one schedule per market pair is chosen.

2.2 Sub-Problem

The sub-problem is formulated as a multi-commodity flow netwok problem. The optimization formulation is shown below:

$$\max z = \sum_{i \in T} \sum_{q \in Q(i)} R_{iq} \lambda_{iq} - \sum_{(j,i) \in A^F} \sum_{k \in K} C_{ji}^k x_{ji}^k$$

Subject to:

$$\sum_{(j,i) \in A} x_{ji}^k - \sum_{(i,j) \in A} x_{ij}^k = 0, \quad \forall i \in T, k \in K \tag{4}$$

$$l \sum_{k \in K} \sum_{(j,i) \in A^F} S^k x_{ji}^k - \sum_{q \in Q(i)} A_{iq} \lambda_{iq} = 0 \quad \forall_i \in T \tag{5}$$

$$\sum_{i \in \mathcal{E}(p)} \sum_{q \in Q(i)} A_{iq} \lambda_{iq} - \sum_{r \in Q(p)} A_{pr} \beta_{pr} = 0 \quad \forall_p \in P \tag{6}$$

$$\sum_{i \in \mathcal{E}(p)} \sum_{q \in Q(i)} R_{iq} \lambda_{iq} - \sum_{r \in Q(p)} R_{pr} \beta_{pr} \leq 0 \quad \forall_p \in P \tag{7}$$

$$\sum_{i} x_{ij}^k + \sum_{i} x_{ji}^k \leq max\_freq + 1 \tag{8}$$

$$\sum_{k \in K} \sum_{(j,i) \in A^F} S^k x_{ji}^k - IntDem \geq 0 \tag{9}$$

$$\sum_{i} x_{ij}^k \leq 1 \quad \forall_i \in T \tag{10}$$

$$\sum_{i} x_{ji}^{k} \leq 1 \ \forall_{i} \in T \tag{11}$$

$$\sum_{q \in Q(i)} \lambda_{iq} = 1 \ \ \forall_{i \in} T \tag{12}$$

$$\sum_{r \in Q(p)} \beta_{pr} = 1 \ \ \forall_{p} \in P \tag{13}$$

$$x \in B_{+}^{|A^F| \times |K|}, \boldsymbol{\lambda_i} \in R_{+}^{|Q(i)|}, \beta_p R_{+}^{|Q(p)|}$$

where:
R_{iq} = Linear segment revenue for time i and segment q
λ_{iq} = Decision variable (0,1) for time i and segment q
C^{k}_{ij} = Direct operating cost for one flight of fleet type k for flight arc (i,j)
x^{k}_{ij} = Decision variable (0,1) for one flight of fleet type k for flight arc (i,j)
l = average load factor
S^{k} = Seats for aircraft of fleet type k
A_{iq} = Linear segment passenger demand for time i and segment q
A_{pr} = Linear segment passenger demand for period r and segment p
R_{pr} = Linear segment revenue for period r and segment p
β_{pr} = Decision variable (0,1) for period r and segment p
τ = Set of 15 minute time windows in the day
ρ = Set of periods in the day
κ = Set of aircraft fleet classes

The objective function maximizes total profit for the markets schedule from the airport. There are 10 constraints numbered 4 through 13.

Constraint #4 creates flow balance constraints that assure that, for each fleet type, there is an equal number of incoming and outgoing aircraft of that type. It also assures that an aircraft must arrive before it can depart and it must remain of the same type.

Constraint #5 assures that there is sufficient supply for the demand, that the aircraft size can accommodate the demand, and that the aircraft does not fly with less than 80% load factor.

Constraint #6 requires that the demand per period be satisfied.

Constraint #7 assures that the airline does not fly any flights that are unprofitable. This does the same for revenue. This is to ensure that even though there is no flight at some time window despite there being demand for it, the demand is still satisfied in the consecutive time window and passengers are not removed from that time period.

Constraint set #8 requires the number of flights into a market is approximately equal to the number of flights out of a market (can differ by no more than one).

Constraint #9 ensures that international passenger demand that is connecting from domestic markets is satisfied. Therefore, we will not eliminate a profitable market which connects domestic passengers to international flights.

Constraints #10 and #11 ensure that there is only one flight between the market pair in the same time window.

Constraint #12 and #13 ensures that only one segment of the piecewise linear approximation for the revenue curve is chosen for each time window and period respectively. The piecewise linear approximation works here because the optimization model is maximizing profit and the revenue versus demand curve approximations are convex.

2.3 Flight Profit Model

The profit for a given flight is defined as the difference between Revenue and Operating Costs.

Profit = Revenue – Operating Cost

Revenue for a flight is the number of passengers multiplied by the average airfare.

Revenue = Number of Passengers * Average Airfare

Operating Cost is defined by the summation of two terms: (1) the non-fuel hourly operating costs multiplied by the block hours, (2) the hourly fuel burn rate multipled by the hedge price of fuel multiplied by the block hours.

Operating Cost = (Block Hours * Non-fuel Hourly Operating Costs) + (Block Hours * Hedged Fuel Price * Hourly Fuel Burn Rate.

Each of the terms in these equations are described in subsequent sections.

2.4 Airfare Model

The airfare model is a scheme to derive accurate airfare statistics from publicly available data. The model developed by Ferguson (2011) adjusts airfare to account for the fees and taxes included in the airfares reported in the BTS DB1B "Market" database.

The domestic taxes and fees not included in the DB1B consist of passenger ticket taxes, flight segment taxes, and passenger facility charges. The amount a passenger pays in taxes and fees on a ticket varies according to the itinerary, including the number of flights on each itinerary, and the origin and destination airports. The passenger ticket taxes for the period under investigation were 7.5% of the ticket airfare and the domestic flight segment tax was set at $3.60 as of January 2009 (ATA 2011).

The Passenger Facility Charges (PFC) for major airports allows for the collection of PFC fees up to $4.50 for every enplaned passenger at commercial airports controlled by public agencies (FAA 2011). These funds are used by the airports to fund the FAA-approved projects to enhance safety, security, or capacity, reduce noise, or increase air carrier competition. The average PFCs for the airports examined in this study were $3.63.

The airlines also include a "September 11" security fee in the airfare reported in the DB1B. This fee is imposed on passengers of domestic and foreign air carriers for air transportation that originates at airports in the United States. The fee, which is collected at the time the ticket is bought, is $2.50 per enplanement and is imposed on not more than two enplanements per one-way trip. The fees are collected by the direct air carriers, who must remit the fees to the Transportation Security Administration on a monthly basis. (ATA 2011).

In addition, the BTS DB1B "Market" database includes revenue generated from cargo flown on passenger flights, and revenue from airline bag, cancelation, change, pets, and frequent flyer charges are not included in the DB1B airfare and must be added. Examination of airline revenue reports reported in the Aviation Daily, show substantial revenue gained by the airlines from cargo flown on passenger flights, airline baggage fees, cancelation fees, change fees, transportation of pets, and frequent flyer charges.
The revenue realized by airlines from freight and mail on passenger flights is estimated at 2.4% of airfare, from Aviation Daily Airline Revenue reports. By aggregating the revenue from fees and dividing by passenger enplanements, this revenue was found to be \$10.17 per passenger enplanement (Table 2).

		2008**	2009
Ancillary Fees*		\$ 7.50	\$ 10.17
	Bags	\$ 2.09	\$ 3.54
	Cancel	\$ 2.20	\$ 3.08
* Bags, Cancel/Change, Pets, Freq Flyer			
** Based on 3rd & 4th Quarter			

Table 2: Airline revenue from Aviation Daily Airline Revenue reports

To reflect true revenue from passengers from the DB1B airfares, the airfare must be reduced by 5.1% (7.5% - 2.4%) and increased by \$0.44 (\$10.17 - \$3.60 - \$3.63 -\$2.50).

Adjusted Airfare \$ = [Airfare – (Airfare * 0.051)] + \$0.44

2.5 Willingness-to-Pay Curves (Cumulative Demand vs. Adjusted Airfare)

There are three traditional models used to describe the relationship between passenger demand and airfare: gravity models, exponential models, and S-curve or logit models. For a description of the differences between these models see Ferguson (2011).
The AFRS-OM model uses the exponential model.

$$\text{Cumulative Passenger Demand} = \text{Market Size Coefficient} * e^{(\text{Airfare Sensitivity Coefficient} * \text{Airfare})}$$

The market Size coefficient and the Airfare Sensitivity Coefficient are computed based on the data available from the Bureau of Transportation Statistics (BTS) The methods for extracting the Average Airfares and Demand are described in the sections below. The data used for the analysis is derived from the Airline Origin and Destination Survey (DB1B) database (U.S. DOT/BTS 2010). The DB1B database is a 10% sample of airline tickets from reporting carriers collected by the Office of Airline Information of the Bureau of Transportation Statistics. Data includes origin, destination and other itinerary details of passengers transported.

The DB1B market database contains directional market characteristics of each domestic itinerary of the Origin and Destination Survey, such as the reporting carrier, origin and destination airport, prorated market fare, number of market coupons, market miles flown, and carrier change indicators. Round trip itineraries are split in two for this database. This database contains direct itineraries and connecting itineraries, as shown in the number of segments in the itineraries in Table 3. In order to evaluate passenger demand for non-stop direct domestic markets or segments the airfares for these connecting itineraries (more than one segment) must be further prorated down to the segments of interest.

Year	Qtr	number segments	# of Itineraries	% of Itineraries	# of Pax	% of Pax
2007	3	1	2,041,131	39%	7,973,245	67%
2007	3	2	2,916,989	55%	3,580,773	30%
2007	3	3	266,179	5%	274,450	2%
2007	3	4 or more	31,684	1%	32,235	0.3%

Table 3: Airline Origin and Destination Survey (DB1B) "Market" database

2.5.1 Estimating Average Airfares

Two traditional approaches to prorating segment fares from an itinerary fare have been used (see Ferguson, 2011). The first method is known as the"yield approach," because the segment's airfare is generated from an average yield or revenue per passenger mile. For example, an itinerary with revenue $400 for 400 miles has a yield of $1 per passenger mile. A proration of this revenue for a 200 mile segment would be $1 per passenger mile times 200 miles, or $200 per passenger. This approach is used to split the fare for round trip itineraries into the DB1B market itineraries. Although this approach is simple, it loses accuracy for itineraries in which the stage length of the segments vary significantly.

A second method prorates the airfares based upon actual direct single segment fares. In this approach, the single direct non-stop segment fares for all of the segments of the itinerary are extracted and then used to determine the proportion of the whole itinerary airfare for each segment. The proportion for each segment is equal to the fraction of each segment's direct non-stop segment airfare over the sum of all the single direct non-stop segment fares for all of the segments of the itinerary. For example, an itinerary with revenue $400 for 400 miles has two segments of 100 and 300 miles respectively. The direct non-stop segment airfares for these segments were $150 and $350 respectively. Then this method would apply 30% ($150/($150+$350)) of the $400 for the itinerary airfare or $120 for the 100 mile segment and the remaining $280 for the 300 mile segment. While this approach is considered the best approach for prorating, it is also very complex and not all segments flown have non-stop segment airfares, so approximation methods have been developed to represent this method.

American Airlines applies an approximation method which prorates airfare based on the square root of the segment distance divided by the sum of the segment distance square roots (Le 2006). GRA, Inc. uses an approximation method which prorates airfare based on the 0.74 power of the segment distance divided by the sum of the .74 power of all itinerary segment distances. Analysis of DB1B data showed that segment distance to the 0.4166 power divided by the sum of the 0.4166 power of all itinerary segment distances was the best fit to approximate method two above.

However, prorating based on the square root of the segment distance performs nearly as well, as shown in Figure 3, which shows an analysis of 2522 itineraries for PHL airport third quarter 2007. Each of these itineraries had three flight segments which could individually be analyzed in the BTS DB1B database for average fares. A comparative analysis is shown between the different approximating techniques used to prorate segment fare versus individual proration by segment fare.

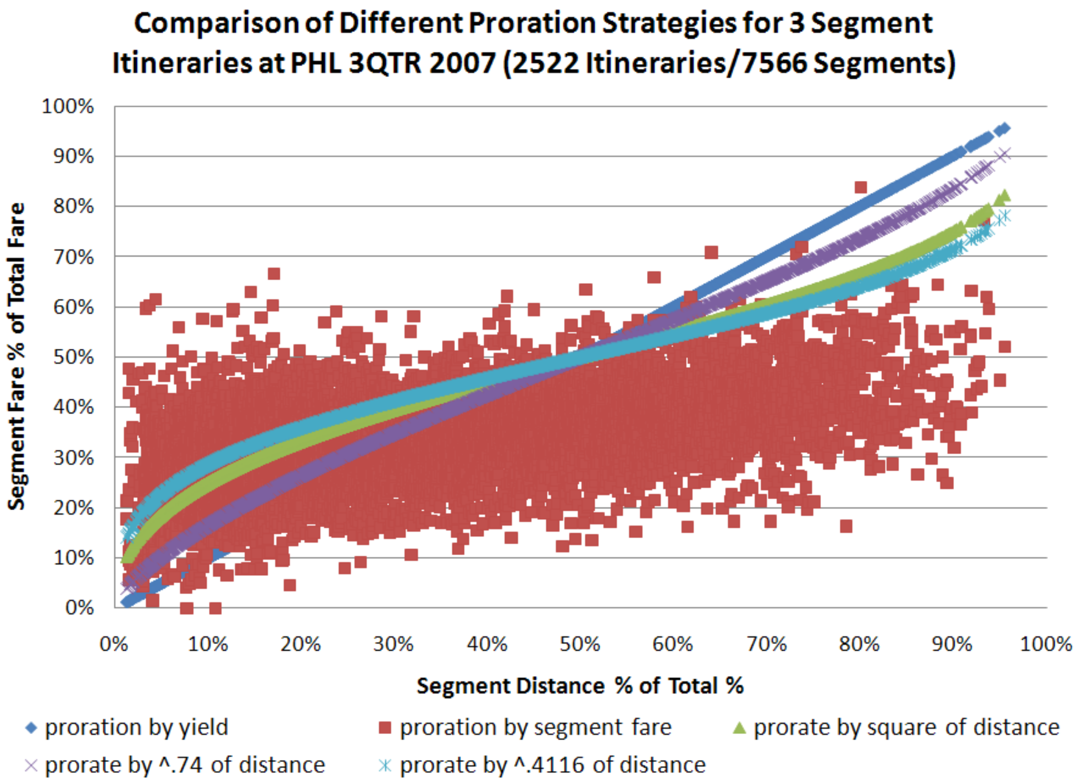

Figure 3: Comparison of different proration approximation techniques versus individual proration by segment fares

In this example none of the approximation techniques exhibited satisfactyory fits to the proration by segment fares technique, however segment fares are not available for all itinerary segments and the approximation techniques eliminate variances between these segment fare percentages. To avoid adding another source of variance in the source data for the ASOM, proration based on the square root of the segment distance is used in this study. Even though the .4166 proration approximation method performs slightly better than the square root method, the square root method is a recognized method in the air transportation industry.

2.5.2 Estimating Cumulative Demand

To generate the cumulative demand the individual passenger itineraries from the DB1B data were aggregated. For example, if there are 2 passengers who bought \$500 segment airfares, 19 passengers who bought \$300 segment airfares, 29 passengers who bought \$200 segment airfares, and 50 passengers who bought \$150 segment airfares, then there are 100 passengers who bought segment airfares at an average fare of \$200. But, not all passengers bought tickets at \$200. Thus, one must consider the curve to determine the loss/gain in passenger demand as prices are increased/decreased. The above simple example suggests that if the airlines were to increase the average airfares for this segment to \$250, then the demand would be reduced to 50 passengers as shown in Table 4; i.e. the cumulative demand of all passengers willing to pay at least \$250 is 50 passengers.

Since the itineraries in the DB1B data represent an itinerary for a quarter (90 days), it is not possible to analyze differences across days of the week, times of the day, and various holidays. Additionally, the

DB1B database reveals no information about the type of ticket purchased (e.g. refundable, coach, frequent flyer upgrade, weekend stay) or how much in advance these tickets were purchased (e.g. six weeks or 3 weeks ahead or day of purchase). Therefore, all of these average behaviors are assumed to be homogeneous in the data.

DB1B Data				Passenger Behavior Data	
Segment Airfare	# of Pax	Segment Revenue	Cumulative Revenue	Average Airfare	Cumulative Pax
$ 500	2	$ 1,000	$ 1,000	$ 500	2
$ 300	19	$ 5,700	$ 6,700	$ 319	21
$ 200	29	$ 5,800	$ 12,500	$ 250	50
$ 150	50	$ 7,500	$ 20,000	$ 200	100

Table 4: Transformation of DB1B data to Passenger Demand Behavior Data

Data representing passenger behavior of demand versus airfares can be found in the Bureau of Transportation Statistics (BTS) Airline Origin and Destination Survey (DB1B) database. (U.S. DOT/BTS 2010). This database is used to determine air traffic patterns, air carrier market shares and passenger flows. For the ASOM this database will be used to derive passenger demand versus revenue curves. The first step of this process is to estimate passenger demand versus airfare curves for each market; this process is discussed in detail in chapter 4.

2.5.3 Estimating Cumulative Demand vs Average Airfare Curves

Once the passenger demand versus airfare curves are derived for the quarterly demand from the DB1B data these curves are extrapolated to the BTS T100 daily demand levels. This is done by multiplying by the ratio of T100 daily demand over the DB1B quarterly demand. These curves are then fit into an exponential representation of passenger demand versus airfare, to derive intercept and slope coefficients from the log-linear regression fit of the data.

Cumulative Passenger Demand = Market Size Coefficient * $e^{(\text{Airfare Sensitivity Coefficient} * \text{Airfare})}$

These derived coefficients are then adjusted to reflect changes in fuel price and its effect on passenger price elasticity and passenger demand. Demand coefficients are decayed 0.52% (adj R2 = 54.0%) for each $1 increase in hedged fuel prices. Price coefficients are decayed 12.59% (adj R2 = 36.7%) for each $1 increase in hedged fuel prices. These decay rates are applied to the individual market demand versus revenue curves to capture the effects of fuel prices changes.

To develop piece-wise revenue versus demand segments, a portion of the revenue curve is plotted from zero demand to four times the historic demand. Departure and Arrival curves are generated for three periods during the day (6:00am to 12:00pm, 12:01pm to 5:00pm, and 5:01pm to 12:00am) and all 15 minute time windows during the day that flights were reported in the ASPM database.

The maximum demand is normalized for the period or 15 minute time window by multiplying the percentage of aircraft seats flown during the period compared to all seats flown. Fifteen piecewise segments are created for the periods and ten for the 15 minute time windows. The demand is calculated in equal intervals up to the maximum demand as shown in the formula below:

Period Demand Intervals = (4 x Daily T100 market demand x (period seats)/(total seats))/15

15 min Demand Intervals = (4 x Daily T100 market demand x (period seats)/(total seats))/10

For each of these data points the demand is plugged back into the fitted exponential demand versus airfare formula, with adjusted coefficients based upon changes in fuel prices as shown below.

