

ANALYSIS OF FACTORS FOR INCORPORATING USER PREFERENCES IN AIR TRAFFIC MANAGEMENT: A SYSTEM PERSPECTIVE

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Abstract

This paper presents an analysis of factors that impact user flight schedules during air traffic congestion. In pre-departure flight planning, users file one route per flight, which often leads to increased delays, inefficient airspace utilization, and exclusion of user flight preferences. In this paper, first the idea of filing alternate routes and providing priorities on each of those routes is introduced. Then, the impact of varying planning interval and system-imposed departure delay increment is discussed. The metrics of total delay and equity are used for analyzing the impact of these factors on increased traffic and on different users. The results are shown for four cases, with and without the optional routes and priority assignments. Results demonstrate that adding priorities to optional routes further improves system performance compared to filing one route per flight and using first-come first-served scheme. It was also observed that a two-hour planning interval with a five-minute system-imposed departure delay increment results in highest delay reduction. The trend holds for a scenario with increased traffic.

1 Introduction

In normal air traffic operations in the United States, the Federal Aviation Administration and the users (e.g., airlines, General Aviation, cargo carriers, air taxis, etc.) collaborate for smooth and efficient operation of the National Airspace

System. However, during times of reduced airspace and airport capacities due to weather or other operational reasons, the users' preferences may not be satisfied. The users always file a single route per flight, which may be replaced with another plan by the air traffic manager. Replacement plans may not conform to user preferences. This can lead to higher system-wide delays and greater passenger dissatisfaction [1, 2]. Flight planning by the users is difficult due to a lack of mechanisms for specifying importance of their flights and concerns about sharing company proprietary information [3]. Research is needed to understand the impact on delay and equity that may be caused by filing multiple route options and better inclusion of users' preferences in flight schedule management.

Reference [4] describes automation allowing users to electronically negotiate multiple flight routes per flight with the FAA. Other research has investigated routing of aircraft around weather cells [5] and assigning slots for arrival/departure aircraft at an airport [6]. Methods for evaluating various routes and assessing their impact on system performance are limited to small airspace regions only [4, 7]. In our previous research [8, 9], a concept of credit points was presented for incorporating users' flight priorities in the pre-departure flight planning process. Feasibility of congestion management and a convergent solution for the concept were presented in [9]. The equity and delay of the concept from users' perspective are

presented in [10], but they remain to be assessed from a system perspective.

This paper presents an analysis of factors involved in incorporating user flight preferences in air traffic demand and capacity management from a system perspective. The research presents a comparison of the simulated baseline case of first-come first-served in today's operations with optional routes and flight priorities. First optional routes are added, with equal priorities for each route for each flight. Then priorities or credits [9] are assigned to each flight for all optional routes using a flight utility function. The metrics of delay and equity for the system and the users are computed. A comparison of planning intervals and system-imposed departure delay increments are also presented for nominal and increased traffic, and for different users.

The research approach is presented in Section 2. The flight priority function, simulation data and factors of planning interval and system-imposed departure delay increment are described in Section 3. The definitions of delay and equity are presented in Section 4. The results of the analysis are illustrated in Section 5. The impact on increased traffic and on different users is also shown. The paper ends with concluding remarks on the research.

2 Research Approach

This section introduces optional routes and flight prioritization through the use of a credit-based concept [9]. These were implemented in the Future ATM Concepts Evaluation Tool (FACET) developed at NASA Ames Research Center [11]. FACET is a National Airspace System (NAS)-based air traffic simulation environment for evaluation of futuristic air traffic management concepts. This software is used to conduct simulations of the optional routes and credits concepts.

2.1 Optional Routes

Currently users do not have the capability to specify optional routes for their flights. The FAA is implementing an electronic data exchange with the users of the airspace. It is

slated to become operational in fall of 2011. The users will be able to specify, through the use of this technology, multiple routes for each of their flights [12]. The users can electronically convey various parameters like primary and alternate route cost, minimum notification time, and valid times for each of their route options. Using these parameters, the users can incorporate their flight route preferences.

In this paper, a comparison is provided for NAS-wide delay and equity, with and without the use of optional routes. Instead of one route per flight, three optional routes were provided for roughly 60% of the total flights. The airport arrival/departure rates and airspace sector capacities were strictly enforced. The resulting system-delays and equity are compared to the first-come first-served scheme.

