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

Research Highlights

- The cost factors from the EC report and costs as reported by US carriers in BTS P52 database follow similar trends.
- 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.

1. 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- routes 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
- extended 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 airlines 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.

2. 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”.

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

The EC report describes the model as an additive model where each component defines a proportion of the total cost. Table 1 shows the costs 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 1 details the inputs and outputs of their model.

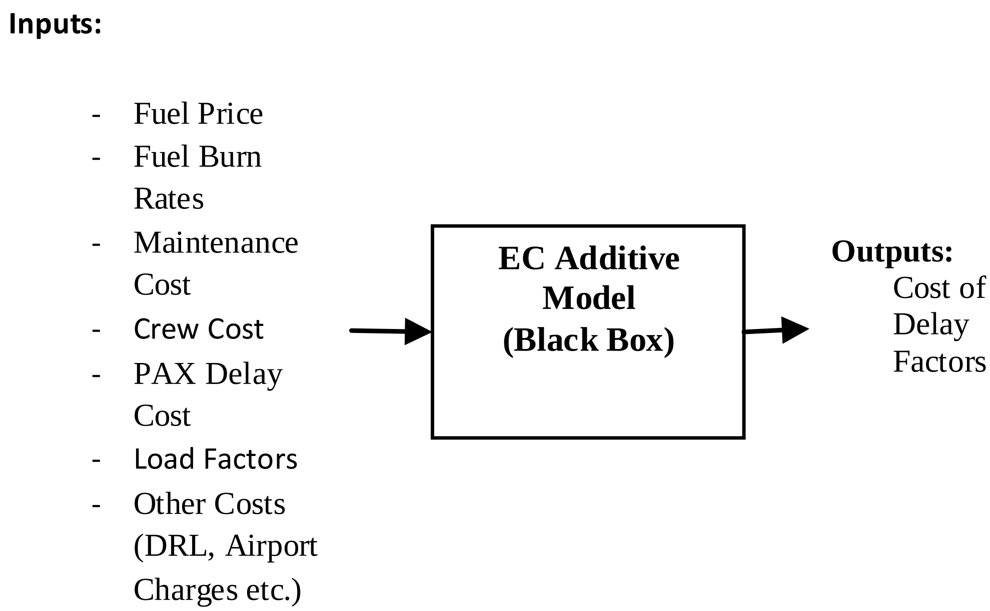

Figure 1 EuroControl (EC) Model

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 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 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]).

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

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 2), delay while taxiing at either airport (Table 3) or delay while airborne (en-route and holding, Table 4). These segments were chosen for discussion because they reflect the fidelity of publically available data.

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 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 4 Tactical airborne delay costs and holding (without network effects)

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.

3. Methodology

3.1. 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:

		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 5 Elements of EU Cost of Delay Model

Table 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).

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

Table 6 2003 BTS % of BHDOC

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 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.

3.2. 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 7, the new derived coefficients are shown in blue.

Gate: Cost Factor Coefficients	Based on 15 min. delay			Based on 65 min. delay		
	cost scenario			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			Based on 65 min. delay		
	cost scenario			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			Based on 65 min. delay		
	cost scenario			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 7 Fitted Coefficients for Crew, Maintenance and Other Costs

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

Chi square goodness of fit tests were done to examine statistically how well these derived coefficients fit the EU report factors, table 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.

3.3. 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 interpolates using the two data points above.

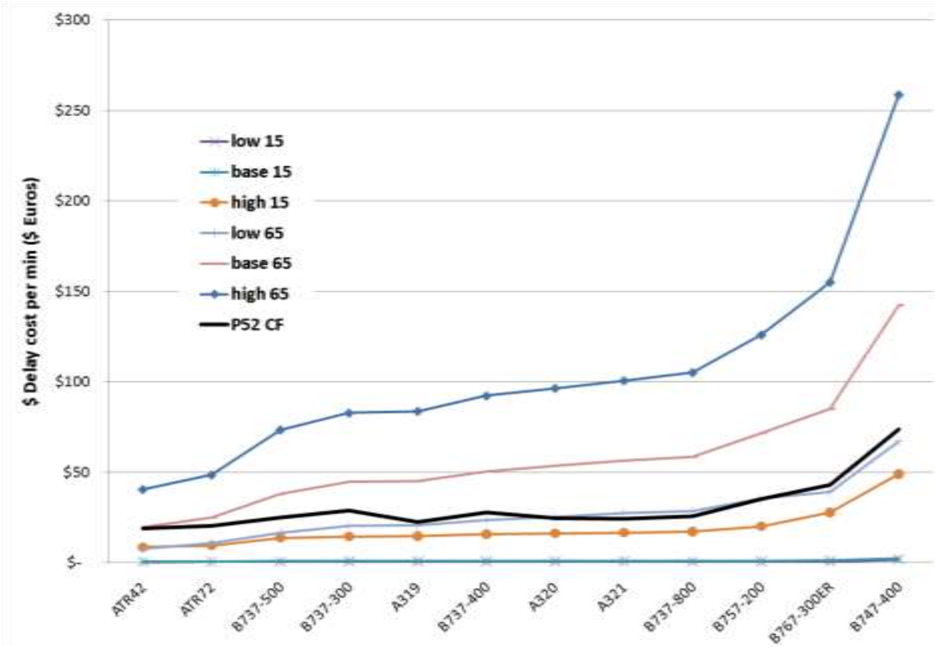

Figure 2 Tactical Ground Delay costs: gate only (without network effect) vs. Operational costs