Piecewise Demand Airfare = (Ln(Piecewise Demand)-Ln(Demand Coefficient))/(Price Coefficient)

The Revenue is then calculated as the Piecewise Demand Airfare multiplied by the Piecewise Demand.

Figure 4 shows an example of derived period revenue versus demand curves for the BOS-ATL market. Periods 4-6 represent periods for arrivals at the market, ATL in this case. Similar curves are generated for all 15 minute time windows with historic flights.

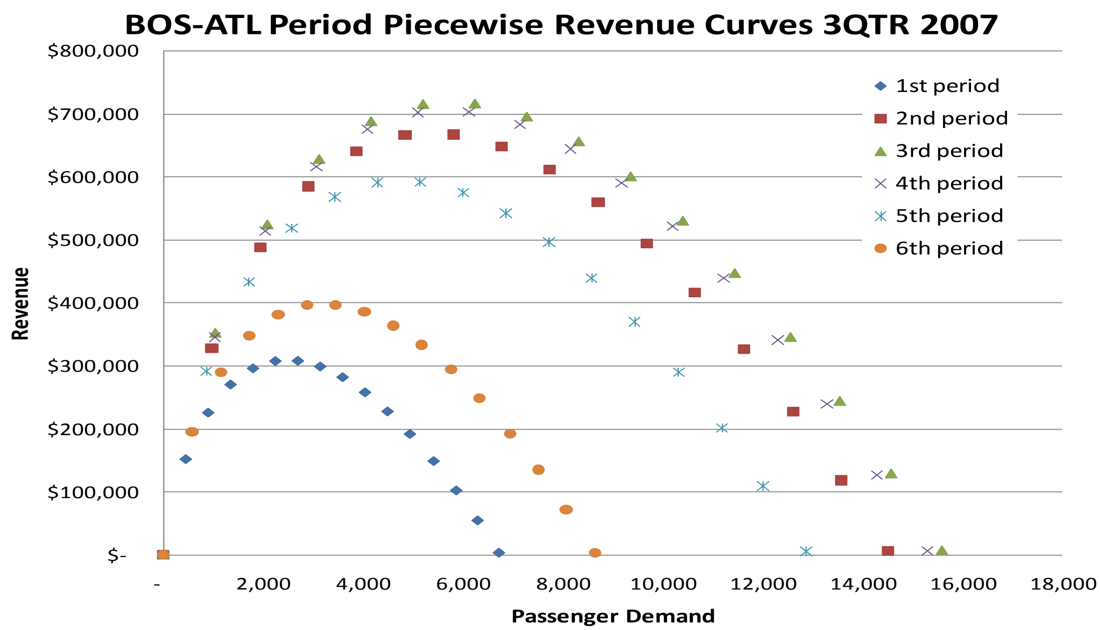

Figure 4: BOS-ATL Period Revenue versus Demand Curves 3QTR 2007

2.6 Model for Adjusting Willingness-to-Pay Curves for Economic Changes

Airfare Sensitivity Coefficients exhibit significant fluctuations as the state of the economy changes (see Figure 5). To account for these changes a unique model was developed by Ferguson (2010) to adjust the market Size Coefficient and the Airfare Sensitivity Coefficient for the exponential willingness-to-pay curves (Figure 6).

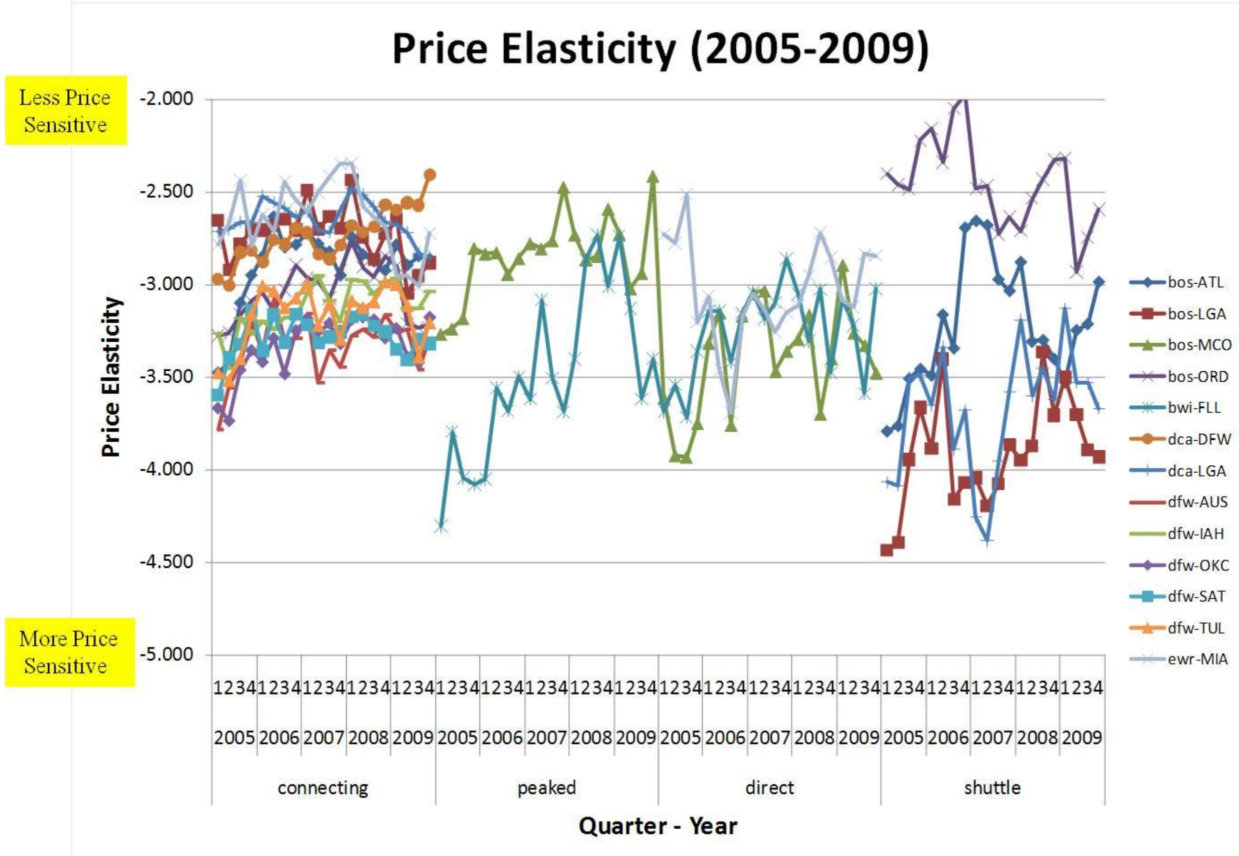

Figure 5: Variation in price elasticity for Q3 from 2005 to 2009.

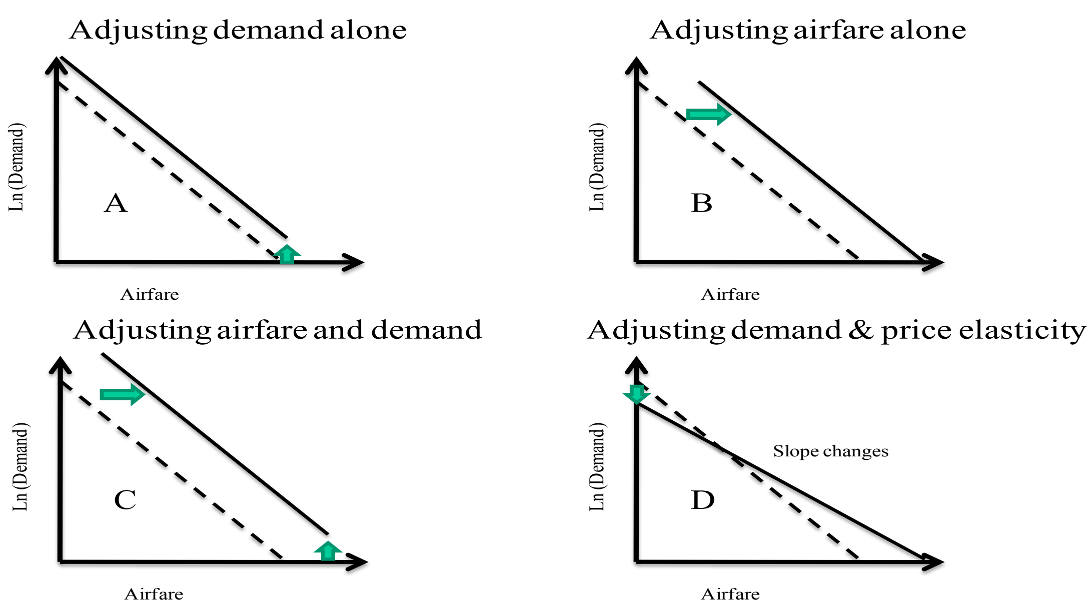

Figure 6: Alternate strategies for adjusting revenue to reflect economic changes

Ferguson (2011) analyzed the effects from fluctuations in fuel prices and national unemployment rates on passenger behavior. The analysis included 600 markets with at least 8 different price points, for 23 quarters, 1st quarter 2005 to 3rd quarter 2010, and from 10 airports (EWR, JFK, LGA, SFO, DFW, BOS, PHL, BWI, IAD, DCA). The markets analyzed in the study are summarized in Table 5.

Airport	small market	large market	Total Markets
BOS	33	19	52
BWI	27	21	48
DCA	39	14	53
DFW	90	12	102
EWR	42	19	61
IAD	50	13	63
JFK	28	18	46
LGA	37	16	53
PHL	58	19	77
SFO	26	19	45
Grand Total	**430**	**170**	**600**

Table 5: Number of Markets examined for effects from Economic fluctuations by size and Airport

Departures from the airports examined in this analysis represented 17.26% of the US domestic departures in 2007, see Table 6.

	Airport Name	% of flights
PHL	Philadelphia International	2.10%
LGA	LaGuardia	1.84%
EWR	Newark Liberty International	1.70%
JFK	Kennedy International	1.47%
SFO	San Francisco International	1.40%
BOS	Logan International	1.72%
IAD	Dulles International	1.38%
DCA	Ronald Reagan Washington National	1.33%
BWI	Baltimore/Washington International	1.27%
DFW	Dallas/Ft Worth International	3.06%
Total Percentage of US Domestic Flights		17.26%

Table 6: Percentage of 2007 US Domestic Flights from Airports in this analysis

The analysis was conducted using a tiered regression approach; first 27,600 regressions were performed in Matlab to quantify the coefficients for the 600 markets for 23 quarters and for two different fitting strategies (600 x23x2=27,600). The market demand coefficient and the price coefficient from the exponential fit of the exponential, is shown in the equation below.

$$Passenger\ Demand = Market\ Demand * exp^{-price\ coeff * avg\ airfare}$$

Next a longitudinal multiple-regression is performed in Mini-tab to determine the functional contribution to the variance between these coefficients from changes in fuel prices and national unemployment.

Additionally, factors that change over time and between markets are used to develop a better model for exponential coefficients over time and between markets. Specifically this analysis attempts to identify the following functional relationships:

$$\begin{aligned} &Exponential\ Market\ Demand\ Coefficient \\ &\quad = intercept + a * fuel\ price + b * unemployment\ rate + c \\ &\quad * effective\ number\ of\ airlines + d * daily\ frequency\ of\ flights\ +\ e \\ &\quad * market\ distance + large\ market\ difference\ from\ small\ markets \\ &\quad + airport\ difference\ from\ Boston\ airport \end{aligned}$$

$$\begin{aligned} &Exponential\ Price\ Coefficient \\ &\quad = intercept + a * fuel\ price + b * unemployment\ rate + c \\ &\quad * effective\ number\ of\ airlines + d * daily\ frequency\ of\ flights\ +\ e \\ &\quad * market\ distance + large\ market\ difference\ from\ small\ markets \\ &\quad + airport\ difference\ from\ Boston\ airport \end{aligned}$$

The following factors are also included in the analysis to capture variances between coefficients for different markets over the 23 quarters of examination. The inverse of the Herfindahl-Hirschman Index (Hirschman 1964) or effective number of airlines for each market is included in the model to capture differences in the coefficients that can be explained by competition differences. The average daily frequency of flights to the market is included in the model to capture differences in the coefficients that can be explained by frequency of service. The market distance is included in the model to capture differences in the coefficients that can be explained by this factor. The correlation analysis of these factors are shown in Table 7.

		Market Distance	Effective # of Airlines
Effective # of Airlines	**pearson correlation coeff**	-0.026	
	P-value	0.002	
Daily Frequency of Service	**pearson correlation coeff**	-0.054	0.004
	P-value	0	0.632

Table 7: Correlation Analysis of Market Factors

Dummy variables (0 or 1) were included in the regression to capture differences in seasonality, market size and differences between airports. Dummy variables for 1st, 2nd and 4th quarter capture the differences in the coefficients from these quarters compared to 3rd quarter. A dummy variable for larger markets captures the differences in the coefficients from large markets compared to small markets. Dummy variables for EWR, JFK, LGA, SFO, DFW, PHL, BWI, IAD, and DCA capture the differences in the coefficients from these airports compared to BOS.

In the end, a longitudinal regression is performed in Mini-tab to determine the functional contribution to the variance between these coefficients from changes in fuel prices and national unemployment. These coefficients of change for the market demand and price coefficients are then regressed against market distance to determine the impact market distance has on the impact of fuel prices and national unemployment on the exponential demand function.

The results of these 24 longitudinal multiple-regressions are shown in Table 8. The analysis shows the difference between airports in their exponential passenger demand versus average airfare curves to fluctuations in economic conditions. The green highlighted cells show positive coefficients for changes in fuel prices or national unemployment rates. The yellow cells highlight coefficients chosen for use in the ASOM to reflect the fluctuations in economic conditions. The empty cells represent cases where no significant statistical relationships exist between demand and price coefficients to changes in fuel prices or national unemployment rates.

Markets	Effect on Exponential Demand Coefficient		Effect on Exponential Price Coefficient	
	$1 Increase in Fuel Price	1% Increase in Unemployment	$1 Incraese in Fuel Price	1% Increase in Unemployment
All	-0.52%	-0.33%	-12.59%	-1.8%
Major	-0.67%	-0.43%	-15.34%	-3.16%
DFW			-13.52%	-1.29%
BOS			-6.81%	1.56%
LGA			-4%	1.57%
JFK	1.8%		-9.49%	-1.17%
EWR	-3.5%	-0.97%	-5.9%	-3.2%
SFO	-1.35%	-0.85%	-18.86%	-3.1%
PHL	0.76%			
BWI			-10.47%	-3.33%
IAD	-2.19%	-0.86%	-25.5%	-5.09%
DCA	-0.88%	-0.39%	-21.27%	-3.475

Table 8: Impact of Fluctuations in Economy on Exponential Demand and Price Coefficients

The analysis of individual airports showed that for several airports the demand coefficient was not sensitive to changes in economic activity. On the other hand JFK and PHL showed positive increases in demand due to significant changes in airline service at these airports (i.e. Delta at JFK and SWA/USAirways at PHL). These anomalies may reflect increased demand due to airport business expansion and since this information is not reflected in any data provided, it is incorrectly reporting the source of demand increases to the economic changes.

The analysis showed that only PHL's price coefficient was insensitive to changes in the economy. In most cases other than BOS and LGA, when the economy worsened either through increased fuel prices or increased unemployment rates passengers became less price sensitive. In other words, as the economy worsened, although total demand decreased, passenger who did fly were less sensitive to price changes. Further longitudinal analysis of the sensitivity of the demand and price coefficients to market distance did not reveal any statistically significant results.

Table 9 Shows the final results from this analysis of economic fluctuations on exponential fits of passenger versus average airfare curves. As previously discussed an increase in fuel prices will reduce passenger demand by 0.52% and reduce passenger price sensitivity by 12.59%. Similarly a 1% increase in the unemployment rate will reduce passenger demand by 0.33% and reduce passenger price sensitivity by 1.80%. The analysis also showed that when an additional flight leaves a market, passenger price sensitivity is reduced 2.71% and passenger demand is reduced 0.94%. Similarly adding additional flights per day for a market reduces the price sensitivity of the passenger by 1.27%.

	Left 5% and Right 10% Trimming	
Effects from:	% Change in demand coefficient	% Change in price coefficient
15% increase in fuel price	-0.52%	-12.59%
1% increase in unemployment	-0.33%	-1.8%
Additional flight leaves a market		-2.71%
Additional daily flight	0.94%	-1.27%
Additional mile of market distance	0.0057%	-0.0459%

Table 9: Effects on Exponential Demand and Price Coefficients from economic or market changes

2.7 Model for Aircraft Operating Cost

Aircraft direct operating costs, flights hours, and gallons of fuel issued for flight operations reported by the airlines for different aircraft types are found in the BTS P52 database. (U.S. DOT/BTS 2010) This data is combined with the average aircraft sizes as reported in the BTS T100 database, to evaluate aircraft costs by seat classes of aircraft as shown in Table 10.