2.2 Credits Concept

In addition to optional routes, it has been proposed that prioritizing the flights would lead to better incorporation of user flight utility preferences. One mechanism [9] for doing that is priority or credit points. Credits are artificial currency. The purpose of credits is to convey to the traffic manager users' flight and route priorities. At the beginning of each day, the users are provided a fixed number of credits based on the size of their operations. The total number of credits allocated is five times the number of departures in a day. The credits expire at the end of each day. The number of credits, as well as their expiration, could be varied to study other operational and economic implications of this concept. In past simulations, typically zero to ten credits were assigned for each flight based on its importance. A user could potentially assign a different amount of credits for each of several route options, as long as the maximum credit assignment for each flight is within the credit balance. The credit assignments of each user are not divulged to other users.

The automated user credit assignment for this research is described in Section 3.1. In reality, the users would provide credit assignments by evaluating their individual business models [13].

Once the users assign credits for each route option for each flight, the credits and routes are submitted to an automated server. This server would reside with the FAA or an impartial entity. The server simulation process flies all flights from origin to destination and identifies regions of excess traffic demand over airspace capacity. Wherever there is excess demand, say in a sector, the primary routes of flights are ranked by credits. The sector is utilized to capacity by the higher credit flights. The lowest credit flights over capacity are assigned their next route preference, and the entire simulation is run again. If no additional route options are available for any flight, it is held on the ground at the origin airport for a fixed amount of time (typically, 15 minutes). The credits corresponding to the granted route are decremented from the user's balance of allocated credits. This iterative process is continued until there are no regions with excess demand. Thus, a new flight departure schedule is created. The flights that have been assigned a route and charged credits are allowed to fly on their routes without any further modification (a contract). The capacities of the sectors they traverse through and the arrival/departure rates of airports they use are correspondingly reduced for subsequent flights.

3 Simulation Parameters

In order to implement the credits concept, a flight priority function that represents how a user will prioritize their flights is required. This function is used in the simulations to assign credits and is described in section 3.1. The air traffic data used for the analysis are described next. The factors of planning interval and system-imposed departure delay increment are discussed last in this section.

3.1 Flight Priority Function

The function, $C(f)$, used to assign credits for individual flights in the simulations is based on three parameters. These are the flight distance, the number of passengers, and the hub-spoke type of operation. This function is defined as follows:

$$C(f) = \frac{1}{2} \left[\frac{D_f}{D_{MAX}} * 10 + \frac{P_f}{P_{MAX}} * 10 + H_f \right] \quad (1)$$

where D_f is the flight distance, D_{MAX} is the maximum flight distance, P_f is the number of passengers, P_{MAX} is the maximum number of passengers, and H_f is the hub-connectivity for each flight. The value of H_f is ten, if the flight is between two hubs of the same user, seven, if the flight is between a hub and a major city, or three, otherwise.

For users that don't have an established hub-spoke system of operations, the flight distance and number of passengers are the dominant parameters. Other factors like load factor, crew legality, and diversions are important for users [13] but are not publicly available.

3.2 Simulation Data

Air traffic data for Aug. 24, 2005 were obtained from the FAA's Enhanced Traffic Management System (ETMS) [14]. These data were simulated in FACET. Data for a four-hour period from 3 P.M. to 7 P.M. Eastern Daylight Time were used. This time interval was selected to correspond to peak air traffic hours in the United States. The total number of flights was 18,688 with an instantaneous peak at 5:40 P.M. of about 5,200 aircraft. The top 40 users were simulated as collaboration participants, and only their flights between the top 70 airports in the United States were used for metric evaluation. All of the other flights were included as background traffic. The number of flights for the top 40 users was 10,514 and for General Aviation was 5,000. The optional routes selected for the top 70 airports were obtained from historical ETMS-filed flight plans. The imposed sector capacities and airport arrival/departure rates were obtained from ETMS. The credits were assigned to flights an hour before departure, based on the flight priority function described in Equation (1).

