COMPARISON OF EFFICIENCY OF SLOT ALLOCATION BY CONGESTION PRICING AND RATION BY SCHEDULE

Saba Neyshaboury,Vivek Kumar, Lance Sherry, Karla Hoffman

Center for Air Transportation Systems Research (CATSR)

George Mason University

Abstract

When airport arrival slots are scheduled in excess of the available capacity, the scheduled flights are assigned slots by a rationing scheme. The traditional approach is to ration slots by schedule (RBS) on a first-scheduled/first-assigned basis. This approach, although meeting equity criteria, can result in inefficient use of the arrival slots in terms of passenger throughput and fuel burn; however, it does not reflect the business decisions with respect to the value of a given flight to an airline. An alternative approach is to allocate the slots based on an airlines' willingness-to-pay a congestion fee, set a priori by a regulator, for use of the slot.

This paper describes a comparison of the allocation of arrival slots using RBS and Congestion Pricing (CP) for flights scheduled into PHL on 10-Jul-2007. The analysis indicates that rationing by CP yielded improved performance in the reduction of average passenger delays by 39.14%, total Passenger Delays by 37.65% and cancelled flights by 66.66% (9 cancellations in RB to 3 cancelled flights in CP). However, rationing by CP decreased average airline equity metric by 34.81%.

Introduction

Delays or cancellation of flights were estimated to cost US air transportation system in 2007, 32 billion dollars [1].

One of the causes of flight delays is airport arrival slots are scheduled in excess of the available capacity. Reduced capacity will change the dynamics of the network by causing delays and cancellations of flights. The challenge for decision makers is to assign flights to slots in the way that maximizes throughput efficiency and equity criteria.

Currently, the scheduled flights are assigned slots by a rationing scheme. The traditional approach is to ration slots by schedule (RBS) on a first-scheduled/first-assigned basis. This approach, although meeting equity criteria, can result in inefficient use of the arrival slots in terms of passenger throughput and fuel burn, but it does not reflect the business decisions with respect to the value of a given flight to an airline. As noted earlier, the alternative approach [2] allocates the slots based on an airlines' willingness-to-pay a congestion fee set by a regulator a priori for use of a specific slot. Qadar looks at flights that are scheduled for a single day.

This paper compares the allocation of arrival slots using RBS and Congestion Pricing (CP) for flights scheduled into PHL on 10-Jul-2007. The analysis indicates that CP results in a 39.14%reduction in average passenger delays. The CP model tends to favor (incurring smaller delays) bigger flights over smaller ones; may increase the delay for carriers with higher representation in the mix; and in terms of equity does not do as well as the RBS method. [3].

This paper is organized into four sections: (1) the methodology and a brief description of the CP model and its assumptions; (2) the Design of Experiment (DOE); (3) the results and comparisons between CP model and RBS; and (4) the conclusion and ideas for future research. The following diagram displays the steps of this paper.

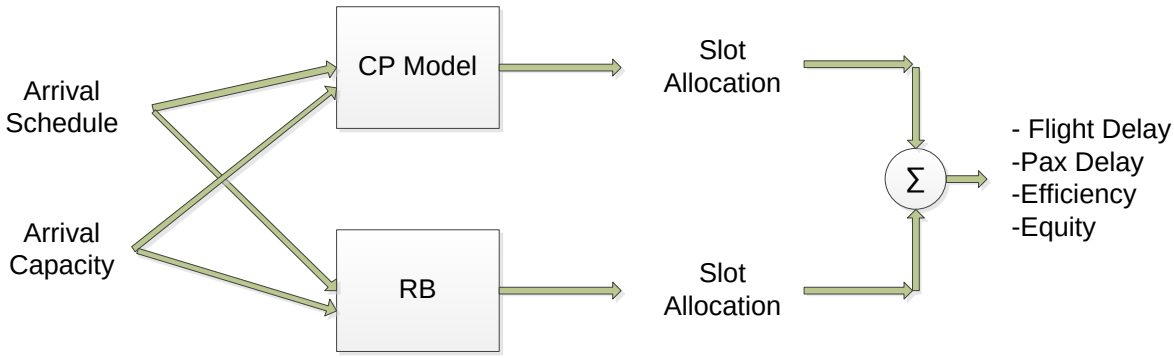

Figure 1 : Diagram explaining the steps taken in the paper

CP Model

CP model uses an optimization based model to produce congestion fee for each time slot of a congested day. For this project, CP is used to calculate the profitability of each flight considering the cost of delay. Costs of fuel, crews, and passenger delays are examples of factors considered to calculate delay costs. For more details refer to the paper in references [4].

The CP model essentially takes into account the costs of operations, crews, and fuel to create priorities for scheduling flights. It calculates prices for airlines to pay for each congested time of the day. The model reschedules flights based on their profitability and the fee for the slot. Therefore, if the fee results in a nonprofit flight it will be moved to another time slot. Here are the assumptions of the CP model:

- All flights flown by international carriers (whether between two domestic airports or one domestic and one international airport) are fixed to be flown.
- All flights flown by domestic carriers to or from international destinations are fixed to be flown.
- All cargo flights, humanitarian and military flights (that appear in ASPM) are fixed to be flown.
- All General Aviation (GA) flights are removed from the system under the premise that the commercial flights have a higher priority than these flights. Any unused capacity can be assigned to GA flights.