Aircraft Type	Gallons Fuel Purchased	Block Hours Flown	Total Flying Operations (Thousands)	Aircraft Fuel (Thousands)	Total Costs	Seat Class (25 incre-ments)	Average Number of Seats
Dassault-Breguet Mystere-Falcon	2403.89	6.26	14256.47	9186.2	27474.84	25	15
Embraer Emb-120 Brasilia	176006.8	1015.66	930287	359298	1373276	25	30
British Aerospace Jetstream 41	33486.27	185.33	171115.2	47609.18	243776.72	25	30
Dornier 328	1956.98	9.81	11525.63	2087.81	19902.7	25	32
Dornier 328 Jet	65247.15	147.93	151197.4	61217.16	209081.4	25	32
Saab-Fairchild 340/B	170075.9	854.23	766019.62	224019.35	1161626.33	25	34
Dehavilland Dhc8-100 Dash-8	45871.36	224.08	229235.62	117181.03	358769.34	25	37
Dehavilland Dhc8-200q Dash-8	78240.45	329.16	384947	126905	607658	25	37
Embraer-135	477869.9	958.14	1240000.74	718826.91	1728413.95	50	38
Embraer-140	539028.2	1127.53	1481180.45	1072785.3	2119802.81	50	44
Aerospatiale/Aeritalia Atr-42	9136.27	36.35	55477.16	9283.13	89056.04	50	46
Canadair Rj-100/Rj-100er	361640.3	737.85	1335160.16	706771.71	1745900.91	50	50
Canadair Rj-200er /Rj-440	4060526	9247.47	14160262.92	6840975.63	18732150.36	50	50
Embraer-145	3139725	6909.48	7807875.66	3369430.95	11212819.03	50	50
Fokker F28-4000/6000 Fellowship	2009	2.49	2857	1636	4644	50	60
Aerospatiale/Aeritalia Atr-72	170343.5	662.94	1137018.16	338903.66	1759517.69	75	65
Canadair Rj-700	1683596	3467.29	5477379.84	3163834.42	7604187.55	75	68

Aircraft Type	Gallons Fuel Purchased	Block Hours Flown	Total Flying Operations (Thousands)	Aircraft Fuel (Thousands)	Total Costs	Seat Class (25 increments)	Average Number of Seats
Embraer 170	228303.4	731.64	570969.61	232515.23	942364.52	75	71
Dehavilland Dhc8-400 Dash-8	200529.6	523.84	833386	413604	1293094	75	75
Embraer Erj-175	64804.75	116.9	98197.93	47384.11	156174.02	75	78
Canadair Crj 900	597189.6	1004.35	1770298.96	1167686.02	2334563.78	75	83
Avroliner Rj85	13782.96	24.63	22109.3	13.7	36775.25	75	87
British Aerospace Bae-146-300	78350.63	91.79	215788.03	99377.96	325445.95	75	87
Mcdonnell Douglas Dc-9-10	31214.94	31.85	79877.72	28730.55	121734.84	100	90
Mcdonnell Douglas Dc-9-15f	15112.48	19.59	61434.37	39173.56	83325.7	100	90
Boeing 727-100	89455.27	73.54	459196	137200	1442355	100	94
Embraer 190	439637.8	606.18	1601305.17	971057.12	1931610.52	100	100
Mcdonnell Douglas Dc-9-30	1231420	1186.76	3117222.08	1932425.05	4620316.34	100	100
Fokker 100	180704	218.7	416299	151980	559666	100	100
Mcdonnell Douglas Dc9 Super 87	47186.41	46.35	127370.33	105501.8	155046.53	100	109
Mcdonnell Douglas Dc-9-40	244007.4	218.76	766548.19	475652.48	1050707.55	100	110
Airbus Industrie A-318	172903.3	195.73	488438.02	338213.44	605169.03	125	114
Boeing 717-200	2100535	2516.82	7367710.04	3818645.19	8933208.22	125	114
Boeing 737-500	2035251	2357.15	6189121	3441500	8179576	125	115
Boeing 737-200c	125265.4	116.75	309217.41	183634.75	518935.59	125	117
Mcdonnell Douglas Dc-8-40	3468.49	1.9	9672.78	778.42	17397.54	125	124
Mcdonnell Douglas Dc-9-50	600379	495.63	1602135	1144273	2040279	125	125
Airbus Industrie A319	5965815	7344.36	19479203.74	11318197.32	24191601.74	125	127
Boeing 737-100/200	631073.6	639.57	1537183.53	733806.84	2319208.55	125	127
Boeing 737-300	7583485	8761.68	21227271.16	11754429.62	30415349.76	125	133
Boeing 737-700/700lr	8033821	9908.06	23099102.02	14313398.33	29167134.48	125	136
Boeing 737-400	1703311	1937.18	5494006.94	3022761.27	7382254.33	150	138
Mcdonnell Douglas Dc9 Super 80/Md81/2/3/7/8	11978567	10523.74	33566244.76	21399313.23	43709105.61	150	140
Boeing 727-200/231a	1213988	807.12	4257408.5	1897688.01	6632034.76	150	141
Airbus Industrie A320-100/200	8783805	10031.71	26972609.73	16743104.12	35359547.69	150	150
Mcdonnell Douglas Md-90	313426.6	318.71	935517	607758	1245212	150	150
Boeing 737-800	7106670	7700.46	23304509.11	13583302.98	29811762.79	150	153
Boeing 737-900	811003.2	848.95	2352272	1561211	3063690	175	170
Boeing 767-200/Er/Em	2517373	1619.52	6349241.16	4260921.76	9158596.93	175	171
Mcdonnell Douglas Dc-8-61	3473.92	1.88	14555	7071	19725	175	180

Aircraft Type	Gallons Fuel Purchased	Block Hours Flown	Total Flying Operations (Thousands)	Aircraft Fuel (Thousands)	Total Costs	Seat Class (25 incre-ments)	Average Number of Seats
Mcdonnell Douglas Dc-8-72	11744.16	7.65	44137.39	30785.85	62830.29	175	180
Boeing 757-200	16694830	14007.83	49377616.45	31022288.05	69973647.76	175	183
Airbus Industrie A321	1060516	1073.18	2842535.73	1936926.57	3600290.58	175	185
Airbus Industrie A310-200c/F	767805	429.74	2991040	1315032	5622999.93	225	220
Mcdonnell Douglas Dc-8-62	97033.14	50.54	254571.52	177533.16	360556.77	225	220
Mcdonnell Douglas Dc-8-63f	59297.74	25.66	198211.21	123187.47	249604.58	225	220
Mcdonnell Douglas Dc-8-71	225865.2	122.47	952129.25	455518.18	1468052.59	225	220
Mcdonnell Douglas Dc-8-73	275093.1	144.99	733154.69	269276.61	1320971.81	225	220
Mcdonnell Douglas Dc-8-73f	87113.69	49.43	374761.49	175154.96	492222.39	225	220
Boeing 757-300	1316069	956.56	3668839.49	2586813.74	4641399.81	225	221
Boeing 767-300/300er	11775727	7131.15	34602079.73	22764068.58	44617006.46	250	239
Airbus Industrie A300b/C/F-100/200	35624.12	15.95	52573.9	2612.92	85749.97	250	250
Airbus Industrie A300-B2	286.91	0.14	1989.61	731.77	1989.61	250	250
Lockheed L-1011-1/100/200	41634.55	14.9	102808.5	51515.48	131640.29	250	250
Mcdonnell Douglas Dc-10-40	19606.23	6.69	70792.74	52398.1	91378.57	250	250
Airbus Industrie A300-600/R/Cf/Rcf	2938942	1553.58	11174746	5465594	15790284.36	275	267
Boeing 767-400/Er	2313675	1243.34	5973817	4604816	7762714	275	268
Mcdonnell Douglas Dc-10-10	1796053	720.14	4412822.22	3172960.74	7847969.14	275	270
Mcdonnell Douglas Dc-10-30cf	138266.4	49.8	419810.23	341994.45	480753.42	275	270
Lockheed L-1011-500 Tristar	124771.2	47.57	321599.69	197890.73	427804.88	275	283
Boeing 777-200/200lr/233lr	10143473	4478.08	26442390	19446111	36478836	300	289
Airbus Industrie A330-200	2018098	1022.81	5668275.9	4254745.83	6844592.38	300	297
Airbus A330-300	188104	93.84	477224	415195	581625	300	298
Mcdonnell Douglas Dc-10-30	2466383	897.04	5951681.62	3621613.94	9268779.23	300	304
Mcdonnell Douglas Md-11	5858319	2263.7	19207907.5	10144587.84	26259951.67	325	323
Boeing 747-400	7696316	2247.73	18252934.26	12401840.53	22459693.11	375	363
Boeing 747c	28365.98	9.68	121403	65763.38	121674.68	400	400
Boeing 747f	1251978	334.63	2841899.82	1993671.56	3555480.71	400	400
Boeing 747-200/300	3772962	1006.65	7151432.56	4482485.25	10198427.08	425	430
Boeing 747-100	791881.6	201.64	1586895.8	1201277.28	2166858.08	450	452

Table 10: BTS P52 reported costs, flight hours and gallons issued 3QTR 2002 – 4QTR2010

This data is aggregated by seat class to provide aircraft direct operating costs by hour and average fuel burn rates by aircraft class for a current aircraft scenario, for a modern aircraft smoothed scenario, and for a best in class (BIC) scenario as shown in Table 11. Note current reporting aircraft are absent for the 200 and 350 seat classes.

	Current as Reported in BTS		**Modern Smoothed**		**BIC Smoothed**	
Size	Gallons/ Hr	Avg $/ hr - fuel	Gallons/ Hr	Avg $/ hr - fuel	Gallons/ Hr	Avg $/ hr - fuel
25	206	$ 616	164	$ 320	139	$ 340
50	452	$ 703	334	$ 618	283	$ 634
75	459	$ 704	511	$ 893	433	$ 882
100	942	$ 1,058	695	$ 1,145	589	$ 1,084
125	843	$ 1,059	885	$ 1,374	750	$ 1,239
150	979	$ 1,144	1082	$ 1,580	918	$ 1,348
175	1201	$ 1,262	1286	$ 1,763	1091	$ 1,411
200	**no historic data reported**		1497	$ 1,923	1270	$ 1,428
225	1589	$ 2,287	1715	$ 2,061	1454	$ 1,398
250	1651	$ 1,660	1939	$ 2,175	1644	$ 1,322
275	2023	$ 2,357	2170	$ 2,267	1840	$ 1,200
300	2282	$ 1,664	2408	$ 2,336	2042	$ 1,200
325	2588	$ 4,004	2652	$ 2,382	2250	$ 1,200
350	**no historic data reported**		2907	$ 2,393	2466	$ 1,200
375	3424	$ 2,603	3162	$ 2,405	2682	$ 1,200
400	3741	$ 2,535	3426	$ 2,382	2907	$ 1,200
425	3748	$ 2,651	3698	$ 2,337	3138	$ 1,200
450	3927	$ 1,912	3976	$ 2,268	3374	$ 1,200

Table 11: ASOM Cost factors and fuel burn rates aggregated by aircraft sizes for current, modern, and best in class scenarios

The hourly air fuel consumption is calculated by dividing total air fuel numbers issued for the aggregate aircraft class by the total hours flown by the same seat class.

The hourly aircraft direct expenses not related to fuel consumption are calculated by subtracting total fuel costs from total direct operational costs for the aggregate aircraft class, then dividing this by the total hours flown by the same seat class. These operational costs varied based upon the aircraft type.

The current aircraft reported in the BTS P52 database, shown in Figure 7, do not reveal smooth curves when plotting direct operating costs minus fuel and fuel burn rates per seat. This was an important observation of the input data for the AFRS-OM model since the model will be maximizing profit by subtracting direct costs from revenue. Early runs of the AFRS-OM model showed the model did not like to choose the 50 or 100 seat classes in the schedules, where historically these sized aircraft are flown. Since the burn rates for these classes are much higher than their neighboring seat classes these flight options were typically avoided. These cost factors and burn rates are used in the current aircraft scenarios.

To develop a modern aviation cost and performance scenario, all aircraft fuel burn rates higher than 10 gallons per seat-hour were removed and regressions were performed to derive new cost factors and burn rates for a modern fleet of aircraft. Putting all the aircraft on the same regression line of costs per seat-hour and gallons per seat-hour, removes any biases of the AFRS-OM choosing an aircraft type over another because of lags which exist in the air transportation fleet modernization programs. These new formulas also allow cost factors and burn rates to be assigned to the 200 and 250 seat classes. The formulas are as follows:

Gallons/ Seat-Hour = (0.0054 Seats) + 6.4057, with an R^2 of 0.4065

Direct $ / Seat-Hour = (-0.0183 Seats) + 13.276, with an R^2 of 0.4722

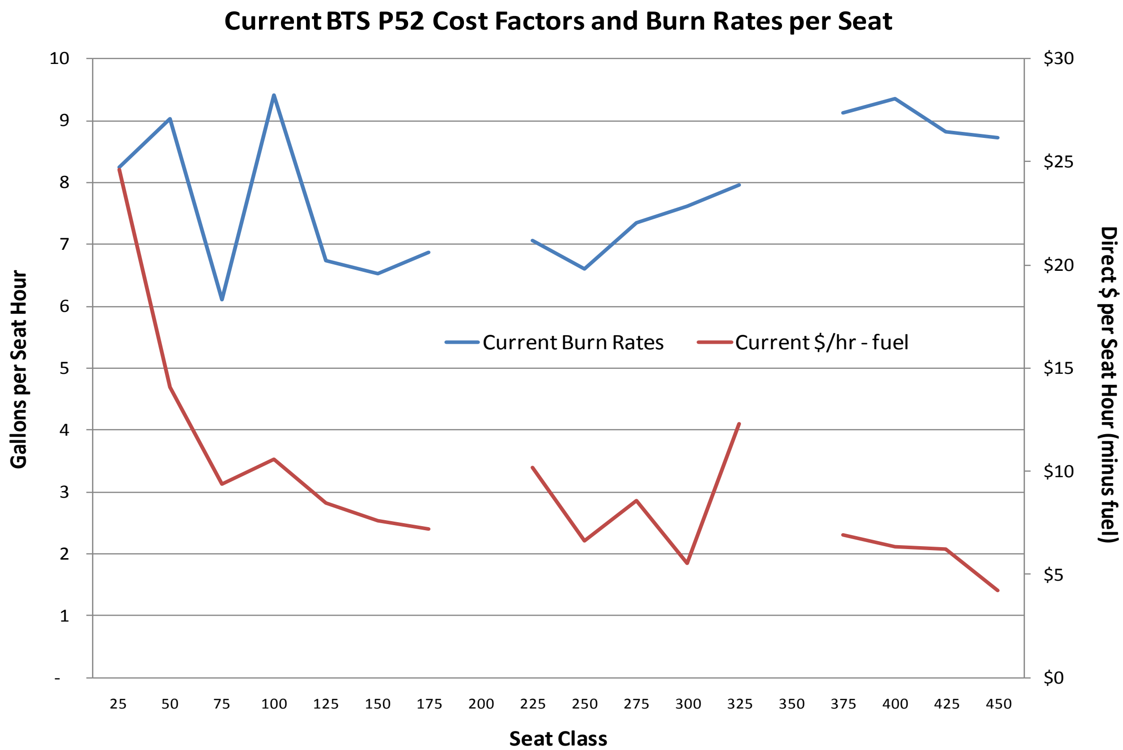

Figure 7: Current BTS P52 Cost Factors and Fuel Burn Rates per Seat

Note (Figure 8) even when eliminating the older less efficient aircraft from this analysis there are no economies of scale observed for aircraft burn rates per seat versus aircraft size.

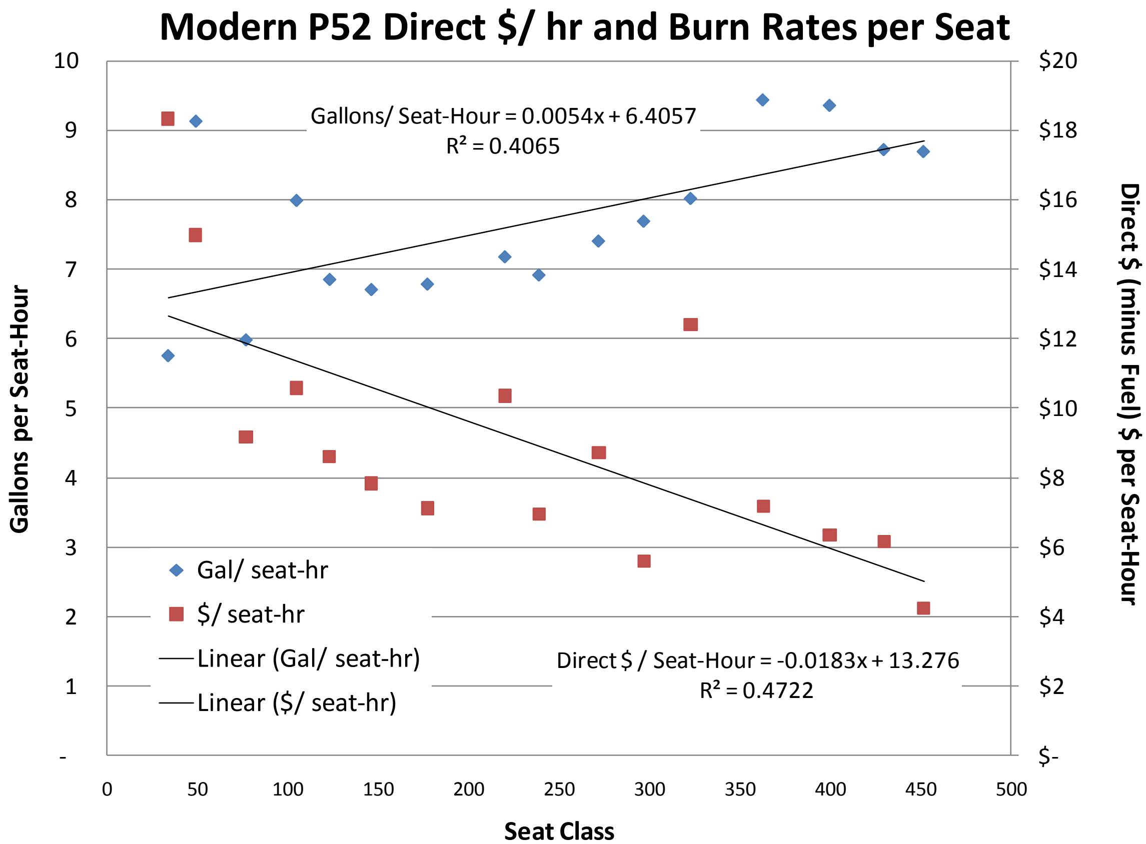

Figure 8: Modern Aircraft scenario Direct Cost Factors and Burn Rates/Seat, with regressions

To develop a best in class aviation cost and performance scenario, the following aircraft in Table 12 were regressed for cost factors and burn rates per seat as shown in Figure 9.