3.3 Planning Interval and System-imposed Departure Delay Increment

Two important factors of credits concept implementation are planning interval and system-imposed departure delay increment. The credits concept can be applied over a 15-minute, a 4-hour, or even a 24-hour period. In this paper, a four-hour period is used. For example, for a one-hour planning interval, the credits were assigned four times beginning at 2 P.M. for the 3 P.M. to 4 P.M. departure flights. At 3 P.M., credits were assigned again for the 4 P.M. to 5 P.M. departure flights, and so on. Three other intervals (15 minutes, 2 hours, and 4 hours) were tried. For the four-hour planning interval run, credits were assigned for all flights departing in the four-hour data all at once.

In today's air traffic operations, typically a flight is delayed on the ground in increments of 15 minutes. It is possible that a smaller increment could serve better. In this paper, an alternative five-minute system-induced departure delay increment is considered.

In order to understand the implementation of the credits concept with higher traffic [15], simulations were conducted with reduced airspace capacities. A reduced airspace capacity of 80% across all sectors corresponds to a relative increase of about 25% of air traffic. The factors of planning interval and system-imposed departure delay increment were varied for increased traffic as well.

4 Metrics

To study variation of the factors mentioned in section 3.3, delay and equity were computed. These metrics are described in this section.

4.1 Delay

For each of the cases considered, the delay was computed for each flight for a baseline case. For the baseline case each flight filed one route and all flights were prioritized equally. The flight delay included departure delay and additional delay required to fly an optional route compared to the baseline. The total delay for each user and maximum delay for each flight were also

computed. The total system delay was computed as the sum of total delay for each user.

Since it is difficult to assign credits to general aviation aircraft, they were grouped together with equal priorities. The delay results for the top 40 users, the GA group, and the remainder of users are presented in the results section.

4.2 Equity

One factor for measuring the benefits of collaboration is the equitable distribution of maximum delay amongst users. A generally accepted metric of equity in a distribution is the Gini coefficient [16]. The Gini coefficient (G) is defined as:

$$G = \frac{\sum_{i=1}^n \sum_{j=1}^n |x_i - x_j|}{2n^2\mu} \quad (2)$$

where n is the number of flights, x_i or x_j is the total delay for the i^{th} or j^{th} user (from all users' perspective), or the maximum delay for the i^{th} flight (from a single user's perspective), and μ is mean value of the distribution.

A value of G close to zero implies equal distribution of delays among all users. This is desired from a system perspective. A value of G closer to one indicates an inequitable delay distribution. This is desired from a user's perspective to distribute delays to satisfy their business needs.

5 Results

The results for the simulation runs are presented below. As described earlier, the simulations were run with planning intervals (PI) of 15 minutes, 1 hour, 2 hours or 4 hours. The system-imposed departure delay increment (SID) was chosen as 5 or 15 minutes.

5.1 Comparison of Optional Routes and Credits with Baseline

Table 1 shows the comparison of planning interval variation for the simulation runs. The system-imposed departure delay increment was held constant at five minutes. The data block in

yellow presents results for the baseline simulations where only one route was used where all flights were equally prioritized with five credits. This is denoted by 1-F for one route and flat credits. The data block in pink shows results for three optional routes for the top 40 users' flights and equally prioritized with five credits. This is denoted 3-F for three routes and flat credits. The data block in green presents results for three optional routes for the top 40 users' flights with credits assigned based on $C(f)$ from Equation (1). This is denoted by 3-C for three routes and $C(f)$ assigned credits. The data block in red shows results for only one route with credits assigned based on $C(f)$. This is denoted by 1-C.

From Table 1, it is observed that system delay for one, two, and four-hour planning interval cases is less than the baseline case 1-F in yellow. For the 3-F case in pink, these values are 30%, 23%, and 14% lower. These values for the 3-C case in green are 30%, 42%, and 23% lower. This implies that adding credits or priorities of flights on top of optional routes reduces system delays even further. This is a significant result because the credits concept was built upon the use of optional routes and the results show the delay benefits. On the other hand, the 1-C results in red indicate that if

optional routes are not used, the assignment of credits can decrease the system performance as the delays increase by 9%, 17%, and 10% compared to the baseline case. It is also observed that the 15-minute planning interval decreases the system performance as the delays increase by 6% and 7% in the 3-F and 3-C cases.

