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Benefits of Direct-To Tool in National Airspace System

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ABSTRACT

Recent initiatives in air traffic management both in the United States and in Europe have been aimed at providing air traffic controllers with automation tools to separate traffic, meet time constraints required for traffic flow and accommodate route preferences of users such as airlines. These efforts are expected to result in the removal of restrictions on users' preferred routes without compromising safety. Thus, aircraft will be able to fly optimal routes such as great circle and wind-optimal routes. In the existing system, only a limited number of flights are authorized to use optimal routes. Widespread use is limited due to lack of automation tools for maintaining air traffic controller's situational awareness and for inter-facility coordination required for safe operations. In addition, aircraft which have only the basic navigation capability needed for flying from one navigational aid to another along the airways are unable to fly these optimal routes. The National Aeronautics and Space Administration has developed the design for a new automation tool, referred to as the Direct-To tool, which advises the controller on direct, time-saving routes for any aircraft irrespective of levels of equippage. In contrast to earlier studies on the potential benefits of direct routes in the National Airspace System (NAS), the objective of this paper is to evaluate the benefits that would result from a specific controller tool. The paper describes the benefits of applying the Direct-To tool to the 20 air route traffic control centers within the continental United States. Benefits are measured in terms of the total time savings accrued by flying direct routes. Results are described for three different implementations dependent on the search region bounding each air route traffic control center. The first region exactly encloses the air route traffic control center airspace, the second is the smallest rectangular

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bounding region, while the third is a bigger rectangular bounding region approximately twice as large as the second region. The direct routing algorithm is shown to not significantly alter the number of conflicts or their spatial distribution, compared to the case in which the aircraft fly along the airways. The results show that the direct routing algorithm can provide significant cost savings to the users without adversely impacting the air traffic management functions.

1. INTRODUCTION

The air traffic flow management and control functions are based on predictability of traffic which, in the United States, is achieved by imposing a route structure consisting of low-altitude *Victor airways* and high-altitude *Jet routes* [1]. These routes are marked by navigational aids which allow the aircraft to navigate from the origin airport to the destination airport. With scheduled aircraft flying along the route structure, the change in day-to-day traffic pattern is small. This relative stability helps the air traffic controller's situational awareness process. The main limitation of the fixed route structure is that it limits flexibility and capacity [2]. The desire for flexibility and capacity improvements is due to technological improvements in navigation and communication that have made it possible for aircraft to fly without ground-based navigation aids and receive weather, delay and schedule information updates in flight to guide cockpit decision making. These capabilities permit the aircraft to fly optimally based on the operators preferences. Many of the preferences and the needs related to flexibility and capacity are discussed in Reference [3].

The flight plan optimization process is described in References [4, 5]. It requires knowledge of aircraft characteristics (performance and fuel), crew costs, crew scheduling requirements, aircraft maintenance schedule, schedule of connecting flights, expected airspace capacity, weather, special use airspace and location of alternative airports [4, 5]. Reference [5] describes the role of flight planning in airline operational control (AOC).

Benefits of simplified optimal routing such as great-circle routing which is the shortest path between the origin and destination airports has been a subject of several studies. The studies in Reference [6], [7] and [8] conclude that substantial cost savings are possible

by flying direct routes. Optimal flight planning criteria and its benefits are described in [9, 10]. These studies suggest that between $42 and $90 million annual cost savings are possible for some 2000 flights per day for an airline.

In the current system it is possible to obtain some of the benefits of direct routing for longer-range flights via the National Route Program (NRP) [11, 12, 13]. Users can file minimum-time/cost routes provided their aircraft are equipped with area navigation (RNAV) equipment. Initially the program was applicable to flights operating at or above flight level 390, but since then the flight level has been lowered to flight level 290 [13]. Like the conventional flight plan, the NRP flight plan also needs to be filed using fixes and jet routes. The main limitations of the NRP program are the altitude base of flight level 290, RNAV equippage requirement and 200 nautical mile egress and ingress requirements. The 200 nautical mile requirement precludes the short-haul flights from reaping the benefits of optimal routing. Approximately 40% of the daily flights are short-haul flights [3]. Reference [12] states that industry savings due to NRP are estimated at $40 million. Estimates also suggest that as many as 1500 flights per day are taking advantage of the NRP program with annual savings of at least $21 million [13].