Name	Seats	gal/hr-seat	$/hr-seat
Dehavilland Dhc8-100 Dash-8	37	5.53	$ 13.52
Aerospatiale/Aeritalia Atr-42	46	5.46	$ 17.03
Airbus Industrie A319	127	6.40	$ 8.75
Airbus Industrie A320-100/200	150	5.84	$ 6.80
Airbus Industrie A321	185	5.34	$ 4.56
Boeing 757-300	221	6.23	$ 5.12
Boeing 767-300/300er	239	6.91	$ 6.95
Boeing 767-400/Er	268	6.94	$ 6.95
Airbus Industrie A330-200	297	6.64	$ 4.65

Table 12: Best in Class Aircraft from BTS P52 database

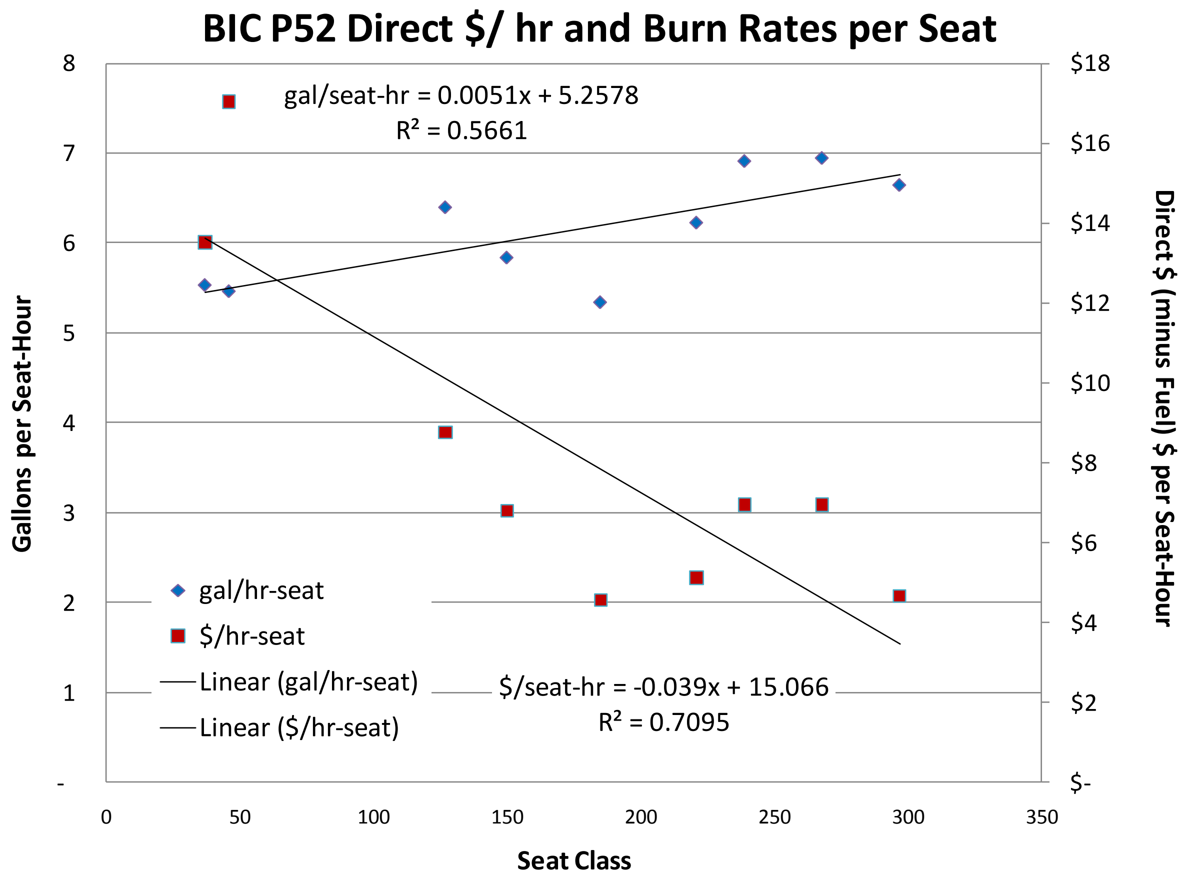

Figure 9: Best in Class Aircraft scenario Direct Cost Factors and Burn Rates per Seat, with regression formulas

Putting all the aircraft on the same regression line of costs per seat-hour and gallons per seat-hour (Figure 10), removes any biases of the AFRS-OM choosing an aircraft type over another because of lags which exist in the air transportation fleet modernization programs. These new formulas also allow cost factors and burn rates to be assigned to the 200 and 250 seat classes. The formulas are as follows:

Gallons/ Seat-Hour = (0.0051 Seats) + 5.2578, with an R^2 of 0.5661

Direct $ / Seat-Hour = (- 0.039 Seats) + 15.066, with an R^2 of 0.7095

Note that even limiting the analysis to the Best-in-Class by aircraft size, there exist only marginal economies-of-scale observed for aircraft burn rates per seat versus aircraft size.

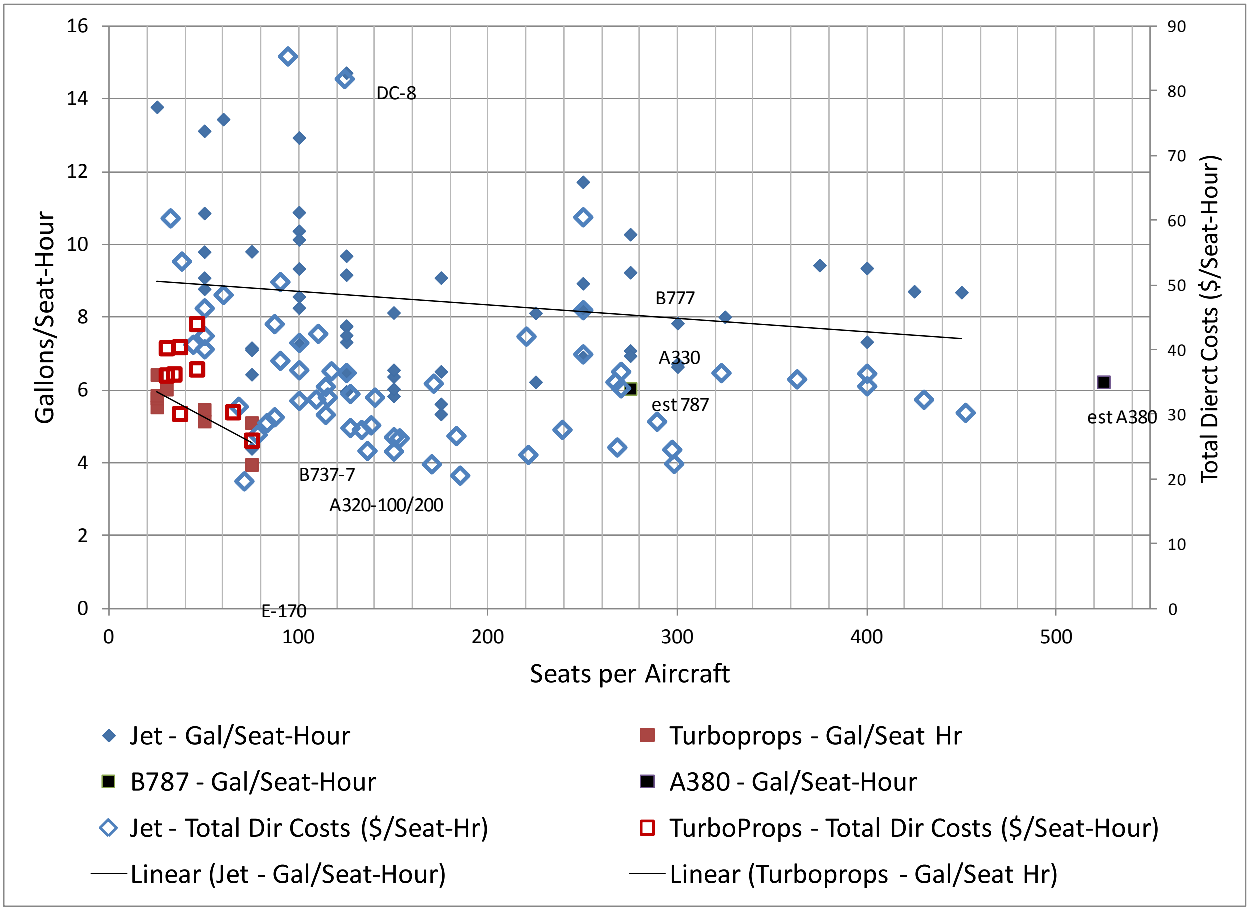

Figure 10: Fuel Burn Rates per Seat (on primary y-axis) and Total Cost Rate (on secondary y-axis) by Aircraft Size. Data Source: BTS P-52 Data.

The flight costs for markets are derived by multiplying the average scheduled flights times from the FAA ASPM database by the aircraft respective cost factors, burn rates and fuel costs as shown below.

Market flight costs = (Direct $/ hr + (Gallons/ hr x Fuel Price) x avg scheduled block times + landing fees

The landing fees applied in the ASOM are shown below in Table 13.

Aircraft that have historically been used for domestic flights are grouped into fleet classes at increments of 25 seats. For example, aircraft between 88 seats and 112 seats would be in the 100 seat fleet class as shown in Table 14. As this table shows 92.14% of the passengers flown and 81.53% of the departures were performed on seven fleet classes for aircraft between 13 and 187 seats. Since the AFRS-OM selects only aircraft for each market’s schedule based on aircraft historically flown to each market, the model will be for the most part choosing between these seven fleet classes to determine the most profitable aircraft class to meet the demand.

Class	Avg Weight	Avg Seats	landing fee	$/ seat-landing
25	39	26	$ 112	$ 4.25
50	48	50	$ 137	$ 2.74
75	76	76	$ 218	$ 2.86
100	116	103	$ 330	$ 3.21
125	125	124	$ 356	$ 2.86
150	129	147	$ 367	$ 2.49
175	241	168	$ 686	$ 4.09
200	192	204	$ 546	$ 2.68
225	332	220	$ 945	$ 4.30
250	317	250	$ 904	$ 3.61
275	373	270	$ 1,062	$ 3.93
300	460	305	$ 1,312	$ 4.30
325	498	327	$ 1,421	$ 4.33
350	537	350	$ 1,530	$ 4.37
375	575	372	$ 1,640	$ 4.40
400	614	394	$ 1,749	$ 4.43
425	652	416	$ 1,859	$ 4.47
450	585	452	$ 1,668	$ 3.69

Table 13: ASOM Landing Fees

Fleet Class	# of Aircraft types	seat range	% Departures	% Passengers
0	42	<13	5.27%	0.24%
25	17	13 - 37	11.59%	2.91%
50	6	38 - 62	24.79%	12.65%
75	11	63 - 87	8.59%	6.55%
100	4	88 - 112	1.65%	1.72%
125	9	113 - 137	24.59%	32.81%
150	6	138 - 162	16.14%	26.24%
175	4	163 - 187	5.78%	12.18%
200		188 - 212	0.00%	0.00%
225	1	213 - 237	0.39%	1.06%
250	1	238 - 262	0.74%	2.14%
275	10	263 - 287	0.43%	1.37%
300	2	288 - 312	0.01%	0.04%
325		313 - 337	0.00%	0.00%
350	1	338 - 362	0.00%	0.00%
375	1	363 - 387	0.03%	0.09%
400	1	388 - 412	0.00%	0.00%
425		413 - 437	0.00%	0.00%
450	1	438 - 462	0.00%	0.00%

Table 14: Summary, seat-capacity groups of aircraft historically used for domestic operations

Flight demand is not captured at the 15 min level of fidelity, as market demand by time of day is assumed to be proportionally equal to supply (seats) by time of day. The aircraft selected in the schedule is assumed to have a load factor of 80% or better. The airline will need to obtain sufficient revenue to have the flight profitable at an 80% load factor, or the optimization will choose a smaller aircraft size or move the flight to an alternative time period. The model allows demand to spill into different time slots, but restricts demand from moving between morning, afternoon, or evening time periods. This is done by nesting demand into 3 periods (12am-12pm, 12pm-5pm and 5pm-12am) to ensure the sum of the 15 minutes demand does not exceed the demand from the period.

2.8 AFRS-OM Outputs

There are two text files created by the model for each run. A sample log file, shown in Figure 11, illustrates the number of markets or sub problems initiated for the model. This file also identifies the number of these initial markets that are profitable. This file shows the number of iterations back and forth between Main and Sub-problems. Lastly, the expected profit from the final airport's schedule is shown.

init_problems():91 markets. (initial markets)

add ABE_0_1 ,z = 14580.140000000003 cost = 13142.0, frequency = 2.0(2), throughput= 300.0, gap=0.0, reduced cost =14580.139000000003

……….

add TYS_0_64 ,z = 1186.4142857142815 cost = 14124.0, frequency = 2.0(2), throughput= 150.0, gap=0.0, reduced cost =1186.4132857142815

Generate columns – 64 Profitable Markets

add ABE_1_65 ,z = 14580.139999999994 cost = 13142.0, frequency = 2.0(2), throughput= 300.0, gap=0.0, reduced cost =14530.138999999994

……….

add TYS_1_128 ,z = 1186.4142857142838 cost = 14124.0, frequency = 2.0(2), throughput= 150.0, gap=0.0, reduced cost =1136.4132857142838

generate_columns() ended with 128columns in master_vars

generate_columns() ended with 64 columns generated at the current node.

Generate columns

add ABE_2_129 ,z = 14580.139999999996 cost = 13142.0, frequency = 2.0(2), throughput= 300.0, gap=0.0, reduced cost =2910.1389999999956

……..

add STL_6_311 ,z = 8221.784615384611 cost = 99270.0, frequency = 10.0(10), throughput= 750.0, gap=0.0, reduced cost =428.78361538461104

add TPA_6_312 ,z = 312182.0929837098 cost = -5.3657078780133816E-12, frequency = 10.0(10), throughput= 2750.0, gap=0.0, reduced cost =312132.09198370983

generate_columns() ended with 312columns in master_vars

Total profit: 6743454.0

Figure 11: AFRS-OM Log File

The second output file is the schedule file, Figure 12. This file shows all of the individual flights on the airport's final schedule. For each flight or row of data the market served, the size of aircraft, the departure time, the arrival time and the frequency is shown.

The aircraft sizes are grouped into classes in 25 seat intervals; to determine the class, the size is multiplied by 25 seats, for example the first row identifies a size 6 as 6*25 = 150 seat aircraft.

The departure and arrival times are shown in 15 min intervals starting with 1 or 12:15am. The arrival or departure time which is less than 96 (there are 96 15-minute intervals in a 24-hour day) determines whether this is an arrival or departure from the airport modeled. To determine the arrival or departure time at the other airport subtract 96 from its number. For example the first row shows a departure from the modeled airport to ABE at 76 (1900 hrs or 7:00pm) and this flight arrives at ABE at 178-96 = 82 (2030hrs or 8:30pm ABE local time). All times reported in the schedule are local times.

This schedule data from ASOM can be copied into a spreadsheet program to generate charts and tables and compare different scenarios based on different input parameters.

Market	Size	Dep Time	Arr Time	Freq
ABE	6	76	178	1.0
ABE	6	176	86	1.0
ACK	2	39	143	1.0
ACK	2	123	35	1.0
……				
TYS	3	73	180	1.0
TYS	3	152	67	1.0

Market	Fleet si	i	j	freq	local ti	seats	year	qtr	airport	cap	fp	dist	ASM
ABE	6	76	178	1	76	150	2009	3	EWR	9	8	67	10050
ABE	6	176	86	1	86	150	2009	3	EWR	9	8	67	10050
ACK	2	39	143	1	39	50	2009	3	EWR	9	8	218	10900
ACK	2	123	35	1	35	50	2009	3	EWR	9	8	218	10900
ALB	3	26	130	1	26	75	2009	3	EWR	9	8	143	10725

Comment	profit & fleet #2			
airport	EWR			
year	2009			
cap	12			
fp	8			
	Values			
Row Labels	**Sum of ASM**	**Sum of seats**	**Sum of freq**	Average Size
ATL	6518750	8750	42	
Grand Total	**99574150**	**94350**	**628**	150.24

Figure 12: AFRS-OM schedule file

3 AFRS-OM VALIDATION AND LIMITATIONS

The following outputs of the ASOM were analyzed: (1) the number of profitable markets served, (2) the daily domestic flights by market, (3) the average revenue per seat, (4) the average aircraft size in seats per operation, and (5) the overall profitability of each airport studied. The controls or exogenous factors for the model are fuel prices and airport capacity limits.

The analysis of statistically significant trends between the exogenous factors and the ASOM outputs required the following multi-step process:

3.1 Validation

Validation of the model is conducted using historic data. The model inputs are set to the actual data from the quarter of the year evaluated. The model outputs are checked against the actual data.
The validation is performed for consistency in trends and in relationships (as the AFRS-OM does not account for flight schedules, or aircraft assigned, for reasons other than profit, e.g. marketshare, strategic positioning, …), and balances arrivals and departures, therefore no banking is allowed.

A summary is shown of a consistency check for markets served, scheduled flights per day and aircraft gauge when compared to the historic behavior of the airlines serving these five airports (LGA, EWR, JFK, SFO, PHL) for three different economic scenarios: 3QTR07 with \$2 fuel prices. The AFRS-OM scheduled on average 2% fewer markets and 12% fewer flights for aircraft 5% smaller. The results are summarized in Table 15.

Statistic	Markets	Flights per Day	Aircraft Size
Mean	-2%	-12%	-5%
Standard Deviation	2%	5%	19%
Range	6%	19%	64%
Minimum	-6%	-21%	-28%
Maximum	-21%	-2%	36%
Count	15	15	15

Table 15: ASOM results for consistency check - geographic access

3.2 Limitations

The AFRS-OM models exhibits the following limitations:

1. The model considers airline decisions on markets, schedule and fleet exclusively based on operational profitability. The decision-making does not account for strategic positioning of aircraft or competitive market share considerations.

2. The model chooses only profitable markets to serve and does not consider staying in unprofitable markets during down economic times in order to retain market share. As a consequence, the model is likely to move out of markets more rapidly than might actually occur during recessionary periods.

3. The model accounts for only a single airline serving these profitable markets, which finds the optimal schedule minus airline competition. For the analysis of EWR and SFO (hubs for large carriers), this assumption may be closer to actual behavior than at airports such as LGA where there is significant competition at the airport. For example, this single airline model will choose to use a larger aircraft in shuttle markets rather than have (as is currently the case) eight departures from LGA to DCA in a single hour.

4. The model balances arrivals and departures and does not model the advantages of banking (i.e. having many incoming flights during one period that would allow passengers to connect to other flights during the next few periods).

5. The model also tries to satisfy the demand based on historic data. Thus, it does not allow demand from the morning to spill into the afternoon.

4 CASE STUDY: EFFECT OF CAPACITY LIMITS AND FUEL PRICES

Ferguson (2011a) describes a case study of the effects of capacity and fuel price on airline decision-making. Specifically, this case-study describes a comparison of the behavior of the air transportation system (e.g. markets served, airfares, delays, load factors, aircraft size) during a run-up in fuel prices at capacity-limited New York airports (EWR, LGA, JFK) and non-slot controlled San Francisco (SFO) and Philadelphia (PHL) airports.

4.1 Design of Experiment

The design of the experiment includes 96 treatments: 8 airports (BOS, DFW, EWR, JFK, LGA, ORD, PHL, SFO), by 3 flight capacity levels (VFR, MVFR< IFR), by 4 hedged fuel prices ($2, $3, $4, $5). The passenger demand versus airfare curves are used for the summer of 2007.

Note: These experiments include analysis of hedged fuel prices of $5/gallon. Historically, fuel prices have not exceeded $3.70/gallon (07/2008). As a consequence the effect on wholesale prices paid by the airline and passenger demand is largely unknown.

4.2 Effects of increase of Increase in Fuel Prices on Airline Behavior

The airline response to changes in fuel prices is driven by the interaction between increased costs of operation and the effect of increased airfares on demand. Fuel prices drive an increase in operating costs. The change in operating costs, shifts the maximum profit point to smaller aircraft accomodating fewer higher airfare passengers.

Overall, the airline transportation system is sensistive to changes in fuel price. Geographic access (i.e. markets served, -1.1%) and frequency of service (-0.3%) are maintained. However, due to increases in airfares ($34 for every $1/gallon increase in hedged fuel price), fewer passengers (-8.7% per $1/gallon increase) are transported in smaller aircraft (-7.5% per $1/gallon increase). This has no effect on congestion (-1.4% reduction in flights per day per $1/gallon increase), but a significant reduction in fuel burn (-8.3% per $1/gallon increase).

