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 [12-13]. Many of these approaches rely on economic feedback, including the cost of delays to the airlines. Therefore, finding the true cost of a delay is essential for air transportation management. A 2004 EuroControl study [2] describes a methodology and presents results detailing the cost to airlines of delays during various segments of a trip. The costs are divided into short delays (less than 15 minute) and long delays (greater than 65). 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. However, their model is not explicitly defined and therefore no sensitivity analysis is possible in case the involved cost factors change significantly (e.g. fuel). Furthermore, the model is generated based on data from EU airlines for only 12 aircraft, so applying these delay costs to other aircraft or US airlines is not possible. This paper details a method for applying these delay costs to other aircraft and other airlines. The individual cost factor delays are applied to US data. The approach allows one to update the cost whenever any of the factors (crew, fuel, maintenance, and ground costs) change. It considers the size of the aircraft when making such calculations, both from the perspective of fuel burn and passenger costs. Data for Philadelphia airport (PHL) is displayed as a case study to show current delay costs.**

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

I. INTRODUCTION

The airline industry moves millions of passengers and tons of cargo annually. The Schumer report estimated that in 2007, airport delays cost about 40.7 billion dollars to the economy [1]. Disruptions in one part of the airspace impact the entire network as delays propagate. It is estimated that almost 50% of the entire airspace delays are caused by delays that originate at the New York/New Jersey/ Pennsylvania airports.

This implies that delays and their true costs are vital to airport and airspace management decision making.

Similarly researchers are applying more holistic approaches to the feedback control of the air transportation system [12-13]. Many of these approaches rely on economic feedback, including the cost of delays to the airlines. Therefore, understanding the true cost of a delay is not only of interest to the airlines that incur these costs but is essential for air transportation management.

We begin this study by considering only the direct costs to the airlines of such delays. We then apply estimates of network effects on delay costs based on a study performed by American Airlines [6]. Future work will examine the social costs of such delays, i.e. the resulting economics costs to the various regions and other industries.

In general a flight can be delayed due to several reasons, mainly:

- Mechanical problems with the aircraft.
- Schedule disruption due to bad weather or air traffic management initiatives (Ground Delay Programs (GDPs) or Air Flow Programs (AFPs)).
- Misaligned crew/ aircraft due to previous delayed flight

Weather is a major cause of delay as it reduces the capacity of both the airspace and the runways. At several highly utilized airports, overscheduling also plays role in causing delays. 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. Holding at a gate is both cheaper and safer than airborne holds, and allows the system to be better managed. Finally, the delays already described induce future delays in the system, because the aircraft or crews may not arrive at their next assignment on time. Even when the crew does arrive, they may not be able to work another flight because they have exceeded their allowable working hours.

We base our work on a final report evaluating true cost of flight delays that was prepared by the Performance Review Unit, EuroControl in 2004[2]. This EC report describes a

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methodology and presents results detailing the cost to airlines of delays during various segments of a trip. The costs are divided into short delays (less than 15 minute) and long delays (greater than 65). The report provides the resultant multiplier (Euros per minute) for any such segment. The types of delays considered include gate delay, access to runway delay (both taxi in and out delays), on 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. However, their model is not explicitly defined and therefore no sensitivity analysis is possible to changes in the cost factors (e.g. fuel). Furthermore, the model is generated based on data from EU airlines and in stated in terms of costs in 2003 Euros.

The motivation of this paper is therefore to:

- Better understand each of the cost factors involved.
- Develop a model that includes each of the cost factors
- Make the model consistent to US data.

This paper is organized as follows. Section II describes the EC report, Section III provides our methodology for determining the cost components and multipliers that make up the final multipliers used in the EuroControl report and describe our validation of the new model on European data from the period of the EC report. In Section IV and V, we apply our methodology to 8 weather days at Philadelphia as a case study and show the resulting delay costs for these flights. Section VI provides conclusions and Section VII points out the future research.