The Direct-To tool (DT2) for enroute controllers is a member of the Center TRACON Automation System (CTAS) and is currently planned for field evaluation at the Fort Worth Center [14]. It is designed to eliminate doglegs in the routes which aircraft fly within the current airways structure and will benefit aircraft without regard to equippage and route length. The savings are achievable since the algorithm does not require a radical shift in how the traffic flow and traffic control functions are accomplished within the current system.

The rest of the paper is organized as follows. Section 2 describes the direct routing algorithm and presents the implementation details. Section 3 presents the simulation environment and a detailed study of the benefits within the Fort Worth (ZFW) air route traffic control center (ARTCC) airspace. The impacts of three different sized regions bounding the ZFW ARTCC are also assessed in this section. The number and the nature of the conflicts with direct routing and flight plan routing are compared in Section 4. Benefits for the 20 ARTCCs within the continental United States are discussed in Section 5. Finally, the paper is concluded in Section 6.

2. DIRECT ROUTING ALGORITHM

The direct routing algorithm described in Reference [14] is used as the basis for the benefit study described in this paper. The algorithm is implemented in two steps. In the first step, a direct routing fix is selected from a database. The chosen fix is either the location of a navigational aid or an airways intersection

that is specified in the flight plan. In the second step, trajectories are generated to determine the flight time to the chosen fix along the flight plan route and the direct route. If the flight time along the direct route is less, the direct route is chosen. Time savings and not distance savings are used because time savings include the effect of winds along the route. Also, time savings can be related to fuel savings. Aircraft operators can maintain their schedules by reducing the airspeed when time savings are predicted such that they arrive at the fix at the scheduled time with less fuel. From a scheduling point of view, time savings have the same effect as the aircraft experiencing a tail wind.

An important aspect of the direct routing algorithm is the fix selection procedure. The choice of fix is a function of the destination of the aircraft. For example, if the destination airport is not a major airport, a fix near or at the airport can be used as a direct routing fix. If the destination is a major airport where the aircraft follows the standard terminal arrival route (STAR) and crosses into terminal radar approach control (TRACON) airspace at the feeder gate, a fix along the STAR can be used as the direct routing fix. The present version of the algorithm does not consider arrivals to the main hub airport due to the metering and arrival rate restrictions. An adaptation database is used for correlating these fixes with the airports in a bounded region around the ARTCC. This database provides the direct routing fix if the destination airport is within the bounded region. If the destination is outside the bounding box, a fix which is nearest to the box boundary is chosen.

To obtain an estimate of the time savings by using the direct route to the chosen fix, two trajectories are predicted: one along the flight plan route and the other along the direct route. The trajectory synthesizer which is a core element of the Center TRACON Automation System (CTAS) uses the current state of the aircraft, an aircraft performance model, a weather forecast and operational procedures to predict these trajectories. The difference between the times of arrival at the fix is the predicted time savings. If the savings is greater than one minute, the aircraft call sign, the direct route along with time savings and conflict status are presented on the controller's screen for further consideration.

In order to evaluate the benefits of DT2 for the 20 ARTCCs, a modified version of the algorithm was implemented within the Future ATM Concepts Evaluation Tool (FACET), which is described in Section 3. Modifications to the basic algorithm were needed for ease of implementation and due to some limitations of FACET. The differences between the CTAS and FACET implementations are as follows. In the CTAS implementation of the direct routing algorithm, only the arrivals at the major hub airport within the ARTCC are excluded while in the FACET implementation all arrivals to any airport within the ARTCC

are excluded. This change was made to avoid ARTCC specific adaptation. The CTAS implementation considers aircraft in both low-altitude and high-altitude sectors for direct routing, while the FACET version only considers aircraft in the high-altitude sectors. This constraint was applied because the current version of FACET does not model the standard instrument departure (SID) routes and the standard terminal arrival routes (STARs). Weather data are unavailable to FACET, while CTAS uses weather (wind velocity) for computation of time savings to the chosen fix. Time savings are equivalent to distance savings for the FACET implementation since wind velocity is ignored. Special use airspace (SUA) is not used in the estimation of benefits since earlier studies have shown 98.8% of the economic benefits of direct route flights can be realized even when aircraft are denied access through SUA [15]. However, SUA will be included in future studies.