The increase in fuel prices results in a shift in the economic "operating point." To maximize profit (Table 16), airlines adjust the airfares (Table 17) to capture fewer higher paying passengers (Table 18) that will fly on smaller aircraft (Table 19). These changes impact the average flights per market (Table 20) which is determined by the flights per day (Table 21), markets served (Table 22), and fuel burn (Table 23).

The "physics" of the travel demand and operating costs, allow the airlines to maintain the same levels of profit as fuel prices increase. On average the loss in profitability in the face of increasing costs is -3.2% across all eight airports. JFK (-6.7%) and SFO (-5.8%) experience the largest loss in profits. BOS (-0.6%), LGA(-1.4%), and EWR (-1.9%) experience the least drop in profit. The total daily loss of profit across all eight airports is $5M.

DAILY AIRLINE PROFITS ($M)									
	BOS	DFW	EWR	JFK	LGA	ORD	PHL	SFO	8 AIRPORTS
$2	5.4	9.5	5.2	4.5	4.9	11.7	4.7	5.7	51.6
$3	5.2	8.9	5	4	4.7	11.3	4.3	5.1	48.5
$4	5.2	8.6	4.8	3.7	4.6	10.6	4.2	4.8	46.5
$5	5.3	8.6	4.9	3.6	4.7	10.6	4.2	4.7	46.6
Change in daily profit for +$1/gal increase	-0.03	-0.30	-0.10	-0.30	-0.07	-0.37	-0.17	-0.33	-1.67
% Change in daily profits for a +$1/gal increase	0.6	3.2	1.9	6.7	1.4	3.1	3.5	5.8	3.2

Table 16: Change in airline profit for 8 airports for fuel price increasing from $2 to $5/gallon

The change in fuel price, results in changes in operating costs, and drives the economics of airline operations to fly fewer higher paying passengers (Table 17). Average airfares increased on average 18.3% for each $1/gallon change in fuel. This was equivalent to a $26.13 increase in average airfares for each $1/gallon change in fuel.

AVERAGE AIRFARE									
	BOS	DFW	EWR	JFK	LGA	ORD	PHL	SFO	8 AIRPORTS
$2	136	131	160	152	132	135	117	180	142.88
$3	152	158	191	175	155	151	138	209	166.13
$4	174	178	221	205	178	186	161	243	193.25
$5	200	204	254	231	200	214	185	282	221.25
Change in average airfare for +$1/gal increase	21.33	24.33	31.33	26.33	22.67	26.33	22.67	34.00	26.13
% Change in average airfare for a +$1/gal increase	15.7	18.6	19.6	17.3	17.2	19.5	19.4	18.9	18.3

Table 17: Change in airfare served for 8 airports for fuel price increasing from $2 to $5/gallon

The change in airfare was homogeneous across all 8 airports. SFO experienced the largest change in average airfare $34 for each $1 increase in fuel, followed by EWR ($31.33). BOS airfares changed the least, $21.33. The average change in airfare across all 8 airports was $26.15 with a median of $25.33.

The change in airfare affected the number of passengers that were willing to pay the price of travel (Table 18). The change in passengers traveling was homogeneous across all 8 airports. On average the higher airfares were reflected in an 8.7% drop in passnegers. ORD (-9.7%), SFO (-9.6%) experienced the largest reduction in percentage of passengers. LGA (-7.4%) and BOS (-7.5%) experienced the smallest reduction in passenger trips. The median percentage reduction in passenger trips, -8.9%, was higher than the mean, -8.7%, indicating a slightly fatter right tail.

PAX TRIPS PER DAY									
	BOS	DFW	EWR	JFK	LGA	ORD	PHL	SFO	8 AIRPORTS
$2	68,126	140,542	61,730	61,134	64,832	169,880	80,000	63,200	709,444
$3	63,466	120,560	53,872	54,644	57,494		70,750	55,680	476,466
$4	57,618	111,328	49,100	48,548	52,894	131,960	62,446	50,120	564,014
$5	52,738	102,646	45,592	45,672	50,374	120,480	58,198	44,960	520,660
Change in pax trips/day for a +$1/gal increase	-5,129	-12,632	-5,379	-5,154	-4,819	-16,467	-7,267	-6,080	-62,928
% Change in pax trips/day for a +$1/gal increase	7.5	9.0	8.7	8.4	7.4	9.7	9.1	9.6	8.9

Table 18: Change in passengers travelling across all 8 airports for fuel price increasing from $2 to $5/gallon

The fewer, higher paying passengers were accomodated on smaller aircraft. For each $1/gallon increase in fuel price, aircraft size decreased by -7.5%, which is equivalent to approximately -8 seats per $1/gallon.

The change in aircraft size across airports ranged from 5.2% to 8.7%. The average reduction in aircraft size was -7.5%, with a median reduction of -7.7%. ORD (-8.7%), SFO (-8.4%) and PHL(-8.3%) experienced the largest reductions. LGA (-5.2%) experienced the least reduction in aircraft size.

The change in fuel price has no effect on the frequency of service. The average change in frequency of service in -0.3% (min -0.2%, max -2%). JFK (-2%), SFO (-1.6%), LGA (-1.5%) and LGA (-1.4%) experienced the largest reductions in frequency. PHL (-0.2%), ORD (-0.3%), and EWR(-0.4%) experienced the least reduction in frequency.

AVERAGE AIRCRAFT SIZE									
	BOS	DFW	EWR	JFK	LGA	ORD	PHL	SFO	8 AIRPORTS
$2	111	110	97	118	89	107	100	115	105.9
$3	103	99	86	106	82	97	89	104	95.8
$4	93	90	79	98	77	85	80	94	87.0
$5	88	85	74	94	75	79	75	86	82.0
Change in average A/C size for +$1/gal increase	-7.67	-8.33	-7.67	-8.00	-4.67	-9.33	-8.33	-9.67	-7.96
% Change in average A.C size for a +$1/gal increase	6.9	7.6	7.9	6.8	5.2	8.7	8.3	8.4	7.5

Table 19: Change in Average Aircraft Size across all 8 airports for fuel price increasing from $2 to $5/gallon

FLIGHTS PER MARKET									
	BOS	DFW	EWR	JFK	LGA	ORD	PHL	SFO	8 AIRPORTS
$2	11.47	12.78	10.14	13.00	13.78	14.76	12.03	12.98	12.62
$3	11.65	12.88	10.08	12.92	14.51	14.77	11.95	12.64	12.68
$4	11.84	12.68	10.08	12.42	14.31	14.66	12.03	12.53	12.57
$5	11.93	12.41	10.00	12.21	14.39	14.64	12.10	12.34	12.50
Change in markets merved for +$1/gal increase	0.15	-0.12	-0.05	-0.26	0.20	-0.04	0.03	-0.21	-0.04
% Change in markets served for a +$1/gal increase	1.4	1.0	0.4	2.0	1.5	0.3	0.2	1.6	0.3

Table 20: Change in flights-per-market for 8 airports for fuel price increasing from $2 to $5/gallon

The changes in frequency of service are a result of the combination of a reductions in flights per day (Table 21) and markets served (Table 22). In both cases, the system is robust to fuel prices, experiencing a reduction in markets served across all eight airports of -1.1%, and flights per day of -1.4%.

The smaller aircraft result in a significant reduction of fuel burn (-8.3 % per $1/gallon increase) and the resulting emissions (Table 23). ORD (-9.5% per $1/gallon increase) experienced the greatest reduction in daily fuel burn. BOS (-5.6% per $1/gallon increase) experienced the least reduction in daily fuel burn.

FLIGHTS PER DAY									
	BOS	DFW	EWR	JFK	LGA	ORD	PHL	SFO	8 AIRPORTS
$2	734	1546	750	624	882	1978	962	688	8164
$3	734	1520	736	620	856	1965	956	670	8057
$4	734	1496	726	596	830	1950	938	664	7934
$5	716	1464	720	586	820	1918	932	654	7810
Change in flights/day for +$1/gal increase	-6.00	-27.33	-10.00	-12.67	-20.67	-20.00	-10.00	-11.33	-118.00
% Change in pax trips per day for a +$1/gal increase	0.8	1.8	1.3	2.0	2.3	1.0	1.0	1.6	1.4

Table 21: Change in flights-per-day for 8 airports for fuel price increasing from $2 to $5/gallon

MARKETS SERVED									
	BOS	DFW	EWR	JFK	LGA	ORD	PHL	SFO	8 AIRPORTS
$2	64	121	74	48	64	134	80	53	638
$3	63	118	73	48	59	133	80	53	627
$4	62	118	72	48	58	133	78	53	622
$5	60	118	72	48	57	131	77	53	616
Change in markets served for +$1/gal increase	-1.33	-1.00	-0.67	0.00	-2.33	-1.00	-1.00	0.00	-7.33
% Change in markets served for a +$1/gal increase	2.1	0.8	0.9	0.0	3.6	0.7	1.3	0.0	1.1

Table 22: Change in markets served for 8 airports for fuel price increasing from $2 to $5/gallon

DAILY FUEL BURN (Million Gallons)									
	BOS	DFW	EWR	JFK	LGA	ORD	PHL	SFO	8 AIRPORTS
$2	1.44	2.51	1.31	1.38	1	3.19	1.31	1.65	13.79
$3	1.41	2.22	1.15	1.23	0.88	2.9	1.16	1.45	12.4
$4	1.3	1.98	1.06	1.12	0.83	2.48	1.03	1.33	11.13
$5	1.2	1.84	1	1.06	0.78	2.28	0.97	1.21	10.34
Change in daily fuel burn for +$1/gal increase	-0.08	-0.22	-0.10	-0.11	-0.07	-0.30	-0.11	-0.15	-1.15
% Change in daily fuel burn for a +$1/gal increase	5.6	8.9	7.9	7.7	7.3	9.5	8.7	8.9	8.3

Table 23: Change in fuel burn for 8 airports for fuel price increasing from $2 to $5/gallon

4.3 Effects of Increased Flight capacity (4 operations per hour) on Airline Behavior

The effect of an increase in flight capacity of 4 operations per hour (i.e. 72 operations per day) across all 8 airports is described in this section. The cost of fuel is $2/gallon.

An increase in flight capacity does not affect the airline “economic operating point.” An increase in flight capacity does allows less profitable flights, that would otherwise fail to meet the minimum profit threshold given the limited flight capacity, to be included. The effect of increasing the number of flights (Table 24), directly increases the number of markets served (Table 25), the number of passenger trips (Table 26), the airline profit (Table 27), and the daily fuel burn (Table 28). The effect of increasing the number of flights, adds to the tails of the distributions causing a shift in the means for airfare (Table 29), aircraft size (Table 30).

FLIGHTS PER DAY									
	BOS	DFW	EWR	JFK	LGA	ORD	PHL	SFO	8 AIRPORTS
Unconstrained	734	1,546	750	624	882	1,978	962	688	8,164
MVFR	730	1,546	738	610	882	1,882	896	688	7,972
IFR	604	1,374	651	540	882	1,696	852	684	7,283
Change in flights/day for increase in +1 ops/hr	3.250	2.688	4.125	3.500	0.000	8.813	4.583	0.167	3.552
% Change in pax trips/day for increase in +1 ops/hr	0.54	0.20	0.63	0.65	0.00	0.52	0.54	0.02	0.05

Table 24: Change in flights per day for 8 airports for increase of +4 ops/hr

The increase in flight capacity enables an increase in the number of flights. Each individual market, serving the focus airport, competes for flight slots at the focus airport. The most profitable flights are included. Overall, a change in 1 operation/hour across all eight airports results in an increase on average of 3.5 flights per day. In some cases, not all the available slots are used as the markets fail to be able to generate profitable flights due to small market size, airfare sensitivity, and/or relatively high costs of service.

Based on the market size and airfare sensitivity coefficients, Boston, Newark, JKF, Chicago and Philadelphia all benefited from increased caapcity. The impact on LaGuardia, Dallas-Fort Worth and San Fransisco was less dramatic. According to the market size and airfare sensitivity parameters used, these non-capped airports are already serving the available profitable demand.

The added flight capacity increases the frequency of service to existing markets as well as enables a few new markets to be serviced (Table 25). On average, approximately three markets to each focus airport would be added by a 72 ops/day increase. Boston and Chicago add the most markets. San Fransisco and LaGuardia, already servicing profitable markets, did not add any new markets.

MARKETS SERVED									
	BOS	DFW	EWR	JFK	LGA	ORD	PHL	SFO	8 AIRPORTS
Unconstrained	64	121	74	48	64	134	80	53	638
MVFR	64	121	73	48	64	134	80	53	637
IFR	60	117	72	47	64	130	79	53	627
Change in markets served for increase in +1 ops/hr	0.10	0.06	0.08	0.04	0.00	0.13	0.04	0	0.04
% Change in markets served for increase in +1 ops/hr	0.2	0.1	0.1	0.1	0.0	0.1	0.1	0	0.0

Table 25: Change in markets served for 8 airports for increase of +4 ops/hr

Additional flight capacity increased the number of passengers able to travel (Table 26). On average an additional 256 passengers were transported at each of the eight airports (0.049% of the total passengers). JFK, Philadelphia, Newark and Boston experienced the most gains in passenger trips.. San Fransisco and LaGuardia, already servicing profitable markets, did not see a big gain in passenger trips.

Additional flight capacity, leading to additional flights, has marginal benefits to the airlines (Table 27). The additonal flights are, by definition, low profit flights and make only a small contribution to the airline bottom-line. Airlines operating at JFK and Philadelphia benefit the most from the additional flight capacity.

The additional flight capacity, leading to additional flights, results in a slight increase in daily fuel-burn and associated emissions (Table 28). The additional flights, capturing smaller markets, tend to be smaller, more fuel efficient aircraft, resulting in a small increase to total fuel burn. Flights operating at Newark, JFK, Boston, and Chicago generate the most fuel burn.

PAX TRIPS PER DAY									
	BOS	DFW	EWR	JFK	LGA	ORD	PHL	SFO	8 AIRPORTS
Unconstrained	68126	140542	61730	61134	64832	169880	80000	63200	8,164
MVFR	68852	140542	61194	59584	64832	166800	77714	63240	7,972
IFR	63780	134702	57874	54118	64832	160280	76122	63120	7,283
Change in pax trips/day for an increase of +1 ops/hr	109	91	161	292	0	300	162	3	4
% Change in pax trips/day for an increase of +1 ops/hr	0.170	0.068	0.278	0.540	0.000	0.187	0.212	0.005	0.049

Table 26: Change in passenger trips for 8 airports for increase of +4 ops/hr

DAILY AIRLINE PROFITS ($M)									
	BOS	DFW	EWR	JFK	LGA	ORD	PHL	SFO	8 AIRPORTS
Unconstrained	5.4	9.5	5.2	4.5	4.9	11.7	4.7	5.7	51.6
MVFR	5.4	9.5	5.2	4.4	4.9	11.6	4.6	5.7	51.3
IFR	5.2	9.3	5.1	4.1	4.9	11.4	4.5	5.6	50.1
Change in daily profit for +$1/gal increase	0.005	0.003	0.004	0.017	0.000	0.009	0.008	0.004	0.006
% Change in daily profits for a +$1/gal increase	0.093	0.033	0.080	0.370	0.000	0.080	0.177	0.073	0.012

Table 27: Change in Airline Profits for 8 airports for increase of +4 ops/hr

DAILY FUEL BURN (Million Gallons)									
	BOS	DFW	EWR	JFK	LGA	ORD	PHL	SFO	8 AIRPORTS
Unconstrained	1.44	2.51	1.31	1.38	1	3.19	1.31	1.65	13.79
MVFR	1.46	2.51	1.3	1.35	1	3.16	1.29	1.65	13.72
IFR	1.37	2.44	1.25	1.26	1	3.07	1.28	1.65	13.32
Change in daily fuel burn for an increase of 1 ops/hr	0.002	0.001	0.003	0.005	0.000	0.004	0.001	0.000	0.002
% Change in daily fuel burn for an increase of 1 ops/hr	0.128	0.045	0.200	0.397	0.000	0.122	0.098	0.000	0.014

Table 28: Daily Fuel-burn for 8 airports for increase of +4 ops/hr

The additional flight capacity, leading to additional flights, results in a slight decrease in average airfare (Table 29). The additonal flights, capturing smaller markets with lower airfares, add to the tails of the airfare distribution. Newark and JFK experienced the largest increase in airfares.

AVERAGE AIRFARE									
	BOS	DFW	EWR	JFK	LGA	ORD	PHL	SFO	8 AIRPORTS
Unconstrained	136	131	160	152	132	135	117	180	142.88
MVFR	135	131	161	153	132	136	118	180	143.13
IFR	138	133	164	156	132	138	119	180	145.00
Change in Average Airfare for an increase in 1 ops/hr	0.050	0.031	0.167	0.167	0.000	0.094	0.083	0.000	0.009
% Change in Average Airfare for an increase of 1 ops/hr	0.036	0.023	0.102	0.107	0.000	0.068	0.070	0.000	0.006

Table 29: Average Airfare for 8 airports for increase of +4 ops/hr

The additional flight capacity, leading to additional flights, results in a slight decrease in average aircraft size (Table 30). The additional flights, capturing smaller markets, add to the tails of the aircraft size distribution. Newark, Philadelphia, Chicago, and Boston experienced the largest growth in average aircraft size.

AVERAGE AIRCRAFT SIZE									
	BOS	DFW	EWR	JFK	LGA	ORD	PHL	SFO	8 AIRPORTS
Unconstrained	111	110	97	118	89	107	100	115	105.9
MVFR	113	110	98	118	89	111	105	105	106.1
IFR	126	119	105	121	89	118	108	115	112.6
Change in average aircraft size for increase in 1 ops/hr	0.375	0.141	0.333	0.125	0.000	0.344	0.333	0.000	0.027
% Change in average aircraft aize for increase in 1 ops/hr	0.298	0.118	0.317	0.103	0.000	0.291	0.309	0.000	0.024

Table 30: Aircraft Size for 8 airports for increase of +4 ops/hr

5 CONCLUSIONS

There are two independent phenomena that determine the markets served, the schedule, and the size of aircraft: aircraft cost of operation (e.g. fuel price) and capacity at the focus airport.

The cost of operation of each aircraft size in the fleet, in conjunction with the demand in each service period of the day (i.e. market size and airfare sensitivity), determine the number of flights per day from a given market and the size of aircraft assigned. These candidates flights for service to/from the focus airport determine the potential revenue, costs and profit generated by providing the air transport service. In the absence of changes in demand, changes in aircraft performance (e.g. fuel price, block hours, fuel-burn-rates) will affect the frequency of service and size of aircraft. For example, in markets with near appropriate profiles of demand by time of day, economies-of-scale in operating costs for larger aircraft would have the effect of maintining seat throughput by upgauging while flying reduced frequency. This phenomenon effectively shifts the the economic operating point for each flight for each market, resulting in new revenue, airfares, costs, and profit.

Flight capacity at the focus airports does not change the the economic operating point. Adding flight capacity allows the less profitable flights, that were previously ranked to low access to the focus airport. Likewise reducing flight capacity eliminates the lowest ranking by profit flights. Revenue, airfares, costs, and profit on each flight remain unchanged.