The method for determining whether to cancel a flight is to consider a cancellation cost (and keep all revenue associated with the flight). The idea is that an airline will have to pay to reconnect passengers to their final destination, but the revenue obtained from each passenger is kept by the airline. Since there is currently no concrete model available to compute cancellation costs, a rule-based working model for cancellation costs is created.

For each flight k, if it is cancelled, the carrier will incur some cost because it must reschedule passengers onto other flights. It was estimated to be \$100 per passenger. The number of passengers $PAX(k)$ is computed by multiplying load factors with the seating capacity of the aircraft flight k is assigned. It will save all the fuel costs associated with that flight, since this flight will not be flown. In order to accomplish this, another parameter is added, $fuel(k)$, which is equal to the total fuel cost per flight k. This is the fuel burn rate of the aircraft multiplied by the total airborne time multiplied by the fuel price. (For more details refer to: [2] and references therein)

The cancellation rule is based on the cost for cancellation; therefore, a flight will be delayed longer than the FAA regulation if it still can be profitable (the big fine is not being applied)

Therefore the model tends to keep the flights in the schedule to fly as long as they are profitable and there is enough available capacity .Here is one the

variants of the mathematical formulation of the CP model [2]:

- Sets:

$$\begin{aligned}
\mathcal{T} &: \text{Time Windows (Periods/Bins)} \\
\mathcal{F} &: \text{Flight segments, indexed by } k \text{ where } 1 \leq k \leq |\mathcal{F}| \\
\mathcal{Y}^k &: \text{copies of } k^{th} \text{ flight with scheduled time window } t(k) \in \mathcal{T} \text{ and multiple} \\
&\quad \text{actual time windows } j \in \mathcal{T} \text{ where } t(k) \leq j \leq t(k) + l^k \\
\mathcal{Y} &: \bigcup_k \mathcal{Y}^k \text{ Union of copies of all flights}
\end{aligned}$$

- Indices:

$$\begin{aligned}
j &: \text{Time periods } j \in \{1, \ldots, |\mathcal{T}|\} \\
k &: \text{Flights } k \in \{1, \ldots, |\mathcal{F}|\}
\end{aligned}$$

- Parameters:

$$\begin{aligned}
R^k &: \text{Revenue of } k^{th} \text{ flight} \\
O^k &: \text{Operating cost of } k^{th} \text{ flight} \\
W^k &: \text{Weight-based landing fee of } k^{tl} \\
\\
t(k) &: \text{scheduled arrival time of } k^{th} \text{flight } t : \mathcal{F} \to \mathcal{T} \\
d_j^k &: \text{delay cost per minute of } k^{th} \text{ flight with delay of "} 15 \times (j - t(k)) \text{"} \\
&\quad \text{minutes (From delay model)} \\
l^k &: \text{number of time windows the } k^{th} \text{ flight can be delayed.} \\
&\quad t(k) + l^k \leq |\mathcal{T}|
\end{aligned}$$

- Variables:

$$x^k := \begin{cases} 1 \ k^{th} \text{ flight flown} \\ 0 \text{ otherwise} \end{cases}$$

$$y_j^k := \begin{cases} 1 \ k^{th} \text{ flight is flown in time window } j \in \mathcal{T} \text{ with delay of } (j - t(k)) \times 15 \text{ minutes} \\ 0 \text{ otherwise} \end{cases}$$

λ_j : Congestion fee at time window $j \in \mathcal{T}$

- Formulation:

$$\max \sum_{k \in \mathcal{F}} \left[R^k - O^k - W^k \right] \times x^k - \sum_{k} \sum_{j=t(k)}^{t(k)+l^k} \left[15(j - t(k)) d_j^k + \lambda_j \right] \times y_j^k$$

s.t.

$$\sum_{j=t(k)}^{t(k)+l^k} y_j^k = x^k \qquad \forall_{k \in \mathcal{F}}$$

$$\sum_{k} y_j^k \leq C_j \qquad \forall_{j \in \mathcal{T}}$$

$$x^k \leq 1 \qquad \forall_k$$

$$y_j^k \leq 1 \qquad \forall_k \forall_j$$

For each flight, for example kth flight (defined by variable xk), there exists an original scheduled time window and the model needs to choose the actual time window which can be different than the original one. Therefore the data copies for each flight are made to give the model the flexibility of moving a flight to different time windows (defined by variable y).

The objective of the function is to maximize the total profit for all those flights considering their revenue, operating costs, landing fees, delay costs and congestion fees.

There are two constraints: (1) each flight can fly at most once and (2) the number of flights cannot exceed the capacity of that time slot. These two constraints are bound constraints meaning that decision variables can at most get the value of one.