5.2 Comparison of Planning Interval (PI)

As seen from Table 1, the system delays decrease under 1-F as the planning interval increases. The exception is the case of PI equal to two hours. There are two main reasons for this exception. First, in this four-hour dataset, average flight time is 90 minutes. Secondly, there is no airborne rerouting or airborne holding delay in this simulation, and the sector and airport capacities are strictly enforced. For PI equal to one hour, the simulation is run in four one-hour intervals for the four-hour dataset. The flights that depart from 4 P.M. to 5 P.M. are not included in the first one-hour interval from 3 P.M. to 4 P.M. For PI equal to two hours, the simulation is run in two two-hour intervals. The flights that depart from 4 P.M. to 5 P.M. are included in the first interval from 3 P.M. to 5 P.M.

Table 1. Comparison of delay difference with increasing PI for a 5-minute SID.

SID = 5 minutes	Baseline (1-F)		Routes only (3-F)	
	System delay (min.)		System delay (min.)	% difference from baseline
15 minutes	4,977		5,285	6
1 hour	3,930		2,750	-30
2 hours	4,190		3,226	-23
4 hours	2,684		2,303	-14
PI	Credits only (1-C)		Routes with credits (3-C)	
	System delay (min.)	% difference from baseline	System delay (min.)	% difference from baseline
15 minutes	4,977	0	5,311	7
1 hour	4,280	9	2,740	-30
2 hours	4,905	17	2,434	-42
4 hours	2,956	10	2,059	-23

The PI equal to two-hours case has slightly higher delays compared to the PI equal to one-hour case because pop-up international and domestic flights. Also, with 18,668 flights in the dataset, this is a very complex traffic scenario.

The one-hour planning interval is best for 3-F case with 30% system delay reduction. The same behavior is seen for 3-C case shown in green. However, the two-hour planning interval results in lowest system delays, 42%, compared to the one-hour planning interval.

The addition of credits did not achieve any benefits without the use of optional routes (1-C case in red). The planning interval of 15 minutes increased the system delays for 3-F and 3-C cases. The results for four-hour planning interval showed lowest system delay reduction. With that in mind, the subsequent results only discuss system behavior for planning intervals of one and two hours.

5.3 Comparison of System-Imposed Departure Delay Increment (SID)

In Table 2, the results for SID equal to 15 minutes are shown. The results show that adding optional routes for PI equal to one hour and two hours reduces system delays between 30% and 32%. The system delay reduction is

not as pronounced as in SID equal to five minutes and PI equal to two hours case of Table 1.

This behavior is due to the following. If airspace congestion is observed during any iteration, a credit ranking of flights is performed and the lowest ranking flights are checked for optional routes. If no routes are available, the flight is given a departure delay (15 minutes in this case). As there are many congested sectors in the NAS, the 15-minute delays add up faster than the 5-minute delays. Therefore, it is concluded that the 5-minute system-imposed departure delay increment with a two-hour planning interval provides maximum delay reduction benefit from a system perspective.

Keeping that in context, the subsequent results discuss system behavior for PI equal to two hours and SID equal to five minutes only.

5.4 Comparison for Increased Traffic

To generate increased traffic, the simulations were run with overall reduced airspace sector capacities. The capacities of all sectors were reduced by 20% of their nominal values. This is roughly an increase of 25% of normal air traffic. The results for two-hour planning interval and five-minute system-imposed

Table 2. Comparison of delay improvement with increasing PI for a 15-minute SID.

SID = 15 minutes	Baseline (1-F)	Routes only (3-F)		Routes with credits (3-C)	
	System delay (min.)	System delay (min.)	% difference from baseline	System delay (min.)	% difference from baseline
1 hour	6,345	4,319	-32	4,329	-32
2 hours	6,900	4,828	-30	4,760	-31

Table 3. Comparison of delay improvement with increasing planning interval for a 5-minute system-imposed departure delay increment with increased traffic.

SID = 5 minutes	Baseline (1-F)	Routes only (3-F)		Routes with credits (3-C)	
	System delay (min.)	System delay (min.)	% difference from baseline	System delay (min.)	% difference from baseline
2 hours	41,115	24,381	-41	20,322	-51

departure delay increment showed dramatic decreases in system delay compared to the baseline. These are shown in Table 3.