Whereas flight capacity changes the threshold for profit for a flight serving the focus airport, aircraft performance shifts the economics of the industry.

The effects of the two treatments evaluated using the AFRS-OM are summarized in Table 31. The table shows the change in each parameter for an increase in $1 per gallon, and the change in each parameter for +4 operations/hour (72 ops/daty) increase in flight capacity.

Metrics	Increase +$1/gallon	Increase in +4 ops/hour
Flights per Day	-1.4%	0.05%
Markets Served	-1.1%	Unchanged
Pax Trips per Day	-8.7%	+0.05%
Average Airfare ($)	+$34	+0.006%
Airline Profits ($M)	+3.2%	+0.12%
Average Aircraft Size (Seats per Aircraft)	-7.5%	+0.024%
Daily Fuel Burn (M gallons)	-8.3%	+0.014%

Table 31: Comparison of the change in each ATS metric for an increase of $0.08 in hedged fuel price, and an increase in +4 operations/hour.

Changes in airport capacity limits (within the range studied) do not have significant negative effects on either markets served or on airfares charged. As capacity limits are lifted (i.e. +4 operations per hour), the number of markets served is remains constant, scheduled flights per day to all markets is increased by a small percent (0.05%), average revenue per seat is increased, average aircraft size is increased, and daily airline profits are increased slightly.

Overall, the airline transportation system is relatively sensitive to changes in the cost of aircraft operation (e.g. fuel price). As the cost of operation increases, geographic access (i.e. markets served, -1.1%) and frequency of service (-1.4%) are reduced. However, due to increases in airfares ($34 for every $1/gallon increase in hedged fuel price), fewer passengers (-8.9% per $1/gallon increase) are transported in smaller aircraft (-7.5% per $1/gallon increase). This has no effect on congestion (-1.4% reduction in flights per day per $1/gallon increase), but a significant reduction in fuel burn (-8.3% per $1/gallon increase).

It should be noted that in certain specific circumstances (e.g. constant demand), the effect of efforts to increase flight capacity (i.e. NextGen, AIP), can be nullified by a sustained fuel price increase.

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APPENDIX A

Estimating Domestic U.S. Airline Cost of Delay based on a European Model

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Abstract

Researchers are applying more holistic approaches to the feedback control of the air transportation system. Many of these approaches rely on economic feedback, including the cost of delays to the airlines. Establishing an accurate mechanism for estimating the cost of delays for each portion of a flight (gate costs, taxiing in and out costs, and en-route costs) is useful for many aspects of modeling airline behavior and for better understanding the likely impact of regulations.

EuroControl (2004) developed a rigorous methodology and collected data for estimating the components of airline delay costs for various segments of a scheduled flight. The model, based on confidential information from European airlines for twelve types of aircraft circa 2003, was not transparent with regards to how each of the major components of cost (crew costs, fuel costs, maintenance, depreciation, etc) impacted that total. This paper describes the development of an airline cost model, based on the Eurocontrol model. The airline cost model explicitly identifies the components of airline costs, is based on U.S. airline cost data, and includes 111 aircraft types. The new model is designed to allow costs to be updated whenever any of the factors (e.g. crew, fuel, maintenance, and ground costs) change. It considers the type of the aircraft when making calculations, both from the perspective of fuel burn and passenger costs. A case-study analysis of airline costs of operation at 12 major U.S. airports is provided.

Keywords-component; airline delay costs; airline delays; economic modeling of airlines

Introduction

The airline industry moves millions of passengers and tons of cargo annually. Recent studies have estimated the cost of delays to the U.S. economy in 2007 ranging from $32.9 billion [NEXTOR, 2010] to $41 billion [JEC 2008]. Researchers have proposed holistic approaches to incentivize the development of increased capacity and improved productivity [Donohue et. al., 2008; Ball et. al., 2007] and feedback control of the air transportation system [NextGen, 2008; Xiong, 2010; Rupp, 2005]. These approaches rely on economic feedback, including the cost of delays to the airlines. An accurate model of the cost of a delay is not only of interest to the airlines that incur these costs, but is essential for air transportation policy, management, and control.

Direct costs are accrued by airlines when flights are delayed. There are two main causes of flight delays: (1) the flight does not depart due to aircraft or flight specific reasons (e.g. mechanical problems, misaligned crew or aircraft, crew work rules), or (2) mismatch between demand and capacity. At several highly utilized airports, systemic over-scheduling and reductions in capacity of both the airspace and the runways due to weather result in delayed flights. Based on weather forecasts and schedules, air traffic management estimates the resulting reduction in capacity within various segments of the airspace and at a variety of airports. It announces Ground Delay Programs (GDPs) that hold aircraft at the departing airport, in order to have the flying aircraft better match the capacity of the system. For capacity reduction in air, Air Flow Programs (AFPs) are employed that suggest/announce alternative routes for the flights. Since holding aircraft at a gate is both cheaper and safer than airborne holds, most delays are gate holds. Delays often propagate through the system, causing future delays, because the aircraft or crews may not arrive at their next assignment in time to allow the next flight to leave on time.

The Performance Review Unit, EuroControl published a report [EuroControl, 2004] describing a methodology for evaluating true cost of flight delays. The methodology presents results detailing the cost to airlines of delays during various segments of a scheduled flight. The costs are divided into short delays (less than 15 minutes) and long delays (greater than 65 minutes). The report provides a cost factor (Euros per minute) for each flight segment. The types of delays considered include gate delay, access to runway delay (both taxi in and out delays), en-route delays, and landing delays (circling or longer flight paths to overcome congestion while approaching the airport). The data used in the study consisted of data collected from European airlines, air traffic management as well as interviews and surveys conducted by the research team. Although each of the factors making up the overall cost factors are explained, the individual factors are not provided because the information was considered proprietary. In the absence of this transparency, the factors provided prohibit the separation of fuel costs from crew or maintenance costs and prohibit an update of the summary factors when any of these costs change or when alternative aircraft need to be considered. Furthermore, the model is based on data from EU airlines for 12 aircraft types.

The motivation of this paper is therefore to:

- identify coefficients for the cost factors
- model each of the individual coefficients and cost factors
- update model with publicly available costs of U.S. airlines
- extend the fleet mix to over 100 aircraft types
- structure the model to enable update of the data over various time periods

This paper is organized as follows. Section II describes the EC report, Section III provides the methodology for determining the cost components and multipliers that make up the final multipliers used in the EuroControl report and describe the validation of the new model on European data from the period of the EC report. In Section IV and V, delay costs are examined for US airline departures from 12 major airports (EWR, JFK, LGA, DCA, BWI, IAD, SFO, OAK, SFO, BOS, PHL, DFW) for one of the busiest months in US aviation history (July, 2007). Delays by segment of flight, by aircraft type, by airline and by hour of day are examined in this case study. Section VI provides conclusions and Section VII points out the future research.

EuroControl Performance Review Unit Report (EC report)

The EC report specifies that delays incurred can be of two types: tactical delay and strategic delay. The report makes the distinction between tactical delays (delays encountered that are greater than the announced schedule, i.e. delays above the anticipated padding of the schedule) and strategic delays (i.e. the delay relative to an unpadded schedule). Both US and European airlines increase the arrival time over unimpeded time so that they can report “on time” performance even when the system is over-capacitated.

Another distinction that the report makes is between gate-to-gate (or single flight) delays and network-level delays. The gate-to-gate delay is the delay that an individual flight incurs based on the environment it encounters, while the network delays are the effects that the flight causes to the rest of the network. The cost of delay discussed in the EC report is the tactical primary delay. In the report, two types of delays have been chosen for demonstration: delays of short duration (15 minutes or less) and delays of long duration (65 minutes or more). Similarly three cost scenarios have been used to "allow more realistic ranges of values".

The EC report describes the model as an additive model where each component defines a proportion of the total cost. Table A - 1 shows the cost factors included as inputs in these cost scenarios under different delay characteristics. For example, to estimate the delay costs for a short delay (15 mins) for a baseline airline, the factors in column 3 are multiplied to the delays and the respective cost factors for each flight segment, and then added together. For details, see [EuroControl, 2004]. Figure A - 1 details the inputs and outputs of their model.

Factor	'short' delay type: **'15 minutes' basis**			'long' delay type: **'65 minutes' basis**		
	low	**base**	**high**	**low**	**base**	**high**
load factor	50%	70%	90%	50%	70%	90%
transfer passengers	15%	25%	35%	15%	25%	35%
arrival / departure [(a)]	domestic	EU	non-EU	domestic	EU	non-EU
turnaround time [(a)]	60 mins	60 mins	60 mins	60 mins	60 mins	60 mins
parking [(g)]	remote	pier	pier	remote	pier	pier
fuel price [(c)]	low	base	high	low	base	high
weight payload factor	50%	65%	80%	50%	65%	80%
airborne fuel penalty [(f)]	none	none	applied	none	none	applied
handling agent penalty	none	none	none	none	none	charged
extra crew costs [(d)]	none	none	low	none	medium	high
airport charges	averaged	averaged	max/2	averaged	averaged	max/2
pax cost of delay to AO, EUR/min [(j)]	0	0	0.05	0.32	0.40	0.48
aircraft depreciation, rentals & leases [(i)]	Strategic cost model used: please see Annex O			Strategic cost model used: please see Annex O		
BHDOC [(b)] scenario	low	base	high	low	base	high
maintenance [(e)] [(h)]	15%	15%	15%	15%	15%	15%

Table A - 1. Low, base and high cost scenarios (from Table 2-5 of [EuroControl, 2004])

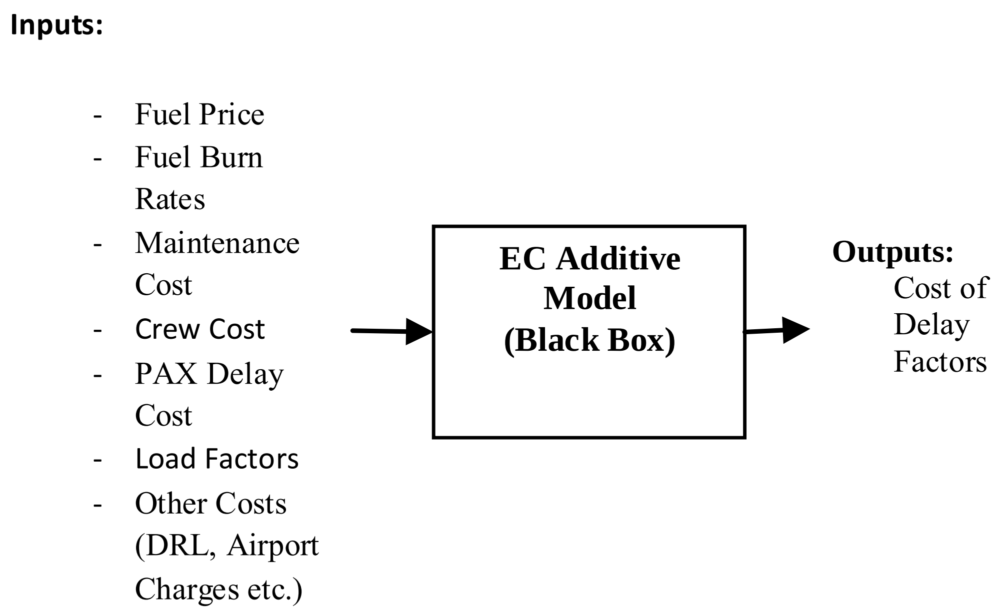

Figure A - 1. EuroControl (EC) Model

Further exploring their cost factors reveals the following costs involved:

Fuel cost: The report provides different fuel burn rates for each aircraft type studied and for all segments of the flights. The prices for all cost scenarios and conversion rates from Euro to Dollars are also provided. (See Table 2-12 and Annex C in [EuroControl, 2004]).

Extra Crew cost: The report defines extra crew cost as the extra cost paid in addition to the usual flight and cabin crew salaries and expenses. It may include employing additional crew (both flight and cabin crew) or incurring additional pay for regular crews due to unexpected increases in hours worked. The report does not specify exactly the methodologies used to obtain the crew cost component of the multiplier in order to preserve confidentiality of airline data. However, the report describes under what circumstances the cost factors will be increased (refer to Table A - 1 of this paper).

Maintenance cost: The maintenance cost is defined to be the cost of maintaining both the airframe and power plant of the aircraft. The additional maintenance cost incurred for a one-minute delay is stated in the report as approximately 15% of the Block Hour Direct Operating Cost (BHDOC). The proportions of how maintenance cost is divided into different segments of the flights are given in Annex J of [Eurocontrol, 2004]. BHDOC's are given in the report for low, base and high cost scenarios for the 12 different aircraft systems studied (see Table 2-11 in [EuroControl, 2004]).

Depreciation Cost: The report assumes that there is no additional depreciation cost caused by delays. Thus, the depreciation component of total delay is taken to be zero for all segments and cost scenarios.

Passenger Delay Cost: Passenger Delay cost (or PAX delay cost) is defined as the compensation paid by the airlines to passengers who have experienced delayed flights. Passenger Delay (in cost per passenger per minute) is given as: zero for low and base cost scenarios, 0.05 for the high cost scenario for 15 minutes of delay and 0.32, 0.40 and 0.48 for low, base and high cost scenarios respectively for 65 minutes delay. The load factors assumed are: 50% for low, 70% for base and 90% for high cost scenarios.

Other Costs: This factor is a catch-all component that attempts to include any other cost factors mentioned in Table A - 1 (such as parking, airport charges, handling agent penalty, weight payload factor etc.). No specific cost factors were given in the report, except details for different Airport charges at different EU airports (see Annex L in [EuroControl, 2004]).

Based on the analysis done, the EC report provides cost of delay factors (in Euros). The delay is divided into three segments of the flight; delay on the ground at the gate (Table A - 2), delay while taxiing at either airport (Table A - 3) or delay while airborne (en-route and holding, Table A - 4). These segments were chosen for discussion because they reflect the fidelity of publically available data.

One point worth mentioning is that the findings of the report are for EU airports only. However, when applying the formulas to US data, the differences between the US and European system must be recognized. For example, passenger compensation costs incurred to the airline in US are far lower than that of EU (due to EU Passenger Bill of Rights or PBR). Similarly, aircraft spend more time taxiing out in the US than in Europe. Also, in the US, Air Traffic Management imposes greater ground delay programs in order to assure that there is little circling at the destination airport. The EC report specifically comments on this difference noting that, on average, the amount of en-route delay is greater than the amount of ground delay for European flights.

Aircraft and number of seats		**based on 15 minutes' delay**			**based on 65 minutes' delay**		
		cost scenario			cost scenario		
		low	base	high	low	base	high
B737-300	125	0.6	0.9	14.5	20.4	44.6	82.8
B737-400	143	0.6	0.9	15.8	23.7	50.3	92.3
B737-500	100	0.6	0.8	13.8	16.6	38.2	73.5
B737-800	174	0.5	0.8	17.1	28.4	58.6	105.2
B757-200	218	0.6	1.0	20.2	35.6	71.7	126.0
B767-300ER	240	0.6	1.2	27.8	39.2	84.9	155.1
B747-400	406	1.8	2.2	49.0	67.1	142.2	258.7
A319	126	0.6	0.9	14.7	20.8	45.0	83.8
A320	155	0.6	0.9	16.3	25.3	53.5	96.5
A321	166	0.7	1.0	16.6	27.3	56.3	100.7
ATR42	46	0.4	0.6	8.6	7.8	19.7	40.6
ATR72	64	0.5	0.6	9.6	10.7	25.0	48.6

Table A - 2. Tactical ground delay costs: at-gate only (without network effects)

Aircraft and number of seats		based on 15 minutes' delay			based on 65 minutes' delay		
		cost scenario			cost scenario		
		low	base	high	low	base	high
B737-300	125	3.0	4.6	19.0	22.9	48.4	87.1
B737-400	143	3.0	4.7	20.3	26.1	54.1	96.6
B737-500	100	3.0	4.6	18.2	19.0	42.0	77.8
B737-800	174	2.9	4.5	21.6	30.8	62.3	109.5
B757-200	218	3.4	5.3	24.9	38.4	76.0	131.0
B767-300ER	240	4.5	7.2	34.0	43.2	91.0	162.1
B747-400	406	10.6	15.9	61.7	76.4	156.3	276.2
A319	126	2.6	4.1	18.4	22.8	48.2	87.4
A320	155	2.6	4.0	20.1	27.3	56.7	100.1
A321	166	3.0	4.7	20.9	29.7	60.1	105.0
ATR42	46	0.6	0.9	8.2	7.9	20.0	40.0
ATR72	64	1.1	1.8	10.3	11.4	26.1	49.2

Table A - 3. Tactical ground delay costs: taxi-only (without network effects)

Aircraft and number of seats		based on 15 minutes' delay			based on 65 minutes' delay		
		cost scenario			cost scenario		
		low	base	high	low	base	high
B737-300	125	9.5	14.8	34.1	28.9	57.8	102.3
B737-400	143	9.2	14.3	34.6	32.0	63.3	111.4
B737-500	100	8.9	13.7	31.6	24.5	50.3	91.1
B737-800	174	7.8	12.5	33.1	36.5	71.3	122.6
B757-200	218	10.3	16.1	40.7	46.2	88.2	149.7
B767-300ER	240	14.2	22.5	57.1	54.2	108.4	189.5
B747-400	406	27.6	42.2	102.4	97.5	188.8	332.7
A319	126	7.1	11.1	29.1	28.1	56.4	101.3
A320	155	7.7	12.0	32.3	32.9	65.3	115.0
A321	166	9.5	14.9	36.2	36.5	70.7	122.2
ATR42	46	1.6	2.6	10.8	9.1	21.9	42.8
ATR72	64	2.2	3.4	12.8	12.7	28.1	52.6

Table A - 4. Tactical airborne delay costs and holding (without network effects)

Regenerating the EC Model

This analysis starts with a similar additive general model for each of the different segments paired with the different cost scenarios that include all the different cost factors. Due to the fidelity of the available US data, the flights are divided into three segments; gate, taxi and en-route (which includes both airborne and holding). For each of these segments, three cost scenarios and two range delays are provided, hence for each of these 18 different cases (segments x cost scenarios x delay ranges) are modeled:

$$
\begin{aligned}
C_{delay} &= c_{fuel} \times \text{fuel burn rate} \times \text{fuel price} \\
&+c_{crew} \times \text{crew cost} \\
&+c_{maintenance} \times \text{maintenance cost} \\
&+ c_{other} \times \text{other cost} \\
&+ c_{pax} \times \text{PA} \quad \text{delay cost} \times (\quad \text{seats}) \quad \text{1 oad factor}
\end{aligned}
$$

Table A - 5 shows the elements of the EU cost of delay model. The elements highlighted in green were provided for all 18 scenarios and 12 aircraft in the report. The elements highlighted in yellow were assumptions made for this analysis or derived inputs from 2003 BTS data. Lastly, the elements highlighted in red were derived from fitting this model to the 216 data points (18 scenarios x 12 aircraft).