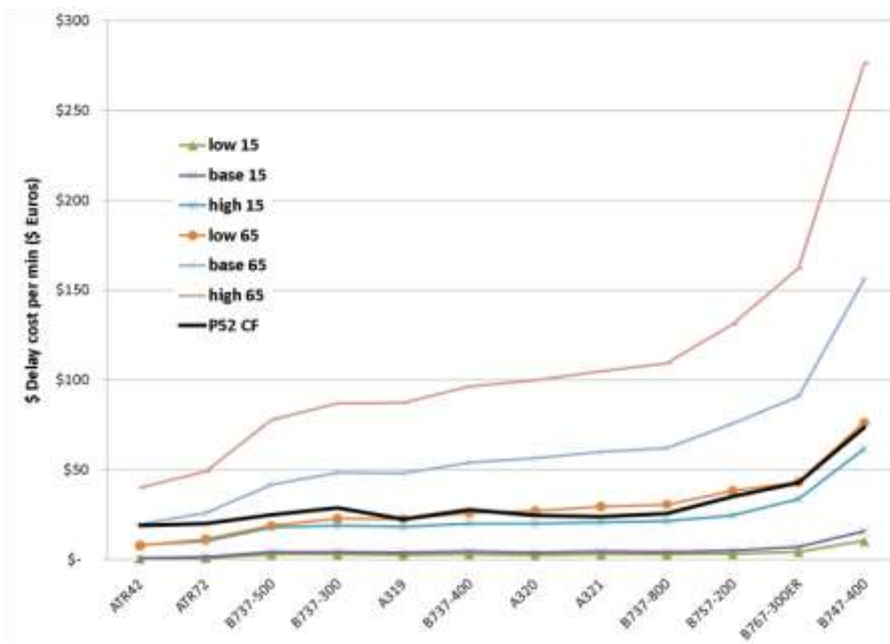

Figure 3 Tactical Ground Delay costs: Taxi only (without network effect) vs. Operational costs

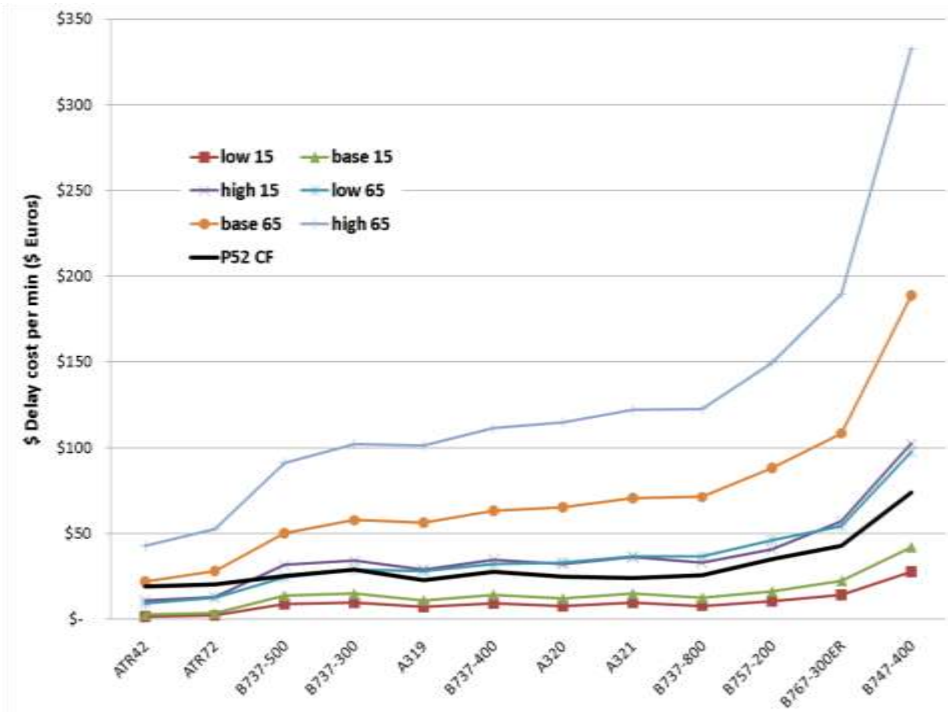

Figure 4 Tactical Airborne Delay Costs en-route and holding (without network effect) vs. Operational costs

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 2, 3 and 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 of that it is appropriate to use BTS crew cost percentages of Block Hour Operating Costs (BHDOC) when calculating total 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.

4. Results of Case Study

This study examines delay costs for US airlines 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. Tables 10-15 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 10 July 2007 Departure delays by segment of flight for selected airports

Table 10 indicates 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.

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 11 July 2007 Departure delays for airlines exceeding $1M in delay costs

Table 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.

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 12 July 2007 Departure delays for aircraft exceeding $1M in delay costs

Table 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.

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 13 July 2007 Departure delay costs by time of day

Analysis of the airline delay costs by time of day (table 13) shows that average cost of delay per flight ramp 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.

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 14 July 2007 Departure delay costs for top 12 market pair delay costs

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

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 15 July 2007 Departure delay costs and delays for departures from 12 selected airports

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

5. 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 are imposed at some airport.

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