A comparison of Table 3 and Table 1 shows that with a reduction in system capacity of 20%, there is a significant delay increase (90%) in the baseline case (1-F) for PI equal to two hours and SID equal to five minutes. With the use of optional routes, a large amount of departure delay can be reduced. This is because flights are assigned on optional routes rather than departure delayed. Use of optional routes (3-F) results in 41% reduction compared to 1-F. Longer flights have a higher probability of encountering congestion compared to shorter flights. Assigning higher credits to longer flights gives them better chance to avoid congestion, and hence, reduce delays. Therefore, the use of credits in addition to optional routes reduces the system delay even more. The system delay value is lower by 51% compared to the baseline increased traffic case.

5.5 Impact on Users

The overall system delay is comprised of delays from the top 40 users, the general aviation group and the remaining users. The delays for the top 40 users during the 3 P.M. to 7 P.M. scenario of Aug. 24, 2005 are presented here. In Table 4, the breakdown of delays is shown for SID equal to five minutes and for PI equal to one hour, two hours, and four hours. The top 40 users are the main players in the system with 10,514 (56%) of the total 18,668 flights and account for a large part of the delays. It is observed that the delays for the GA users (with 5,000 flights accounting for 27% of total flights) and the remainder of users (3,154 flights with 17% of total flights) are significantly lower than the top 40 users. Table 4 shows that PI equal to four hours has the lowest absolute delays, which implies that a larger horizon may be beneficial to the system.

**Table 4. Total delay for various users with
SID = 5 minutes and PI = 1, 2, and 4 hours.**

Users	Baseline (1-F)	Routes only (3-F)	Routes with credits (3-C)
PI = 1 hour			
Top 40	2,800	1,720	1,750
GA	865	770	720
Rest	265	260	270
Total	3,930	2,750	2,740
PI = 2 hours			
Top 40	2,980	2,011	1,604
GA	905	925	566
Rest	305	290	264
Total	4,190	3,226	2,434
PI = 4 hours			
Top 40	1,990	1,697	1,816
GA	403	359	119
Rest	291	247	124
Total	2,684	2,303	2,059