II. 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".

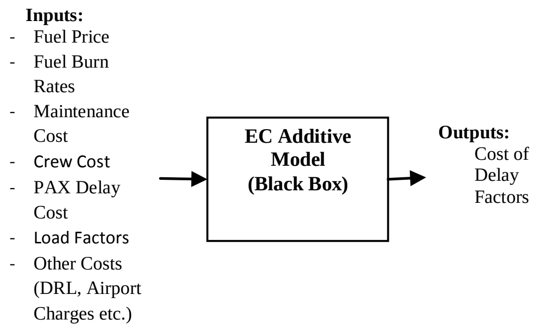

Figure 1: EuroControl (EC) Model

TABLE 1: LOW, BASE AND HIGH COST SCENARIOS (FROM TABLE 2-5 OF [2])

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%

The EC report describes the model as an additive model where each component describes some proportions of the total cost. Table 1 shows what costs factors are included as inputs in these cost scenarios under different delay characteristics. For details, see [2]. Figure 1 details the inputs and outputs of their 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 at all segments of the flights. The prices for all cost scenarios and conversion rate from Euro to Dollars are also provided. (See Table 2-12 and Annex C in [2]).
- **Extra Crew cost**: The report defines extra crew cost as 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 [2]. 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 [2]).
- **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: none 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 are provided (see Annex L in [2]).

TABLE 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	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

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.

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	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 4: TACTICAL AIRBORNE DELAY COSTS AND HOLDING (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

Since the data is in Euros, we have used the conversion rate of 1 Euros = 1$ (as used by the report).

One point worth mentioning is that the findings of the report are for EU airports only. We validate their cost factors by applying the imputed cost factors to their data. However, once we have obtained these costs factors, when applying the formulas to US data, we recognize the differences between the US and European system and adjust the calculations accordingly to reflect these differences. 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.

III. METHODOLOGY

A. Regenerating the EC Model

For our analysis, we start 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, we divide the flight into three segments; gate, taxi and en-route (which includes both airborne and holding). For each of these segment, three cost scenarios and two range delays are provided, hence for each of these 18 different cases (segments x cost scenarios x delay ranges), we have the following model:

$$C_{delay} = c_{fuel} \times \text{fuel burn rate} \times \text{fuel price}$$
$$+c_{crew} \times \text{crew cost}$$
$$+c_{maintenance} \times \text{maintenance cost}$$
$$+ c_{other} \times \text{other cost}$$
$$+ c_{pax} \times \text{PAX delay cost} \times (\#\ \text{seats}) \times \text{load factor}$$

All costs factors are in minutes. The coefficients in this cost model were determined so that we obtain a good fit to the EC data, as presented in the report. The validation was done using each of the three scenarios (low, base and high) and each of the 12 aircraft types in that report. Since fuel burn is directly applied in the formulation with no multiplier, the fuel coefficient (i.e. c_{fuel}) is 1 for airborne and taxi segments and 0 for gate segment. . We fix the catch-all category "Other Costs" to be $1.6 [1] and the other cost coefficient (i.e.c_{other}) to be 0.15 for gate segment and 0 otherwise, since these are consistent with the EC report. The PAX cost coefficient (i.e.c_{pax}) is set to be 1 for validation purposes. However, we revise this when applying it to US data. Hence, the only two variables that we need to determine are the coefficients for crew costs and for maintenance cost.

Specifically, we need to determine the factors for all combinations of the two delay ranges, the three scenarios, and the three flight segments, or 18 (possibly different) sets of coefficients in all. We note, however, that we have assumed that the coefficients were independent of aircraft type.

[1] This represents the other cost of operations which is $1.87 in 2008 Dollars(see [4])

B. Modify Model for US Data

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

- We used cost factors from the BTS P52 database (fuel price, crew and maintenance cost) [3].
- We used the fuel burn rate while en route from the BTS P52 database. For taxi burn rate, we used ICAO engine emissions databank. (See [5]).
- We set the PAX delay cost coefficient to 0, since in US; it is not incurred by the airlines.

For other delay ranges, we used the following formulas: for any delay less than or equal to 15 minutes, we used 15 minutes cost factor, similarly for any delay above 65 minutes, we used the cost factor for 65 minutes and above delay. For delays between 15 and 65 minutes, we interpolate using the two data points.

For the network effect of these delays, we use the delay multipliers based on American Airlines case study (see Table 2-20 in [2] or [6]).