		Source	Gate Delay Cost	Taxi Delay Cost	Airborne Delay Cost
FUEL	Fuel Burn Coefficient	Assumed	0	1	1
	Taxi Burn Rate	EU Report	N/A	given	N/A
	Burn Rate	EU Report	N/A	N/A	given
	Fuel Cost per Gallon	EU Report	N/A	given	given
Crew	Crew Coefficient	Not provided	Identified in this analysis		
	% of BHDOC	BTS (2003)	28%	28%	28%
	BHDOC	EU Report	given	given	given
Maint	Maint Coefficient	Not provided	Identified in this analysis		
	% of BHDOC	BTS (2003)	15%	15%	15%
	BHDOC	EU Report	given	given	given
PAX	Pax Coefficient	Assumed	1	1	1
	Seats per aircraft	EU Report	given	given	given
	Load Factor	EU Report	given	given	given
	Pax Cost per minute	EU Report	given	given	given
Other	Fuel Burn Coefficient	Not provided	Identified in this analysis		
	Other Cost per minute	Assumed	$1	$1	$1

Table A - 5. Elements of EU Cost of Delay Model

While the percentage of the Block Hour Direct Operating Costs (BHDOC) was provided for maintenance in the EU report, the percentage of the BHDOC was not provided for crew. Therefore, the same percentage of crew costs for European and US BHDOCs are assumed. Table A - 6 shows the 2003 BTS percentages for BHDOC for fuel, crew, maintenance, and depreciation. These percentages were normalized for the given 15% of BHDOC for maintenance, given in the EU report. Thus, 28% of BHDOC for crew costs is assumed for this analysis.

		Fuel %	crew %	maint %	dep %
BTS BHDOC for 12 aircraft	2003 data	41%	25%	22%	11%
	normalized for 15% maint	45%	28%	15%	12%

Table A - 6. 2003 BTS % of BHDOC

Fitting the EU Model to find unknown coefficients

Microsoft Solver was used to find the crew, maintenance and the other cost factors coefficients for each segment, each cost scenario and each delay range (3x3x2). The sum of the squared difference between EU report delay cost factors for the 12 aircraft versus the fitted model's cost facts were minimized to find the best fit for each segment. The coefficients were constrained to be positive, larger or equal to coefficients for each lower cost scenario and larger or equal to coefficients for each lower delay range. The results of these fits are shown in Table A - 7, the new derived coefficients are shown in blue.

Gate: Cost Factor Coefficients	Based on 15 min. delay cost scenario			Based on 65 min. delay cost scenario		
	low	base	high	low	base	high
Fuel	-	-	-	-	-	-
Crew	0.03	0.03	0.33	0.03	0.46	1.07
Maint	0.00	0.00	0.00	0.00	0.00	0.00
Pax	1.00	1.00	1.00	1.00	1.00	1.00
Other	0.21	0.21	0.21	0.21	0.21	0.21

Taxi: Cost Factor Coefficients	Based on 15 min. delay cost scenario			Based on 65 min. delay cost scenario		
	low	base	high	low	base	high
Fuel	1.00	1.00	1.00	1.00	1.00	1.00
Crew	-	0.00	0.26	-	0.43	1.01
Maint	0.00	0.00	0.00	-	0.00	0.00
Pax	1.00	1.00	1.00	1.00	1.00	1.00
Other	0.12	0.12	0.12	0.12	0.12	0.12

Airborne: Cost Factor Coefficients	Based on 15 min. delay cost scenario			Based on 65 min. delay cost scenario		
	low	base	high	low	base	high
Fuel	1.00	1.00	1.00	1.00	1.00	1.00
Crew	-	0.01	0.29	-	0.46	1.09
Maint	0.00	0.00	0.00	0.00	0.00	-
Pax	1.00	1.00	1.00	1.00	1.00	1.00
Other	0.10	0.10	0.10	0.10	0.10	0.10

Table A - 7. Fitted Coefficients for Crew, Maintenance and Other Costs

Table A - 8 shows the goodness of fit of the new derived model compared to the EU Delay cost factors by aircraft type, segment, cost scenario and delay range. Values highlighted in green were overestimated by the new model by more than 10% and values highlighted in red were underestimated by more than 10%. These aircraft represent 28% of the US domestic operations from 2005 to 2009.

Aircraft and Number of seats		Based on 15 min. delay cost scenario			Based on 65 min. delay cost scenario			% of US Domestic operations (2005-2009)
		low	base	high	low	base	high	
ATR42	46	-2%	-7%	-12%	0%	-6%	-9%	0%
ATR72	64	4%	1%	-1%	0%	-1%	-2%	0%
B737-500	100	-14%	-14%	-10%	-2%	-2%	-3%	3%
B737-300	125	-12%	-13%	-6%	-1%	1%	1%	2%
A319	126	12%	9%	8%	1%	4%	4%	1%
B737-400	143	-10%	-11%	-4%	-1%	1%	1%	7%
A320	155	5%	3%	4%	1%	1%	3%	5%
A321	166	0%	-2%	4%	0%	3%	5%	1%
B737-800	174	13%	8%	5%	1%	-1%	1%	5%
B757-200	218	10%	8%	8%	1%	3%	4%	4%
B767-300E	240	12%	10%	7%	1%	0%	3%	0%
B747-400	406	21%	21%	4%	2%	-1%	-7%	0%

Tactical Airborne Delay Costs enroute and holding (% Diff from EU Report)

Aircraft and Number of seats		Based on 15 min. delay cost scenario			Based on 65 min. delay cost scenario			Domestic operations (2005-2009)
		low	base	high	low	base	high	
ATR42	46	-10%	-11%	-16%	0%	-7%	-12%	0%
ATR72	64	6%	-3%	-4%	0%	-1%	-3%	0%
B737-500	100	9%	6%	-1%	1%	0%	-2%	3%
B737-300	125	9%	6%	5%	2%	3%	3%	2%
A319	126	1%	-3%	4%	0%	3%	4%	1%
B737-400	143	9%	4%	4%	0%	2%	2%	7%
A320	155	1%	-1%	3%	1%	0%	4%	5%
A321	166	2%	-2%	7%	0%	4%	5%	1%
B737-800	174	13%	8%	1%	1%	-1%	0%	5%
B757-200	218	6%	3%	5%	0%	3%	4%	4%
B767-300E	240	11%	5%	2%	1%	-1%	2%	0%
B747-400	406	13%	13%	-7%	1%	-2%	-7%	0%

Tactical ground delay costs: taxi only (% Diff from EU Report)

Aircraft and Number of seats		Based on 15 min. delay cost scenario			Based on 65 min. delay cost scenario			Domestic operations (2005-2009)
		low	base	high	low	base	high	
ATR42	46	1%	-7%	-19%	0%	-7%	-13%	0%
ATR72	64	-10%	7%	-7%	0%	-1%	-4%	0%
B737-500	100	-7%	5%	-4%	0%	-1%	-3%	3%
B737-300	125	-7%	0%	6%	1%	2%	3%	2%
A319	126	-4%	4%	8%	0%	4%	4%	1%
B737-400	143	2%	5%	5%	-1%	2%	2%	7%
A320	155	-3%	-3%	8%	0%	0%	5%	5%
A321	166	-8%	0%	11%	0%	4%	6%	1%
B737-800	174	1%	-4%	0%	0%	-2%	0%	5%
B757-200	218	11%	4%	5%	0%	3%	4%	4%
B767-300E	240	28%	5%	0%	0%	-2%	2%	0%
B747-400	406	-24%	-23%	-25%	-1%	-4%	-9%	0%

Tactical ground delay costs: at-gate only (% Diff from EU Report)

Table A - 8. Percentage Difference of model versus EU Report factors

Examination of this data shows that the model fits the data especially well for all long delays (over 65 minutes). It also fits well for taxiing out and at-gate delays. For both the baseline and high cost scenarios, the taxiing out delays fit all but the very largest and smallest aircraft which compose only 1% of the flights in the US. These estimates do show a significant discrepancy for the low scenario for large aircraft while airborne. However, this low-cost scenario would not be recommended for use in the described modeling efforts and in all other cases, the data match very well the Eurocontrol factors.

Chi square goodness of fit tests were done to examine statistically how well these derived coefficients fit the EU report factors, and are shown in Table A - 9. All cost scenarios were examined for airborne, taxi and gate delay cost factors. The chi square results showed 99.8% or better confidence that the model fit the original EU report factors for all cost scenario and segments.

Chi Square Goodness of Fit		Cost Scenario			
		All	Low	Base	High
Degrees of Freedom		71	23	23	23
Statistic for 99.8% confidence that model fits data		**41.51**	**8.21**	**8.21**	**8.21**
Airborne	Statistic	10.81	2.19	3.52	5.10
Taxi	Statistic	5.18	0.41	0.84	3.94
Gate	Statistic	0.84	0.19	0.77	8.16

Table A - 9. Chi Square fit of Delay Cost Model versus EU report Factors

Modify Model for US Data

To apply this model to the US data, the following changes are made that are more consistent to the US airlines.

Cost factors derived from the BTS P52 database (fuel price, crew and maintenance cost) [BTS 2003 & 2007] are used.

The fuel burn rate while en route from the BTS P52 database is used. And taxi burn rates, derived from the ICAO engine emissions databank are used. (See ICAO report, 2009).

The PAX delay cost coefficient is set to 0, since in the US, it is not incurred by the airlines.

For other delay ranges, the following formulas are used:

For any delay less than or equal to 15 minutes, the 15 minutes cost factor is used.

For any delay above 65 minutes, the cost factor for 65 minutes and above delay is used.

For delays between 15 and 65 minutes, a cost factor is interpolated using the two data points above.

Before beginning the work to determine the cost coefficients for the new model, an examination of overall cost factors in the US compared to those incurred in Europe was undertaken. The delay cost factors were computed, based on the EC factors, for the different types of segments (gate, taxi and airborne-and-holding) and for the given 12 aircrafts. These delay cost factors were compared with the average operational cost per minute using P52 [BTS, 2003] data from the BTS database for US airlines.

Figure A-2, Figure A - 3, and Figure A - 4 show that, in each of these flight segments, the shape of the curves are similar, affirming the fact that these cost factors are consistent with the operational costs in the US.   These results support the assumption that it is appropriate to use BTS crew cost percentages of Block Hour Operating Costs (BHDOC) when calculating total costs.

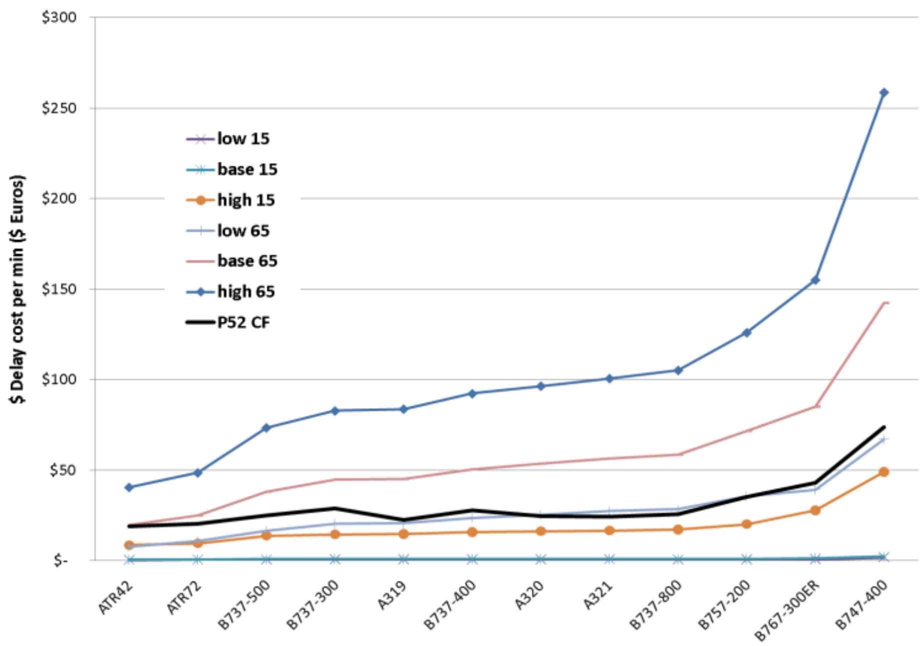

Figure A-2. Tactical Ground Delay costs: gate only (without network effect) vs Operational costs

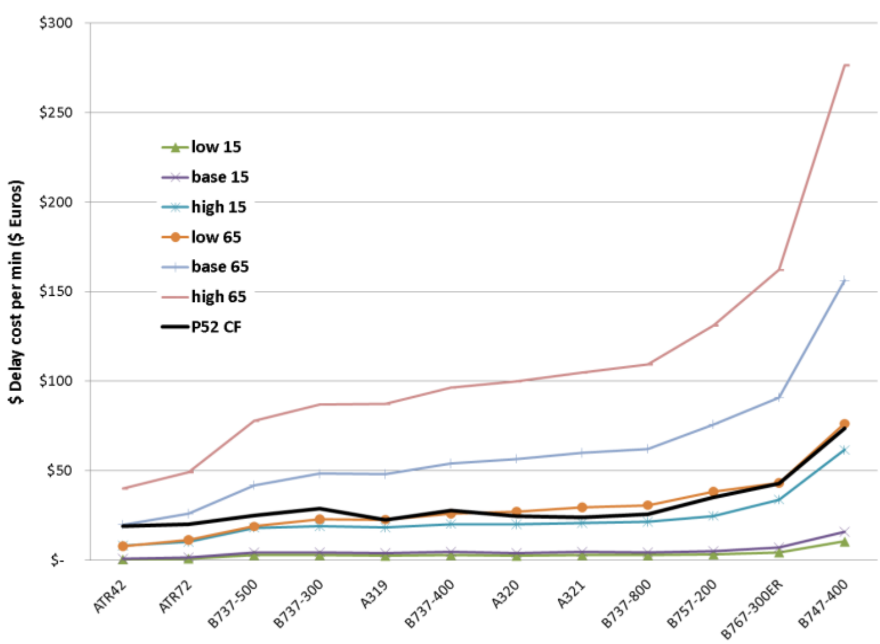

Figure A - 3. Tactical Ground Delay costs: Taxi only (without network effect) vs. Operational costs

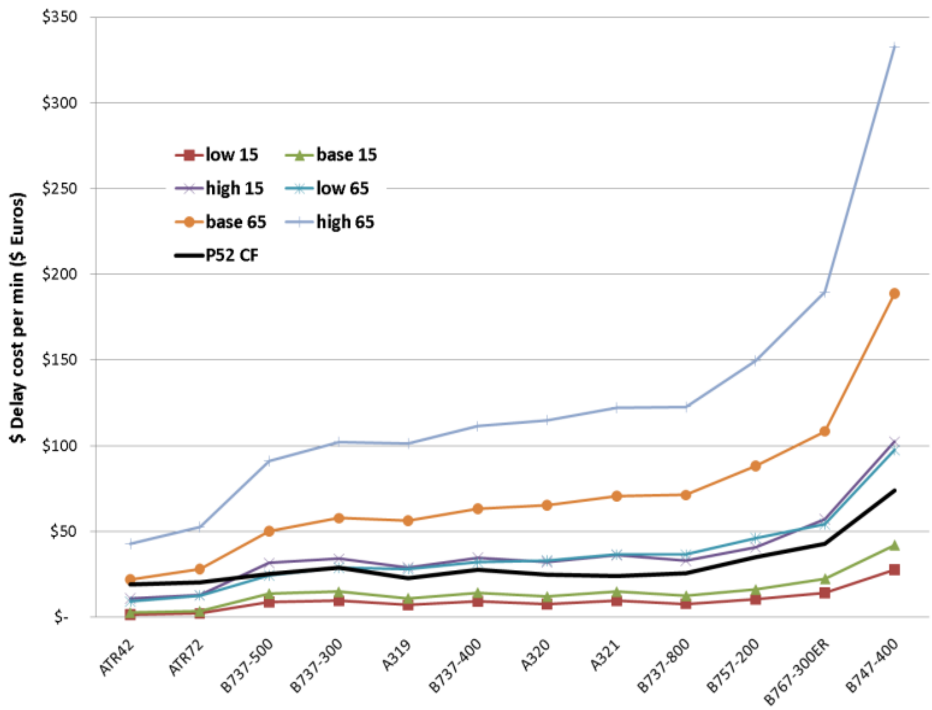

Figure A - 4. Tactical Airborne Delay Costs en-route and holding (without network effect) vs. Operational costs

This paper will next show results from this methodology for computing the operational delay costs using the delay cost factors as derived above, for aircraft not described in the EuroControl. Such aircraft represents 72% of aircraft operations in the US. These factors can be derived for any time period that historical BTS cost data is available.

When using the same model but using fuel burn rates as reported in US databases, the analysis shows that fuel burn rates reported in the US are lower than reported in the EC report. This means that even using the model postulated in the EC report, US airlines show slightly lower costs for equivalent delays than that of the EC report. Coefficients for the base cost scenario will be used for developing US delay cost factors. For the network effect of these delays, the delay multipliers based on American Airlines case study (see Beatty, 1998 or Table 2-20 in [Eurocontrol, 2004]) can be used.

Results of Case Study

This study examines delay costs for US airline departures from 12 major airports (EWR, JFK, LGA, DCA, BWI, IAD, SFO, OAK, SFO, BOS, PHL, DFW) for one of the busiest months in US aviation history (July, 2007). Delays by segment of flight, by aircraft type, by airline and by hour of day are examined in this case study. Table A - 10 show the results of this case study.

	Gate Delay	Taxi out Delay	Airborne Delay	Taxi in Delay	Total Delay
July 2007 Delay costs	$ 8,492,145	$ 10,754,556	$ 41,441,667	$ 3,110,810	$ 63,799,178
Delay cost per flight	$ 30.26	$ 38.33	$ 147.69	$ 11.09	$ 227.37
Delay minutes	4,022,321	2,276,214	1,052,131	728,188	$ 8,078,854
Delay cost per minute	$ 2.11	$ 4.72	$ 39.39	$ 4.27	$ 7.90

Table A - 10. July 2007 Departure delays by segment of flight for selected airports

These Table A - 10esults indicate that even though the majority of delays occur on the ground (87%), the airlines incur the greatest delay costs while their flights are airborne (65%). Since a flight delayed in the air is twenty times the cost of an aircraft delayed at the gate, there is an economic advantage for airlines to hold flights at the origin airports rather than delayed in the air.

Table A - 11 shows the airlines that exceeded one million dollars in delay costs for July 2007 from the selected airports in this study. American Eagle realized the lowest delay costs per flight, largely due to their more fuel efficient fleet of CRJ-700s, Embraer ERJ-135/145s, and SAAB 340 turboprops. Delta Airlines, on the other hand, showed the greatest delay costs per flight, mostly due to their less fuel efficient fleet.