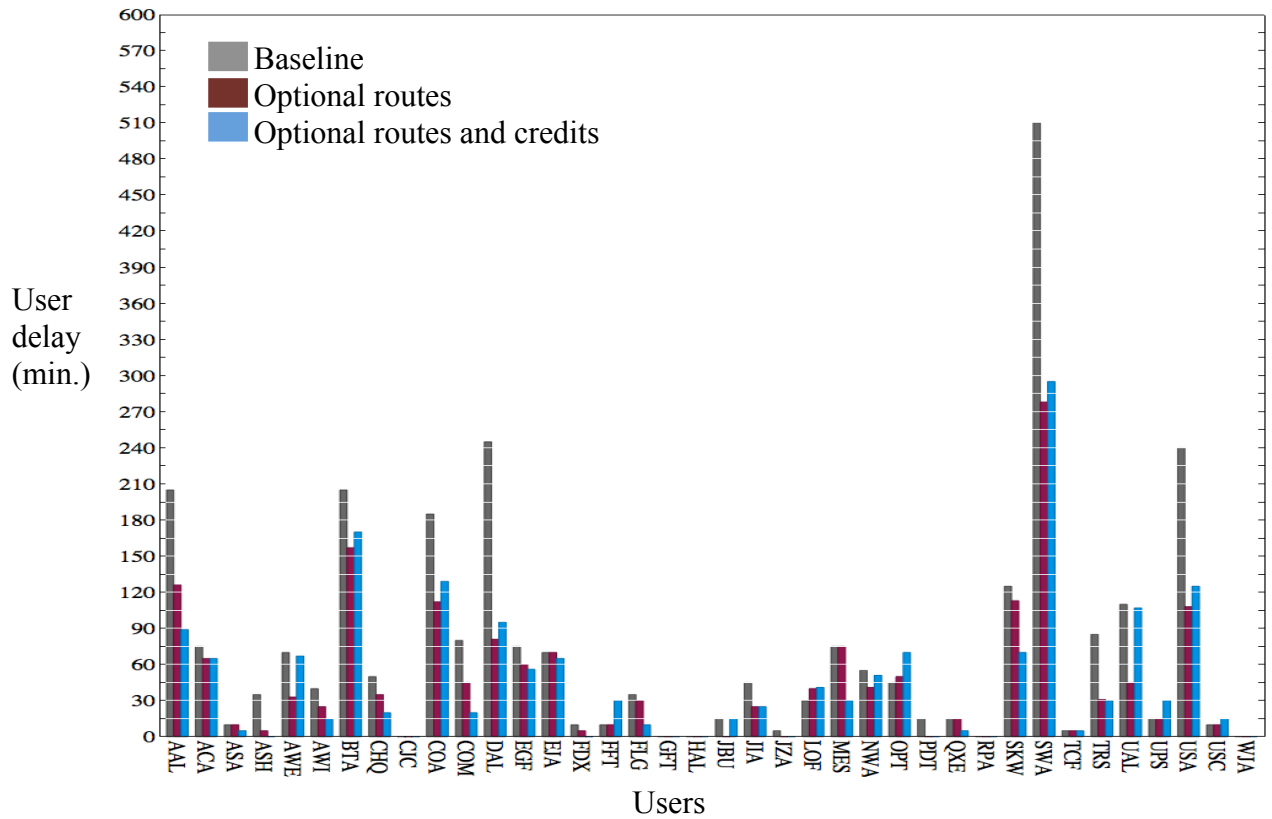


Fig.1. Distribution of delays for the top 40 users for a PI = 1-hour and SID = 5-minutes with 1-F (gray), 3-F (maroon) and 3-C (blue) cases.