Design of the Experiment (DOE)

The experiment compared two allocation schemes:

- **Efficiency**: This category of metrics includes the typical delay measures - flight delays, passenger delays, fuel burn, and number of flights canceled.
- **Equity**: This category of metrics quantifies the proportionality of the distribution of delays across different airlines. These metrics capture the "level of fairness" of allocation of delays to the airlines.

An experimental scenario included the 24 hour data from July 10, 2007. The maximal called capacity and actual throughput at the airport were used as the declared capacity in CP model. The scenario is described below:

All arrivals into PHL including the flights that were canceled (9 flights) on July 10, 2007 at PHL are included in the input set of flights to the model. The plots in Figure 2for each time period show: the number of scheduled flights, actual flights, CP model output flights, and actual cancelations.

Results

The Following table (Table 1) summarizes the results of the two models:

Table 1 : Summary of the results for comparison between RBS and CP

	RBS	CP
Scheduled Flights (24 h)	534	534
Total Capacity (24 h)	510	510
Total Flight Delays (#slots)	1934	1955
Cancelled Flights	9	***3***
Total Pax Delay	171434.7	***106654.7***
Average Pax Delay (total Pax)	3.96	***2.41***
Average Pax Delay(Delayed Pax)	6.48	***3.30***
Aircraft Size Equity	0.89 (Small AC) 1.10 (Large AC)	1.71 (Small AC) 0.34 (Large AC)
Average Equity (Airline)	1.01	0.6583

EFFICIENCY METRICS

For this analysis, all the 534 flights that arrived at PHL on July 10, 2007 were input to the CP model.

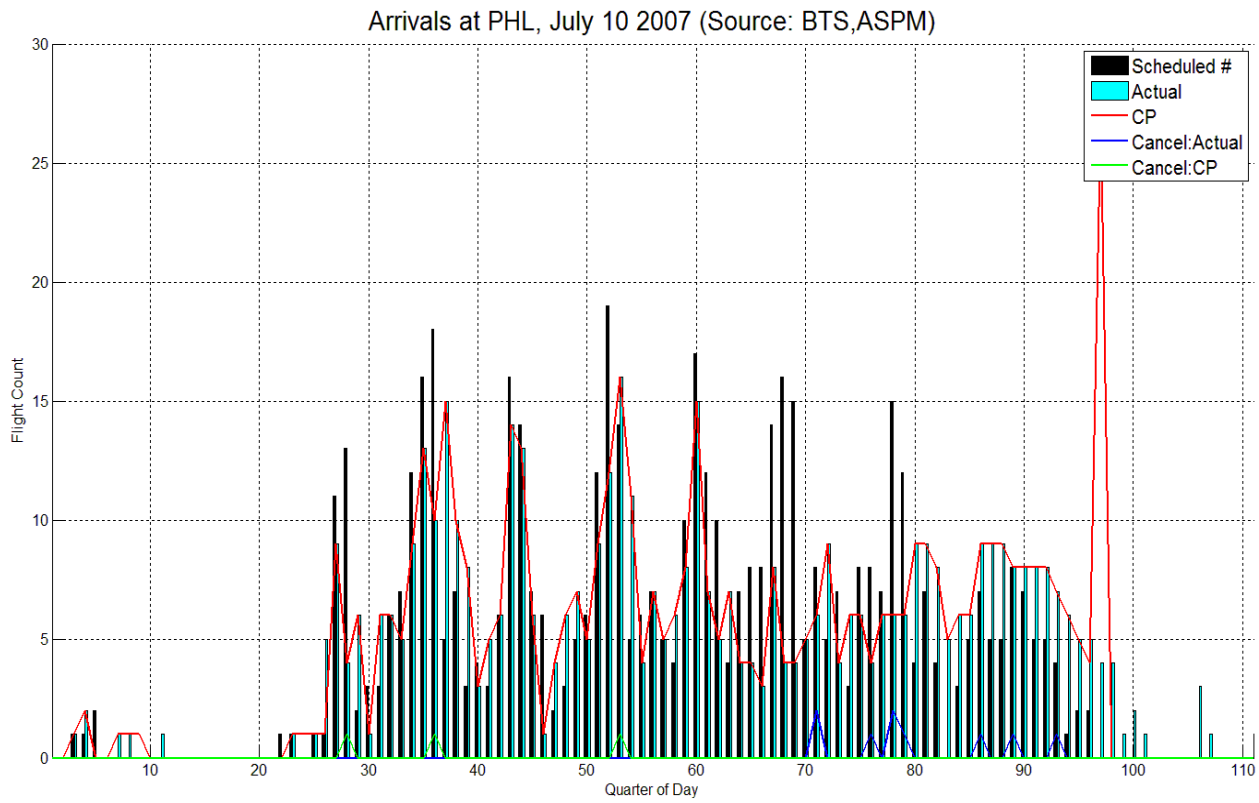

Figure 2 : All flights including canceled flights used as input for the CP model

Figure 2 shows a summary of the behavior of the two different models (CP and RBS). The graph indicates how both CP and RBS outputs are plotted against the schedule for flights to show how each model has changed the schedule. Black Bars show the schedule for the flights for the day of our experiment. Blue bars show the rescheduling done by RBS which is the actual rescheduling done on that

day. Red line displays the rescheduling of flights done by CP model. Blue and green lines show the cancellations done by RBS and CP respectively.