Airline	Gate Delay	Taxi out Delay	Airborne Delay	Taxi in Delay	Total Delay	# Flights	$ per flight
american	$ 1,272,838	$ 1,828,159	$ 5,859,727	$ 873,476	$ 9,834,200	38,399	$ 256.11
southwest	$ 581,768	$ 581,715	$ 6,201,624	$ 229,303	$ 7,594,410	28,722	$ 264.41
delta	$ 727,080	$ 1,215,887	$ 3,079,572	$ 290,221	$ 5,312,760	13,233	$ 401.48
us airlines	$ 416,258	$ 892,844	$ 3,764,669	$ 196,096	$ 5,269,868	15,129	$ 348.33
united	$ 550,133	$ 1,030,883	$ 2,945,020	$ 254,389	$ 4,780,425	19,015	$ 251.40
continental	$ 885,487	$ 1,111,575	$ 2,341,061	$ 218,211	$ 4,556,335	14,387	$ 316.70
jet blue	$ 626,087	$ 1,001,468	$ 2,048,026	$ 183,966	$ 3,859,548	14,752	$ 261.63
northwest	$ 184,893	$ 364,349	$ 1,536,632	$ 99,053	$ 2,184,927	7,048	$ 310.01
american eagle	$ 423,625	$ 376,629	$ 851,741	$ 142,279	$ 1,794,274	24,508	$ 73.21
air tran	$ 393,055	$ 287,737	$ 927,879	$ 103,138	$ 1,711,810	7,670	$ 223.18
air wisconsin	$ 204,604	$ 133,906	$ 1,204,321	$ 28,433	$ 1,571,264	12,259	$ 128.17
com air	$ 223,066	$ 337,824	$ 939,059	$ 69,319	$ 1,569,268	8,556	$ 183.41
ExpressJet	$ 321,204	$ 348,175	$ 586,765	$ 51,283	$ 1,307,427	11,211	$ 116.62
Republic Airlines	$ 131,820	$ 75,043	$ 886,370	$ 16,935	$ 1,110,167	5,147	$ 215.69

Table A - 11. July 2007 Departure delays for airlines exceeding $1M in delay costs

Table A - 12 shows the aircraft that exceeded one million dollars in delay costs for July 2007 from the selected airports for this study. As shown earlier in Table 10, the fuel efficient Embraer ERJ-135/145s showed the lowest delay costs per flight. However the older less fuel efficient MD88s and B757-200s show the greatest delay costs per flight.

Analysis of the airline delay costs by time of day (Table A - 13) shows that average cost of delay per flight ramps up from lows in the early morning (5-6am) to a peak between 5-6pm and then begin to subside with relatively small costs by 10pm. The gate delay costs are highest in late afternoon (5-7pm), whereas taxi out delays are highest between (4-6pm) and airborne delays are highest in the early mornings (6-9am). Overnight flights can have significant delay costs, but these reflect the few large aircraft flights that, when delayed, exhibit these as costly airborne delays.

Analysis of the airline delay costs for the top 12 markets for delay costs (Table A - 14) shows that parity rarely exists between opposite markets. An extreme case of opposite markets is highlighted in red (JFK-ANC and ANC-JFK), the average delay costs at these markets varies by $754. Another extreme pair is highlighted in green (SFO-LAX and LAX-SFO), because the average delay costs per flight at these markets are within $28 of each other.

Aircraft	Gate Delay	Taxi out Delay	Airborne Delay	Taxi in Delay	Total Delay	# Flights	$ per flight
B752	$ 794,859	$ 1,435,696	$ 3,691,511	$ 444,658	$ 6,366,725	18,662	$ 341.16
B737	$ 602,399	$ 582,814	$ 4,649,791	$ 204,566	$ 6,039,570	22,570	$ 267.59
MD82	$ 619,102	$ 895,085	$ 3,230,645	$ 455,587	$ 5,200,419	20,840	$ 249.54
A320	$ 666,428	$ 1,315,475	$ 2,594,288	$ 294,020	$ 4,870,211	20,241	$ 240.61
B733	$ 574,161	$ 618,854	$ 3,464,556	$ 181,687	$ 4,839,259	19,561	$ 247.39
A319	$ 308,906	$ 603,246	$ 2,826,820	$ 145,379	$ 3,884,352	14,650	$ 265.14
CRJ2	$ 333,964	$ 333,642	$ 2,528,964	$ 78,126	$ 3,274,695	22,824	$ 143.48
B738	$ 523,472	$ 683,996	$ 1,764,857	$ 190,269	$ 3,162,595	12,479	$ 253.43
E145	$ 542,696	$ 422,478	$ 1,808,727	$ 109,635	$ 2,883,536	23,464	$ 122.89
MD88	$ 295,444	$ 503,327	$ 1,659,392	$ 98,798	$ 2,556,961	6,142	$ 416.31
E170	$ 189,513	$ 119,199	$ 1,321,926	$ 29,081	$ 1,659,718	7,637	$ 217.33
B735	$ 355,881	$ 430,128	$ 741,454	$ 79,724	$ 1,607,188	6,102	$ 263.39
MD83	$ 187,480	$ 233,817	$ 1,015,068	$ 119,692	$ 1,556,057	5,900	$ 263.74
E190	$ 211,808	$ 228,699	$ 1,021,585	$ 31,092	$ 1,493,185	4,694	$ 318.11
E135	$ 256,153	$ 276,426	$ 711,110	$ 63,297	$ 1,306,986	13,355	$ 97.86
B712	$ 262,947	$ 197,903	$ 700,814	$ 71,115	$ 1,232,779	6,894	$ 178.82
CRJ1	$ 177,892	$ 252,791	$ 732,486	$ 54,852	$ 1,218,021	6,498	$ 187.45
B734	$ 120,198	$ 213,059	$ 819,107	$ 54,217	$ 1,206,580	4,268	$ 282.70

Table A - 12. 3 July 2007 Departure delays for aircraft exceeding $1M in delay costs

Time of Day	Gate Delay	Taxi out Delay	Airborne Delay	Taxi in Delay	Total Delay	# Flights	$ per flight
12-1am	$ 22,765	$ 14,804	$ 120,664	$ 5,632	$ 163,865	500	$ 327.73
1-2am	$ 12,931	$ 6,853	$ 64,375	$ 3,217	$ 87,376	201	$ 434.71
2-3am	$ 5,270	$ 5,212	$ 52,553	$ 3,717	$ 66,751	118	$ 565.69
3-4am	$ 9,587	$ 13,905	$ 97,884	$ 1,881	$ 123,258	127	$ 970.53
4-5am	$ 11,819	$ 4,340	$ 52,281	$ 1,176	$ 69,616	109	$ 638.68
5-6am	$ 43,822	$ 26,166	$ 304,460	$ 16,053	$ 390,500	2,254	$ 173.25
6-7am	$ 120,525	$ 361,186	$ 2,990,143	$ 194,745	$ 3,666,599	20,175	$ 181.74
7-8am	$ 217,893	$ 493,522	$ 3,373,441	$ 231,127	$ 4,315,984	19,756	$ 218.46
8-9am	$ 289,591	$ 784,156	$ 3,124,226	$ 215,999	$ 4,413,972	20,182	$ 218.71
9-10am	$ 259,797	$ 650,089	$ 2,511,443	$ 180,034	$ 3,601,363	17,617	$ 204.43
10-11am	$ 264,222	$ 491,762	$ 2,638,476	$ 165,847	$ 3,560,307	17,238	$ 206.54
11-12pm	$ 335,033	$ 493,040	$ 2,771,531	$ 208,298	$ 3,807,903	17,859	$ 213.22
12-1pm	$ 431,748	$ 506,069	$ 2,937,395	$ 211,522	$ 4,086,734	18,161	$ 225.03
1-2pm	$ 565,399	$ 625,994	$ 2,876,425	$ 223,525	$ 4,291,344	17,660	$ 243.00
2-3pm	$ 644,341	$ 721,229	$ 2,540,171	$ 213,641	$ 4,119,382	16,385	$ 251.41
3-4pm	$ 778,806	$ 783,087	$ 2,689,679	$ 230,410	$ 4,481,982	16,913	$ 265.00
4-5pm	$ 802,846	$ 1,047,412	$ 2,617,860	$ 212,301	$ 4,680,419	18,232	$ 256.71
5-6pm	$ 975,523	$ 1,093,879	$ 2,637,803	$ 238,021	$ 4,945,226	18,302	$ 270.20
6-7pm	$ 813,213	$ 891,570	$ 2,105,195	$ 186,777	$ 3,996,754	15,983	$ 250.06
7-8pm	$ 754,016	$ 749,206	$ 1,773,709	$ 145,386	$ 3,422,317	15,585	$ 219.59
8-9pm	$ 584,859	$ 561,539	$ 1,317,165	$ 103,529	$ 2,567,092	12,381	$ 207.34
9-10pm	$ 343,817	$ 253,808	$ 982,618	$ 59,593	$ 1,639,837	8,867	$ 184.94
10-11pm	$ 111,404	$ 117,220	$ 504,545	$ 31,724	$ 764,893	3,793	$ 201.66
11-12am	$ 92,917	$ 58,507	$ 357,626	$ 26,655	$ 535,705	2,203	$ 243.17
Grand Total	$ 8,492,145	$ 10,754,556	$ 41,441,667	$ 3,110,810	$ 63,799,178	280,601	$ 227.37

Table A - 13. July 2007 Departure delay costs by time of day

Market	Gate Delay	Taxi out Delay	Airborne Delay	Taxi in De	Total Delay	# Flights	$ per flight	diff
DCA-LGA	$ 14,499	$ 71,972	$ 342,688	$ 4,114	$ 433,273	919	$ 471.46	
LGA-DCA	$ 16,547	$ 62,979	$ 169,572	$ 6,584	$ 255,682	920	$ 277.92	$ 193.55
JFK-LAX	$ 43,668	$ 167,542	$ 156,062	$ 26,318	$ 393,590	709	$ 555.13	
LAX-JFK	$ 29,592	$ 34,487	$ 273,140	$ 28,438	$ 365,657	715	$ 511.41	$ 43.73
BOS-LGA	$ 22,719	$ 46,799	$ 313,541	$ 5,794	$ 388,854	961	$ 404.63	
LGA-BOS	$ 17,641	$ 68,828	$ 241,567	$ 7,473	$ 335,509	950	$ 353.17	$ 51.47
ATL-LGA	$ 50,207	$ 70,232	$ 205,080	$ 27,704	$ 353,222	835	$ 423.02	
LGA-ATL	$ 51,346	$ 106,689	$ 151,247	$ 17,844	$ 327,126	845	$ 387.13	$ 35.89
LGA-ORD	$ 30,354	$ 111,835	$ 187,679	$ 13,913	$ 343,781	892	$ 385.41	
ORD-LGA	$ 24,352	$ 59,329	$ 148,979	$ 13,082	$ 245,741	890	$ 276.11	$ 109.29
JFK-ANC	$ 23,588	$ 45,255	$ 265,200	$ 970	$ 335,013	223	$ 1,502.30	
ANC-JFK	$ 6,733	$ 6,783	$ 147,021	$ 14,380	$ 174,917	234	$ 747.51	$ 754.79
JFK-SFO	$ 27,699	$ 125,408	$ 156,253	$ 10,428	$ 319,788	562	$ 569.02	
SFO-JFK	$ 21,095	$ 29,069	$ 201,833	$ 20,438	$ 272,435	589	$ 462.54	$ 106.48
ATL-EWR	$ 55,128	$ 51,721	$ 145,523	$ 6,169	$ 258,541	676	$ 382.46	
EWR-ATL	$ 40,611	$ 56,130	$ 84,972	$ 11,654	$ 193,366	682	$ 283.53	$ 98.93
SFO-LAX	$ 27,771	$ 29,325	$ 175,898	$ 25,051	$ 258,045	1049	$ 245.99	
LAX-SFO	$ 47,983	$ 41,140	$ 133,639	$ 10,419	$ 233,182	1067	$ 218.54	$ 27.45
ATL-PHL	$ 35,457	$ 35,830	$ 174,688	$ 6,140	$ 252,115	635	$ 397.03	
PHL-ATL	$ 29,554	$ 55,115	$ 75,821	$ 11,129	$ 171,619	632	$ 271.55	$ 125.48
LAX-OAK	$ 11,536	$ 11,823	$ 216,957	$ 7,632	$ 247,948	883	$ 280.80	
OAK-LAX	$ 11,007	$ 14,764	$ 181,690	$ 8,932	$ 216,394	885	$ 244.51	$ 36.29
MCO-PHL	$ 23,899	$ 24,717	$ 189,311	$ 9,549	$ 247,476	598	$ 413.84	
PHL-MCO	$ 28,373	$ 44,707	$ 91,317	$ 6,824	$ 171,220	597	$ 286.80	$ 127.04

Table A - 14. July 2007 Departure delay costs for top 12 market pair delay costs

This analysis of the airline delay costs and delays for the top 12 selected airports is shown in Table A - 15. This analysis shows that average delay costs for departures out of JFK are twice the average delay costs of departures from DFW.

Airport	Gate Delay	Taxi out Delay	Airborne Delay	Taxi in Delay	Total Delay	# Flights	$ per flight	Total Delay	$ per min	delay per flight
DFW	$ 959,984	$ 881,398	$ 2,674,620	$ 213,078	$ 4,729,080	26,013	$ 181.80	715,435	$ 6.61	27.50
JFK	$ 701,569	$ 1,819,817	$ 1,929,810	$ 132,221	$ 4,583,418	12,594	$ 363.94	675,469	$ 6.79	53.63
PHL	$ 505,110	$ 1,006,537	$ 2,147,482	$ 127,386	$ 3,786,516	17,089	$ 221.58	585,909	$ 6.46	34.29
LGA	$ 409,444	$ 1,035,883	$ 1,895,051	$ 119,169	$ 3,459,548	14,760	$ 234.39	533,884	$ 6.48	36.17
EWR	$ 594,332	$ 1,093,532	$ 1,296,275	$ 115,202	$ 3,099,341	13,075	$ 237.04	535,720	$ 5.79	40.97
BOS	$ 416,529	$ 475,273	$ 2,035,500	$ 147,260	$ 3,074,561	11,680	$ 263.23	367,926	$ 8.36	31.50
SFO	$ 262,320	$ 328,623	$ 1,933,248	$ 151,861	$ 2,676,051	12,782	$ 209.36	280,038	$ 9.56	21.91
DCA	$ 214,479	$ 322,695	$ 1,838,970	$ 90,158	$ 2,466,301	11,087	$ 222.45	266,938	$ 9.24	24.08
IAD	$ 244,891	$ 356,161	$ 1,575,527	$ 87,773	$ 2,264,352	11,246	$ 201.35	292,379	$ 7.74	26.00
BWI	$ 264,315	$ 264,049	$ 1,585,187	$ 99,819	$ 2,213,370	10,248	$ 215.98	242,499	$ 9.13	23.66
OAK	$ 96,497	$ 95,769	$ 1,227,613	$ 64,249	$ 1,484,127	6,875	$ 215.87	125,457	$ 11.83	18.25
SJC	$ 66,585	$ 44,986	$ 1,049,198	$ 55,618	$ 1,216,387	5,843	$ 208.18	89,718	$ 13.56	15.35

Table A - 15. July 2007 Departure delay costs and delays for departures from 12 selected airports

Conclusions

From the analysis, the following conclusions are made:

- The cost factors from the EC report and costs as reported by US carriers in BTS P52 database follow similar trends. Thus, the general approach taken by EuroControl can be applied, with minor modifications, to compute the cost of delays for US flights
- The appropriate multipliers for crew and maintenance costs are determined that, when combined with the other factors, produced multipliers close to those reported in the EC report.
- Airborne delays, when incurred, dominate ground delay costs, so airlines are economically encouraged to maximize ground delay costs.
- Newer more fuel efficient aircraft provide airlines with the least delay costs.
- The cost of delay is not proportional to the flights flown. One reason for this non-intuitive result is that when a flight is cancelled, it is recorded as having zero delay. Future research will address how to cost cancelled flights.

The calculations of the cost of delayed flights (ignoring all cancelled flights) total $63.8M for July 2007. Many economic modeling and analysis efforts require a good understanding of the costs that an airline will incur when it experiences delays at the gate, while taxiing or while en-route. This paper has presented a relatively straightforward mechanism for calculating such costs and for predicting how such costs are likely to increase when there is a change in fuel costs, aircraft type, or when some other cost might be added to the overall cost structure. It is informative in explaining why airlines are currently down-gauging the aircraft size: the newer regional jets are more fuel efficient and airborne fuel costs dominate the overall cost. Fuel costs, coupled with the fact that the airlines can offer increased frequency and observe higher load factors, encourage airlines to down-guage. Although such policies are favored by the industry, they result in less efficient use of both the airspace and airport runways.

Future Work

Future analysis will both expand and apply this model in a variety of efforts currently underway:

A mechanism for including the costs of cancellations in the overall cost calculations needs to be developed. The research of Xiong [2010], Wang, et al. [2006], Rupp [2005], Sherry [2010] and Bratu & Barnhart [2005] will assist in this effort.

Sensitivity analysis needs to be done on the model to determine how robust it is to significant cost changes in fuel or crew, and/or changes in aircraft usage. Having separated the cost factors into their component parts, alternative cost factors can be applied to a variety of aircraft types not studied in the EC model. Initial work in this direction is reported in Kara et al. [2010].

Analysis, based on these costs, needs to be done to predict which flights are most likely to be cancelled or delayed when weather conditions result in the initiation of a Ground Delay Program.

The delay costs as provided in the above study are needed to evaluate savings to airlines of possible changes to ground delay program rules that use market-based mechanisms to determine departure order. See Gao et. al. [2010] for more on this effort.

The delay costs as provided in the above study need to be included as part of a larger equilibrium model that predicts the actions of airlines under various policy decisions. See Ferguson et. al. [2010] for more on this effort.

These delay costs will be used as a tool in a congestion-pricing model to determine the flights that are most likely to be cancelled first when capacity at an airport is reduced. An understanding of airline behavior (based on their cost structure and network configuration) is necessary when attempting to determine the prices that a regulator would need to charge in order to have supply approximately equal demand when congestion pricing is imposed at an airport.

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14. ABSTRACT
This report describes the Airline Fleet, Route, and Schedule Optimization Model (AFRS-OM) that is designed to provide insights into airline decision-making with regards to markets served, schedule of flights on these markets, the type of aircraft assigned to each scheduled flight, load factors, airfares, and airline profits. The main inputs to the model are hedged fuel prices, airport capacity limits, and candidate markets. Embedded in the model are aircraft performance and associated cost factors, and willingness-to-pay (i.e. demand vs. airfare curves). Case studies demonstrate the application of the model for analysis of the effects of increased capacity and changes in operating costs (e.g. fuel prices). Although there are differences between airports (due to differences in the magnitude of travel demand and sensitivity to airfare), the system is more sensitive to changes in fuel prices than capacity. Further, the benefits of modernization in the form of increased capacity could be undermined by increases in hedged fuel prices.

15. SUBJECT TERMS
Air transportation; Airlines; Aviation; Aviation operations; Metroplex

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