C. Case Study

Finally, as a case study, we applied our cost factors to 8 representative weather days at Philadelphia Airport (PHL) that have cancellation rates ranging as low as 1% to a very bad day where 68% of the flights were cancelled. The data is taken from ASPM database [7]. We used 2/13/2007, 3/16/2007, 3/23/2007, 8/9/2007, 2/1/2008, 2/12/2008, 2/22/2008, and 6/23/2008 for the case study. We chose these days because, in every case, there were Ground Delay Programs that forced large delays.

Our next section describes all the results and observations we found during our analysis.

IV. RESULTS

Before beginning the work to determine the cost coefficients for the new model, we first examined whether overall cost factors in the US appear to be similar to those incurred in Europe. We computed, based on the EC factors, the different types of delay cost (gate, taxi and airborne-and-holding) for the given 12 aircrafts and compared it with the average operational cost per minute using P52 [3] data from the BTS database for US airlines.

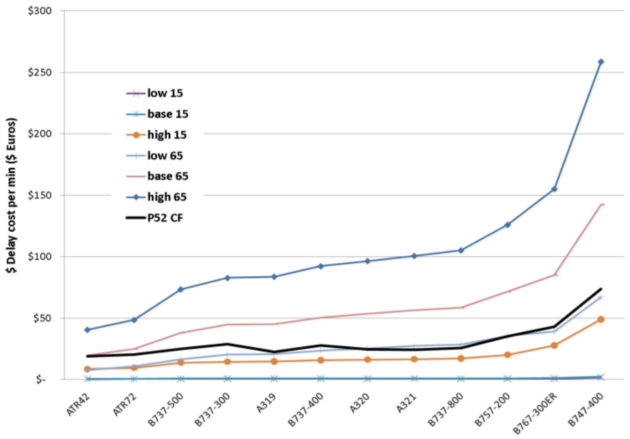

Figure 2: Tactical Ground Delay costs: gate only (without network effect) vs. Operational costs

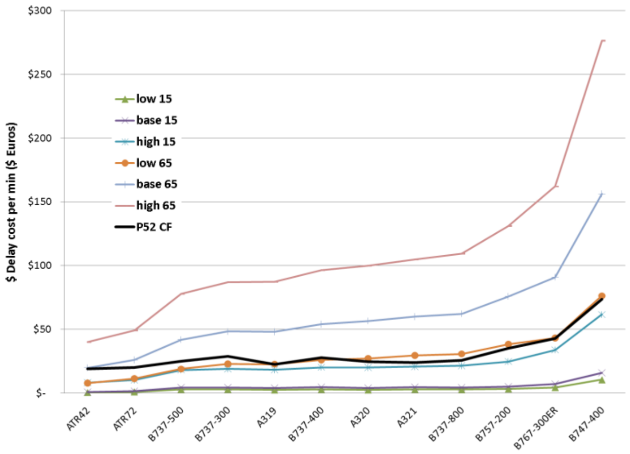

Figure 3: Tactical Ground Delay Costs: Taxi only (without network effect) vs. Operational costs

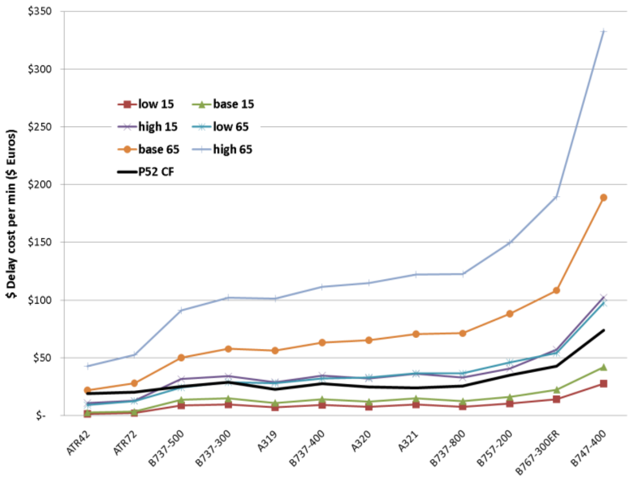

Figure 4: Tactical Airborne Delay Costs en-route and holding (without network effect) vs. Operational costs

Figure 2, 3 and 4 show that, in all of these flight segments, the trends are similar affirming the fact that these cost factors are consistent with the operational costs in the US.