The comparison of *aggregate flight statistics* for the actual (RBS) and the CP model output for this scenario is shown in Figure 3. The values are shown in Table 1. There were 9 cancelations in the "actual" schedule, whereas the CP model cancelled only 3 flights. Also, there are 86 early arrivals in the actual schedule. However, the CP model does not allow early arrivals so there are no such flights in the output of the model. Because of these early arrivals, the number of flights delayed in CP model output (415) is higher than the actual schedule (317). The number of deviations from the schedule in actual data is 403 flights.

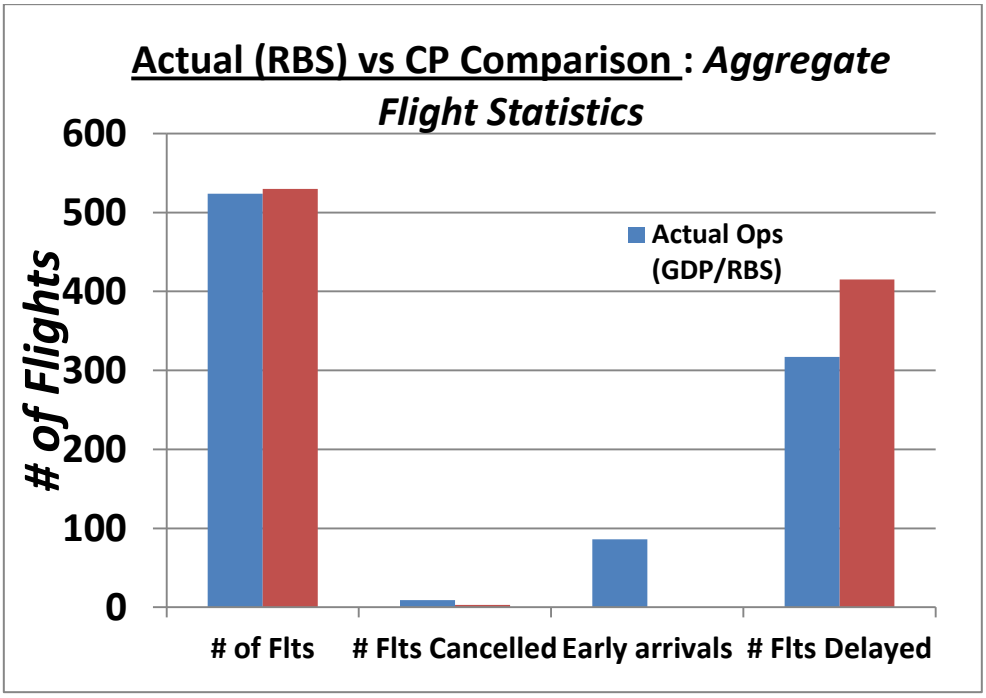

Figure 3 : Aggregate Flight Statistic

Table 2 : Comparison of aggregate statistics for the actual operations VS CP model output

	# of Flts	# Flts Cancelled	Early arrivals	# Flts Delayed	Tot Flt Del(time periods)	Avg Flt Del	Total PAX Del	Avg PAX Del
RBS	525	9	86	317	1934	3,69	171434,7	3,96
CP Model	531	3	0	415	1955	3,69	106654,7	2,41

The plots in Figure 4 shows a comparison of the Actual and CP Model output in terms of the total and average for flight and passenger delays. The values of delays are in time-periods, where each time-period is in 15 minute quarter bins. Assuming a uniform distribution of flight times in this 15 minute bin, to convert these time-periods to minutes, the values need to be multiplied by 7.5 minutes (mean of uniform distribution [0, 15]).

It can be observed in Figure 4 that the total and average flight delays for both the RBS scenario and the CP model is the same. The small difference (1955-1934 = 21 time periods) is due to the fewer (3 vs 9) cancelations in the CP model output. This is expected because the total flight delay in the system is conserved in both scenarios as all the available capacity is being exhausted. The only difference is "which" flights are assigned more delays.