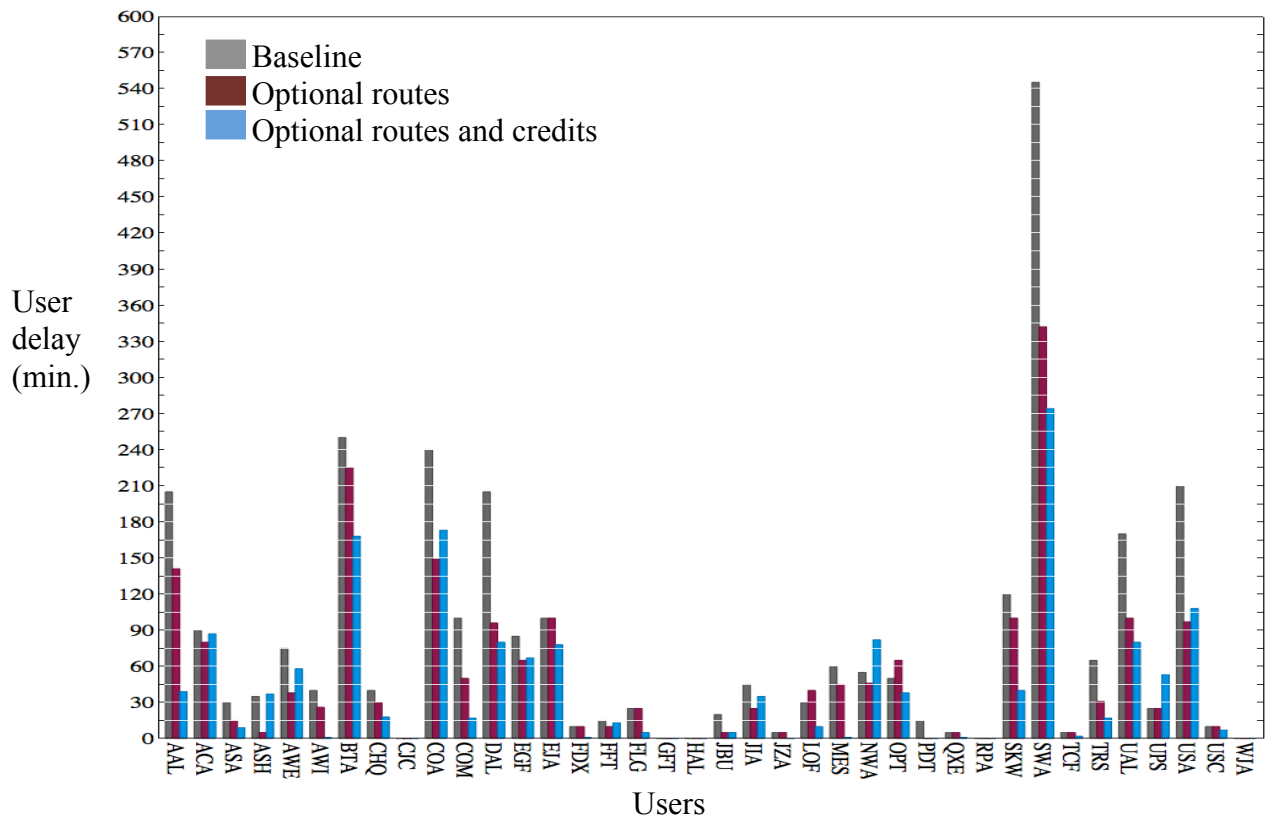


Fig.2. Distribution of delays for the top 40 users for a PI = 2-hours and SID = 5-minutes with 1-F (gray), 3-F (maroon) and 3-C (blue) cases.

For each of the top 40 users, three bars are shown in Figs. 1 and 2. The left bar in gray is for the baseline (1-F) case. The middle maroon bar is for the optional routes only (3-F) case, and the right bar in blue is for the optional routes and credit assignment (3-C). Figure 1 shows the delays for each user for the five-minute system-imposed departure delay increments and one-hour planning interval. Figure 2 shows the same data for the two-hour planning interval case. 80% of the top 40 users' have smaller delays for routes and credits (3-C, blue bar) in Fig. 2 than in Fig. 1. Also, the overall delays are much smaller for the blue bars in Fig. 2, as seen in Table 1. As mentioned earlier, optional routes and credits can have better system performance because not only the traffic spreads out for a better airspace utilization, but it is prioritized for users' business preferences as well.

5.6 Equity of Delay Distribution

For this research, the Gini coefficient defined in Equation (2) is used to measure equity of delays. Using SID equal to five minutes, it was observed that the Gini coefficient for maximum delays changed less than 0.05 between the optional routes (3-F) and credit assignment (3-C) cases over the baseline (1-F). This was over all planning intervals of 15 minutes, 1 hour, 2 hours, and 4 hours. The average value was around 0.45. The baseline (1-F) case G value was 0.45. The same trend held for SID equal to 15 minutes. Therefore, neither the optional routes, nor the assignment of credits provided significant delay equity with variation in PI or SID for these simulations. The reason for this could be that the optional routes were the same for each origin-destination pair. From the users' perspective, most G values varied between 0.95 and 0.99 for all PI.

Only the case of SID equal to five minutes and PI equal to two hours was used for equity with increased traffic. The use of optional routes (3-F) provided a negligible improvement (2%) over the baseline case. Using assigned credits in conjunction with optional routes (3-C) provided a 15% improvement in the Gini coefficient. It should be noted from Table 3,

that both 3-F and 3-C provide significant reduction delay, so the Gini coefficient just addresses the distribution of that delay.

6 Concluding Remarks

Currently, in air traffic management, users file one route for their flights. A new technology is being developed by the FAA in collaboration with users to file optional routes. A previously proposed concept allows users to provide priorities of flights for each of the routes. In order to use optional routes and assigned priorities on those routes for air traffic management, the impact of planning interval and system-imposed departure delay increment was computed. Air traffic data from Aug. 24, 2005 were used for simulations. The top 40 users and top 70 airports were selected based on their operations. For each of the simulation runs, four different cases were considered, with and without optional routes and assigned priorities. The automated flight priority was a function of distance, number of passengers and hub-spoke operation parameters. In reality, dispatchers would provide the credit assignments. Four values of the planning interval and two values of departure delay were considered. It was shown that the use of optional routes results in reduced system delay, while adding priorities through the use of credits resulted in even further reduction.

The system delay reduction was highest when a two-hour planning interval was used in conjunction with a five-minute system-imposed departure delay increment compared to the baseline case. The performance was measured in terms of total delay and equity. An additional case of a traffic scenario with roughly 25% increase was also studied. Using the credits concept with optional routes reduced the system delay over 50%.

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