Next we worked to determine the multipliers for crew and maintenance costs that would, when combined with the other factors sum to the resultant multipliers provided in the EC report. Table 5 provides the computed multipliers. To illustrate how close we come to the multipliers provided in the report, we combine the individual multipliers into the summarized single multiplier for total delay cost and compare this multiplier to that provided in the EU report. These resultant multipliers are provided in Tables 6-8 below. Green cells indicate the cases where EC cost factors are 10 % higher than ours; Red cells indicate the cases where our cost factor is 10% higher than EC reports. All the remaining cells have values with difference of within 10%. There are instances where the variations are off by more than 10%, but mostly they are in the 15 minute delay category and mostly, our numbers are lower than those of the EC estimates. We assert, therefore, that the derived numbers are likely to estimate well the costs of long delays.

TABLE 5: COEFFICIENTS COMPUTED ON FITTING THE EC DATA

Gate Only						
Cost Factors	Based on 15 Minutes Delay cost scenario			Based on 65 Minutes Delay cost scenario		
	Low	Base	High	Low	Base	High
Fuel	0	0	0	0	0	0
Crew	0	0	0.5	0	0.85	2
Maintenance	0.02	0.02	0.05	0.05	0.05	0.05
PAX delay	1	1	1	1	1	1
Other	0.15	0.15	0.15	0.15	0.15	0.15
Taxi Only						
Cost Factors	Based on 15 Minutes Delay cost scenario			Based on 65 Minutes Delay cost scenario		
	Low	Base	High	Low	Base	High
Fuel	1	1	1	1	1	1
Crew	0	0	0.5	0	0.85	2
Maintenance	0.02	0.02	0.05	0.05	0.05	0.05
PAX delay	1	1	1	1	1	1
Other	0	0	0	0	0	0
En-route						
Cost Factors	Based on 15 Minutes Delay cost scenario			Based on 65 Minutes Delay cost scenario		
	Low	Base	High	Low	Base	High
Fuel	1	1	1	1	1	1
Crew	0	0	0.5	0	0.85	2
Maintenance	0.02	0.02	0.1	0.05	0.05	0.1
PAX delay	1	1	1	1	1	1
Other	0	0	0	0	0	0

TABLE 6: TACTICAL GROUND DELAY COSTS: GROUND ONLY. DIFFERENCE BETWEEN EC AND OUR COST FACTORS FOR GIVEN 12 AIRCRAFTS (COMPARED TO TABLE 2 OF THIS PAPER)

Aircraft and Number of seats		Based on 15 min. delay cost scenario			Based on 65 min. delay cost scenario		
		low	base	high	low	base	high
ATR42	46	0.30	0.31	0.20	(0.02)	0.08	0.12
ATR72	64	0.05	0.14	0.07	(0.02)	0.02	0.03
B737-500	100	(0.05)	(0.01)	0.03	(0.03)	0.01	0.03
B737-300	125	(0.05)	(0.01)	(0.02)	(0.03)	(0.02)	(0.03)
A319	126	0.03	0.09	(0.01)	(0.02)	(0.02)	(0.03)
B737-400	143	(0.05)	0.01	(0.01)	(0.02)	(0.02)	(0.02)
A320	155	0.03	0.07	(0.01)	(0.02)	0.00	(0.04)
A321	166	0.02	0.08	(0.04)	(0.01)	(0.03)	(0.05)
B737-800	174	(0.09)	(0.03)	0.01	(0.02)	0.02	0.00
B757-200	218	(0.03)	0.03	(0.03)	(0.01)	(0.02)	(0.03)
B767-300E	240	(0.09)	(0.00)	0.00	(0.02)	0.02	(0.02)
B747-400	406	(0.12)	(0.10)	0.08	(0.03)	0.03	0.08

TABLE 7: TACTICAL GROUND DELAY COSTS: TAXI ONLY. DIFFERENCE BETWEEN EC AND OUR COST FACTORS FOR GIVEN 12 AIRCRAFTS (COMPARED TO TABLE 3 OF THIS PAPER)