For the RBS scenario, the total and average passenger delays are 171434.76 (measured in time windows) and 3.96 time periods respectively. However, the schedule given by CP model has a total and average passenger delay of 106654.7 and 2.41 time-periods respectively. This is a 39.1% reduction in average passenger delay. Also if we only consider the delayed passengers in calculation of average passenger delays, CP shows 49% reduction in average passenger delay (RBS average Pax delay is 6.48 while CP incurred 3.30 (Measured in time windows))

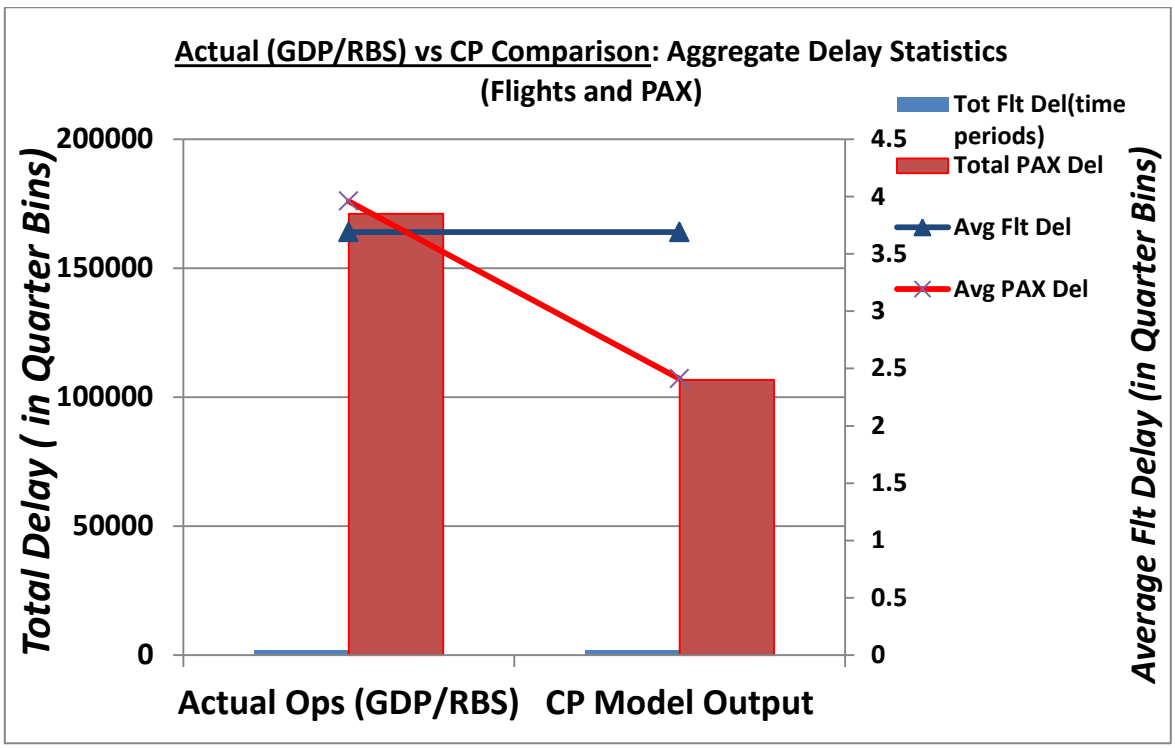

Figure 4 : Total and Average Delay Statistics comparison for Actual (RBS) vs CP

Results from this experiment show that CP model tends to assign smaller delays to bigger flights. For this reason, we broke flights into two sets of small aircrafts (less than 100 seats) and big aircrafts (more than 100 seats) and calculated the equity metric for each category in each model. Based on the results in Table 1, CP assigns far less delay to larger aircrafts comparing to their population in the fleet while RBS does the same however the ratios calculated for RBS are very close to 1 which shows the equity. The scatter plot in Figure 5also shows the distribution of delays (comparing RBS and CP) for different number of passengers. Every point on the plot is a flight. The x-axis is the number of PAX in that flight. The y-axis is the difference between the delay allocated to that flight by the CP model and in

the actual operation. So the higher the y-value, the higher the delay assigned to it by the CP model when compared to the actual operations. The red dotted oval shows a concentration of flights with higher number of PAX having negative y-axis values, i.e. CP model assigning lower delays than the actual operations. Conversely, the green oval shows how CP model assigns more delays (+ve y value) to flights with fewer number of PAX.

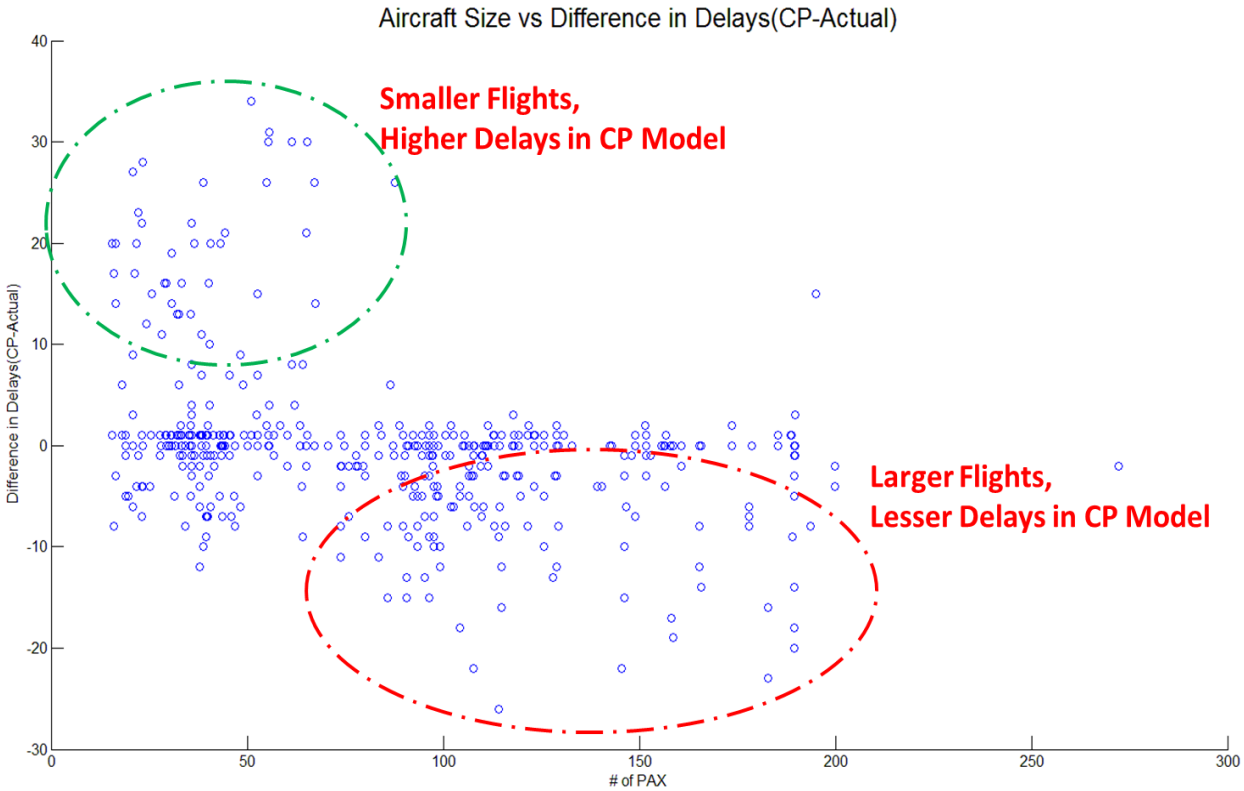

Figure 5 : Comparison of CP & Actual Delays VS Aircraft Size (number of PAX)

Also, it was observed that of total flights 347 flights were carrying less than 100 passengers while remaining 184 flights were carrying greater than 100 passengers. Thus, 100 passengers were chosen to be the crossing point from a "small flight" to a "big flight". The output results from CP model indicated the average delay for small flights is 5.03 time windows while the same parameter for big flights is only 1.13 time windows.

The plots in Figure 6 show the comparison of the total and average flight delays for different carriers for the Actual and CP Model. The flights are grouped into major carriers and ultimately binned into 6 major carriers, namely AAL (American Airlines), UAL (United Airline), DAL (Delta Airline), SWA (Southwest Airlines), AWI (Air Wisconsin) and USA (US Airways). The number in the parenthesis on the x-axis represents (number of flights, % of total flights). For example: AAL (17,3%) means American Airlines had 17 flights in the experimental scenario, which translates to approximately 3% of the total number of flights.

US Airways which has the 53% of flights in the population is assigned maximum total flight delay by the CP model as well as in the actual scenario. However, the CP model assigns higher delays to USA and AWI (red bars higher than the blue bars) and these extra delays are then shaved off from the other carriers. The pattern here seems to suggest that the carriers with lower % of flights in the mix get a reduction in average delay of flights at the expense of the carriers with higher representation in the fleet. In order to quantify the fairness of the distribution of

delays to different carriers, more analysis was done on equity.