Aircraft and Number of seats		Based on 15 min. delay cost scenario			Based on 65 min. delay cost scenario		
		low	base	high	low	base	high
ATR42	46	0.30	0.31	0.20	(0.02)	0.08	0.12
ATR72	64	0.05	0.14	0.07	(0.02)	0.02	0.03
B737-500	100	(0.05)	(0.01)	0.03	(0.03)	0.01	0.03
B737-300	125	(0.05)	(0.01)	(0.02)	(0.03)	(0.02)	(0.03)
A319	126	0.03	0.09	(0.01)	(0.02)	(0.02)	(0.03)
B737-400	143	(0.05)	0.01	(0.01)	(0.02)	(0.02)	(0.02)
A320	155	0.03	0.07	(0.01)	(0.02)	0.00	(0.04)
A321	166	0.02	0.08	(0.04)	(0.01)	(0.03)	(0.05)
B737-800	174	(0.09)	(0.03)	0.01	(0.02)	0.02	0.00
B757-200	218	(0.03)	0.03	(0.03)	(0.01)	(0.02)	(0.03)
B767-300E	240	(0.09)	(0.00)	0.00	(0.02)	0.02	(0.02)
B747-400	406	(0.12)	(0.10)	0.08	(0.03)	0.03	0.08

TABLE 8: TACTICAL AIRBORNE DELAY: ENROUTE AND HOLDING. DIFFERENCE BETWEEN EC AND OUR COST FACTORS FOR GIVEN 12 AIRCRAFTS (COMPARED TO TABLE 4 OF THIS PAPER)

Aircraft and Number of seats		Based on 15 min. delay cost scenario			Based on 65 min. delay cost scenario		
		low	base	high	low	base	high
ATR42	46	0.08	0.07	0.15	0.00	0.07	0.11
ATR72	64	0.00	(0.02)	0.04	(0.00)	0.02	0.04
B737-500	100	0.15	0.14	0.12	0.02	0.03	0.05
B737-300	125	0.13	0.13	0.08	0.01	(0.00)	0.00
A319	126	(0.10)	(0.11)	(0.06)	(0.01)	(0.03)	(0.02)
B737-400	143	0.11	0.10	0.06	0.01	(0.00)	0.00
A320	155	(0.04)	(0.04)	(0.02)	(0.01)	(0.00)	(0.02)
A321	166	0.01	0.01	(0.02)	(0.00)	(0.03)	(0.03)
B737-800	174	(0.12)	(0.09)	(0.04)	(0.01)	0.01	(0.00)
B757-200	218	(0.09)	(0.09)	(0.07)	(0.01)	(0.03)	(0.03)
B767-300E	240	(0.11)	(0.11)	(0.05)	(0.01)	0.01	(0.02)
B747-400	406	(0.20)	(0.22)	(0.03)	(0.02)	0.01	0.08

V. APPLICATION TO US DATA

When using the same model but using fuel burn rates as reported in US databases, we observed 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, we will have slightly lower costs for equivalent delays than that of the EC report. Table 9 shows the final cost factors computed using the model with our data. We have used the coefficients for the base cost scenario.

We next apply these cost factors to the 8 weather days at PHL. We first compute the non-network costs and then, use the delay multipliers from American Airlines case study (Table 2-20 in [2] or [6]) to compute the network delays and their resulting costs. Figures 5-9 provide some of the results of this case study.

TABLE 9: OUR COEFFICIENTS FOR DIFFERENT COST FACTORS FOR US DATA

Cost Factor	**Gate**		**Taxi**		**En-route**	
	15 min	**65 min**	**15 min**	**65 Min**	**15 min**	**65 min**
Fuel	0	0	1	1	1	1
Crew	0	0.85	0	0.85	0	0.85
Maintenance	0.02	0.05	0.02	0.05	0.02	0.05
PAX	0	0	0	0	0	0
Other	0.15	0.15	0	0	0	0