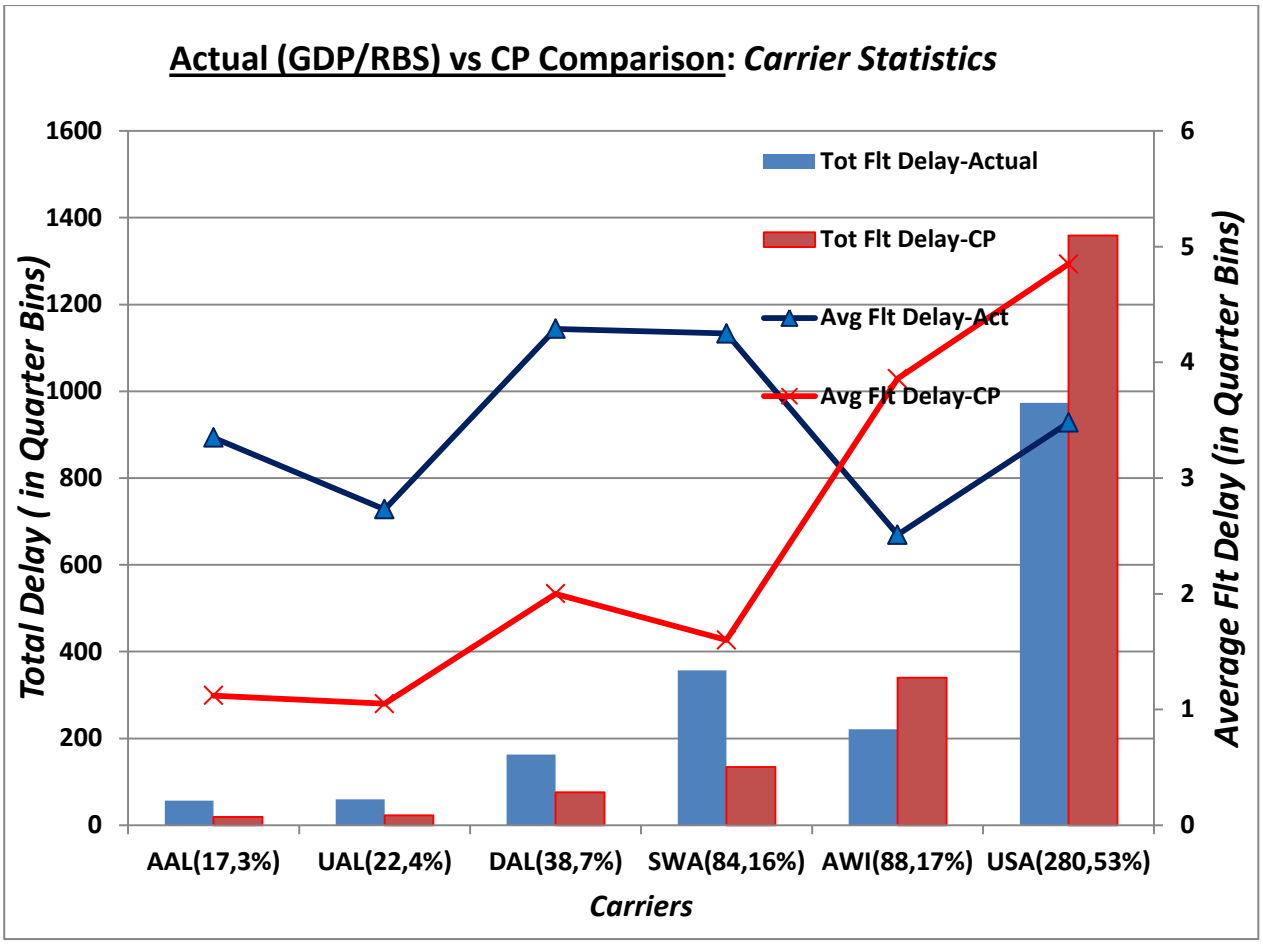

Figure 6 : Comparison of Total and Average flight delay across Carriers

EQUITY METRICS

To quantify the fairness of distribution of delays across the different carriers for the 2 different schemes, the following Equity index is used (for more information on equity see [5]):

Equity Index (carrier i) = (% of total delay attributed to carrier i)/ (% of flights of carrier i in the population)