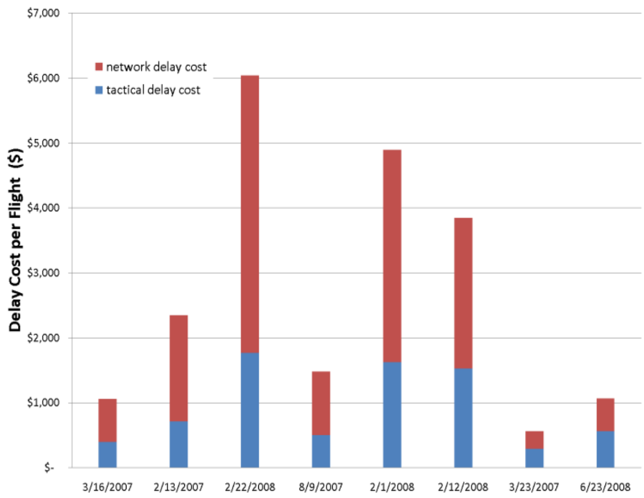

Figure 5: Cost of delay per Flight for observed days

Looking at the cost of delay for each observed day (Figure 5), we see that the cost of delay is not proportional to the proportion of flights cancelled that day. For example, day "2/22/2008", despite having only 22% cancelled flight has the highest cost of delay while day "3/16/2007" with the highest number of cancelled flight has very low cost of delay. One possible explanation for this result is that all cancelled flights are recorded as having zero delay. Thus, a day with more delays but lower cancellations will have lower costs. Future research will evaluate how to better cost out cancelled flights.

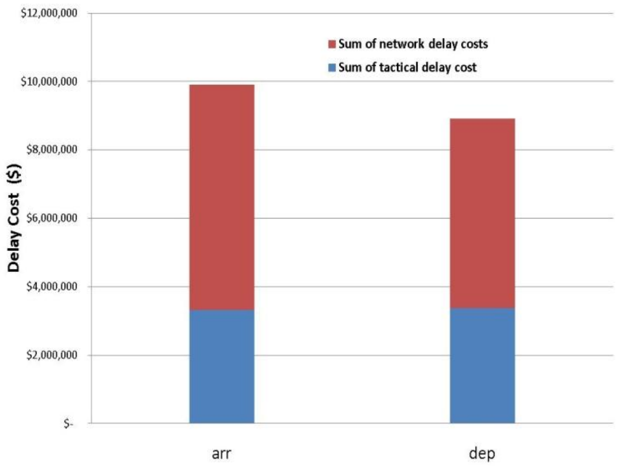

Figure 6: Delay costs (arrivals vs. departures at PHL)

The total costs of delay for departures and arrivals at PHL are very similar, Figure 6. However, arrivals show more network delay costs.

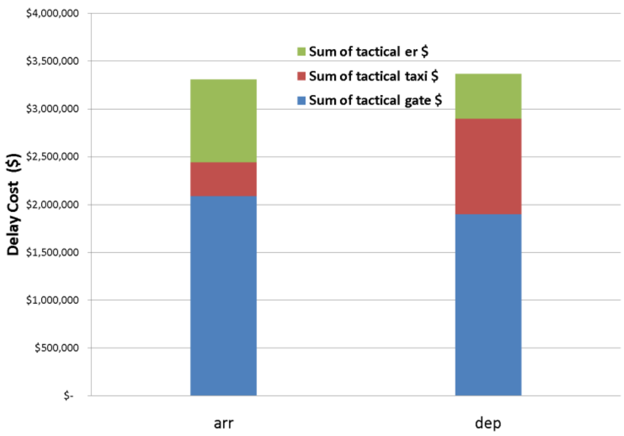

Figure 7: Arrival vs. Departure Tactical Delay costs across all segments of flight

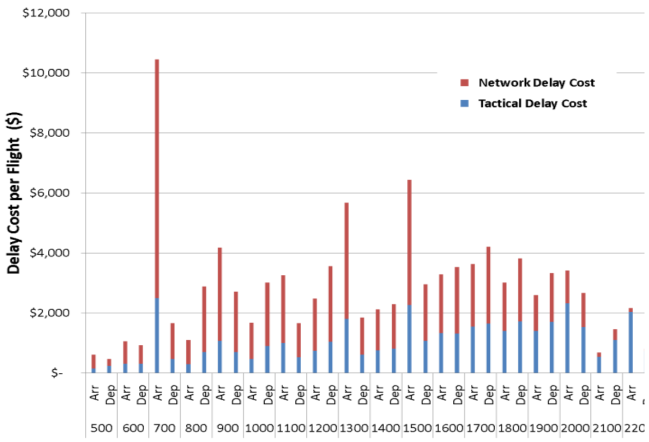

Figure 8: Departure vs. Arrival cost of delay per flight by time of day

Comparing the total cost of primary delay for arrivals vs. departures at PHL for the segments of flights, Figure 7, we see the total delay cost is approximately the same. However, arrivals show slightly more gate delay costs and significantly more airborne delay costs than are observed with departures. And departures show significantly more taxi delay costs than are observed with arrivals.