$$EquityIndex(i) = \frac{\%TotalDelay(i)}{\%Flight(i)}$$

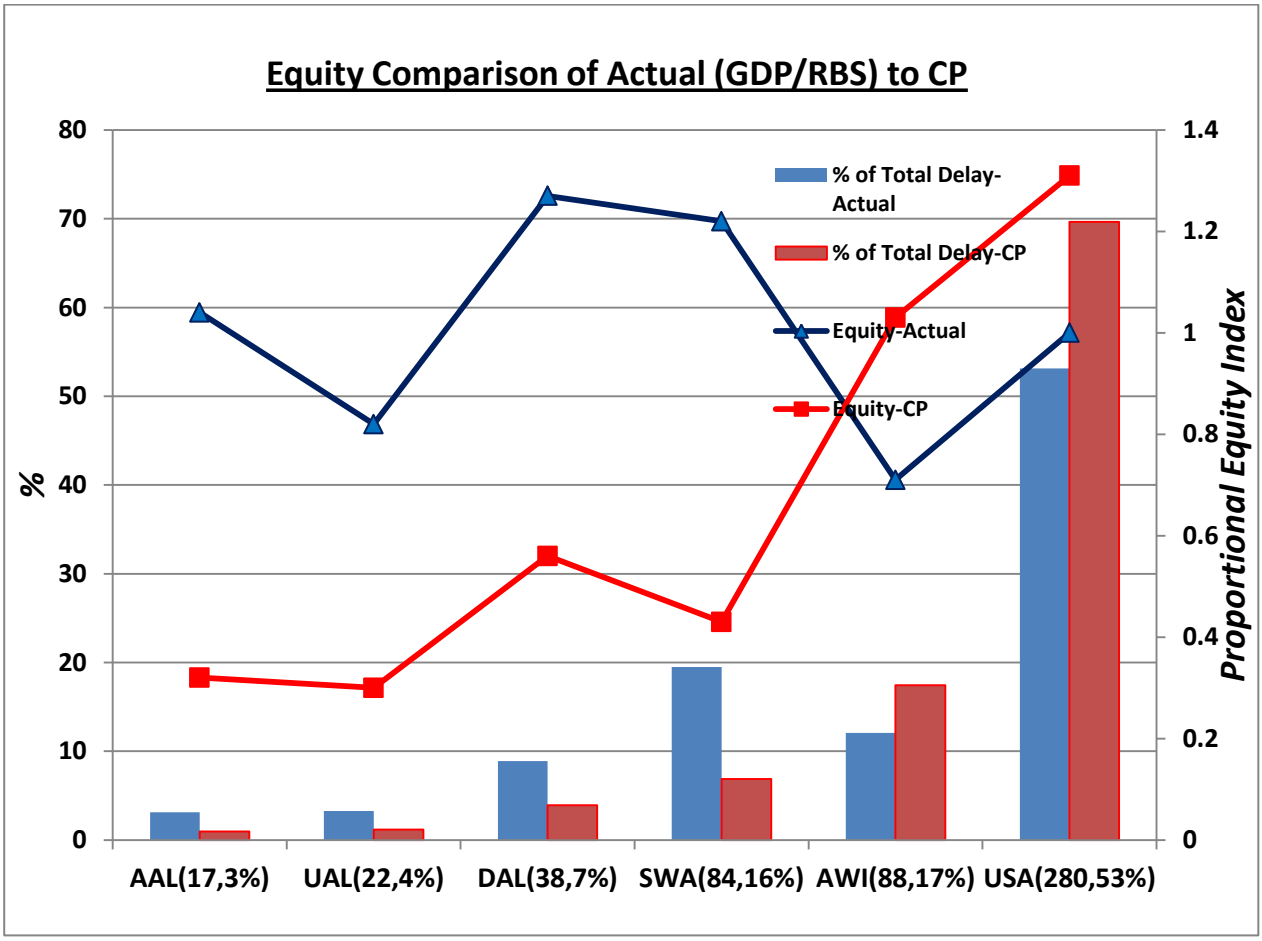

Figure 7 : Comparison of Equity across carriers

Airline equity compares how much flight delay is assigned to an airline compared to its number of scheduled operations. Total flight and passenger delays are important efficiency metrics. However, they don't imply any information about the fairness of delay distribution across carriers. If the equity index described above is 1, it is called "perfect equity". If an airline's equity is less than 1, the airline is given less delay than is fair. If the equity index is above 1, the airline is given more delay than is fair.

In our case, as shown in Figure 7, the equity index of different carriers is shown for the two different schemes. For USA, the equity index is 1 and 1.31 for the actual scenario and CP respectively. For AWI, the equity index is 0.71 and 1.03 for the actual scenario and CP respectively. For both these carriers with 53% and 17% in the total mix, the proportional equity index values increases in the CP model. In other words, the allocation of delays to these carriers increases. For all the other carriers, the proportional equity index value decreases, i.e. they get fewer delays assigned to them by the CP model.

Table 3 :Table showing proportional equity across different Carriers for Case 1(Equity CP = 1, suggest perfect equity)

	% of Total Delay-Actual	Equity-Actual	% of Total Delay-CP	Equity-CP
AAL(17,3%)	3.11	1.04	0.97	0.32
UAL(22,4%)	3.28	0.82	1.18	0.3
DAL(38,7%)	8.9	1.27	3.9	0.56
SWA(84,16%)	19.5	1.22	6.87	0.43
AWI(88,17%)	12.07	0.71	17.43	1.03
USA(280,53%)	53.14	1	69.66	1.31
Average		1.01		0.658333

Conclusion and Future Research

There are fundamental differences between RBS and CP model in terms of the criteria used to make rescheduling decisions. RBS keeps equity in mind while not considering the network throughput and efficiency metrics. CP, on the other hand, concentrates on costs of the delay which includes fuel and other non-fuel operating costs. The CP model tries to maximize the profit or basically minimize the costs.

Based on the results CP reduces the average passenger delay by 39.14% and favors larger flights with more passengers over smaller flights.

In terms of equity, CP does not perform as well as the RBS which is understandable because equity metrics are not included in CP model at all.

Finally, CP can be recommended as a method for solving lack of capacity in order to better manage the network throughput and reduce the costly delays.

In terms of future research, it might be applicable to further develop the CP model to include equity metric for airlines as a multi-objective problem. Designing auctions and Game Theory Based models can also be proposed since in this model it is assumed that airlines are in fact paying the fees that are announced however in reality airlines might make different decisions or the value of a flight to an airline might be different than what is calculated by the model.

REFERENCES

[1] NEXTOR, 2010. Total Delay Impact Study. Report.

[2] Kara, A., 2011. A Congestion Pricing Model to Handle “Day of Operations” Airport Capacity Reductions.

[3] Sherry, L. & Kumar, V. & Neyshabouri, S. 2011. Congestion Pricing Project (Final Report)

[4] Ferguson, J. et al., 2010. Estimating Domestic U.S. Airline Cost of Delay based on European Model. *ICRAT.*

[5] Manley, B. & Sherry, L., 2008. The Impact of Ground Delay Program (GDP) Rationing Rules on Passenger and Airline Equity.