Analysis of the departure and arrival delay costs per flight by time of day is shown in Figure 8. Arrival delay costs per flight are shown to be much higher for 0700, 1300 and 1500 hrs arrivals.

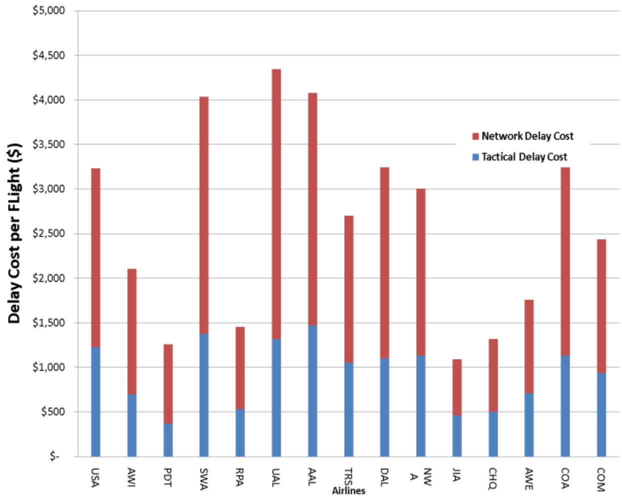

Figure 9: Top 15 Airlines cost of delay per flight

Analysis of the top 15 airlines cost of delay per flight is shown in Figure 9. One interesting result shows that not all airlines incur similar delay costs at PHL. Southwest, United Airlines, Delta Airlines and American Airlines all have higher costs of delay at PHL than does the dominant carrier, US Air. Also, the regional airlines have lower costs of delay than the larger ones.

VI. CONCLUSIONS

From our analysis, we conclude the following:

- 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 [3] the EC report can be applied, with minor modifications, to compute the cost of delays for US flights
- We determined appropriate multipliers for crew and maintenance costs that, when combined with the other factors produced multipliers close to those reported in the EC report.
- The US data shows that very long taxi delays at PHL, which has one dominant airline, US Air. We presume that this airline schedules its flights at peak times in order to restrict competition.
- 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.

- We observe peaking at PHL and this scheduling of departures above runway capacity results in larger delay costs. The network delays are not necessarily larger for these peak times.
- One interesting result shows that not all airlines incur similar delay costs at PHL. Southwest, United Airlines, Delta Airlines and American Airlines all have higher costs of delay at PHL than does the dominant carrier, US Air. Also, the regional airlines have lower costs of delay than the larger ones. Here too, the issue may be one of the way in which the data is recorded. The regional jets are more likely to be cancelled than the larger aircraft and, when cancelled, the data records such flights as having zero delay.
- Our calculations of the cost of delayed flights (but not cancelled flights) total $18M for these 8 days.

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 other major alternative in the cost structure. It is informative in explaining why airlines are currently down-gauging the size of the aircraft used even at airports with substantial capacity restrictions.

VII. FUTURE WORK

We intend to both expand and apply this model in a variety of efforts currently underway:

- We need to devise a mechanism for including the costs of cancellations in the overall cost calculations. The research of Hansen et al. [9], Wang, et al. [10] and Barnhart and Batu [11] will assist in this effort.
- We wish to apply the model and investigate its sensitivity to significant cost changes in fuel or crew, and changes in aircraft usage. By separating the cost factors into their component parts, we are now able to apply the model to aircraft types not studied in the EC model. For application to the US environment, this capability is imperative.
- We will next apply this model to a variety of different airports and see how airline costs vary based on different mixes of aircraft, varying amounts of airline dominance, and alternative government policies (such as slot-controls, rules about entry into the airport, etc.)
- We intend to examine if, based on these costs, we can predict which flights are most likely to be cancelled or delayed when weather conditions result in the initiation of a Ground Delay Program.
- Once this model has been validated for a variety of different congestion scenarios and airports, we intend to include the model as part of a larger equilibrium model that predicts the actions of airlines under various policy decisions. See [8] for more on this effort.
- We intend to use this 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, and thereby to determine the prices that would be needed to have supply approximately equal demand if congestion pricing where imposed at some airport imposed.

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