3. BENEFITS IN FORT WORTH CENTER

Studying the benefits of DT2 in the National Airspace System required a software system that could model air traffic within the entire United States, implement the direct routing algorithm and provide analysis and visualization tools. FACET easily met these requirements and was chosen for the study.

FACET provides the infrastructure needed for evaluating concepts that are implemented as algorithms in software. FACET contains geometric descriptions of the 20 ARTCCs within the United States including all of the sectors contained within each ARTCC. Only the Alaska and Hawaii ARTCCs are currently unavailable. The database also contains the *Victor* airways and the *Jet* routes, along with the location of navaids and intersections. An airport database is also provided that contains locations of more than 15,000 airports worldwide. Performance models provide climb, cruise and descent characteristics of over 500 different types of aircraft. These characteristics are used in the equations of motion to simulate aircraft flight. FACET provides capabilities to simulate traffic along great-circle (direct) and flight plan routes. For simulation along the direct routes, only locations of the origin airports and the destination airports are needed. For flights along flight plans, a parser within FACET is used for decoding flight plans into a sequence of waypoints specified in terms of latitudes and longitudes. A closed-loop great-circle guidance law is used for steering the aircraft along the route of flight. In the flight plan case, aircraft fly from one waypoint to the next using the great-circle guidance law. The initial conditions for the simulation (e.g., aircraft types, departure airports, departure times, destination airports and flight plans) were obtained from the Enhanced Traffic Management System (ETMS) data. ETMS fuses the flight plan and track data provided by the host computers of all the ARTCCs to create a composite database of air traffic within the

entire country.

In order to calibrate the benefits obtained by the modified direct routing algorithm in FACET against the CTAS implementation of the direct routing algorithm [14], traffic for 24 hours was simulated for a 1000 × 600 nautical miles box surrounding the Fort Worth ARTCC. The initial conditions and flight plans for this FACET simulation were obtained from a 24-hour recording of ETMS data. Figure 1 shows the histogram of the savings for ZFW. Time savings up to
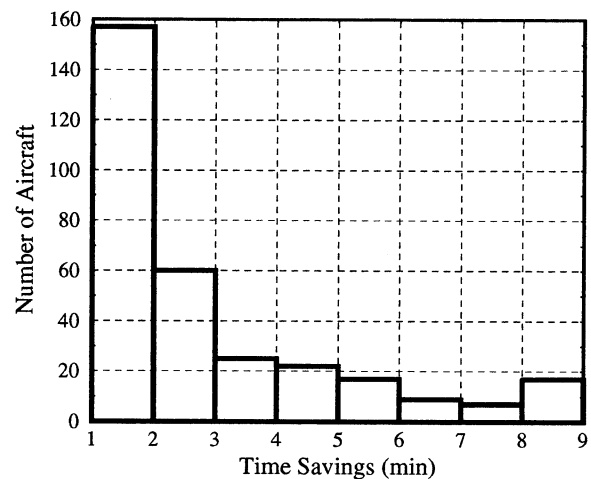

Figure 1: Savings for Fort Worth ARTCC.

nine minutes were considered. Savings greater than nine minutes were discarded because closer examination revealed that the aircraft in these cases were being rerouted to avoid weather and dense traffic areas. Direct routing is unreasonable in these cases. The total savings for this day was found to be 20.6 hours and the average savings was 3.5 minutes per aircraft using a direct-to route. These savings compare favorably with the average savings of 2.5 minutes obtained using CTAS. The difference is due to the limitations discussed earlier in Section 2 and also due to the day-to-day variations seen in the traffic data. The CTAS and FACET estimates are for different days. Moreover, the traffic data in the case of the FACET implementation is simulated, while the CTAS implementation used actual traffic data provided by the ARTCC host computer.

The benefits of implementing DT2 at an ARTCC depends on the size of the bounding box, and the bounding box size also influences the approach for providing DT2 coverage in the entire NAS. To understand the influence of the bounding box, in addition to the 1000 × 600 nautical miles box that was used earlier, two additional regions of different sizes were used to study direct routing benefits. The three regions are shown in Figure 2. The first region exactly encloses the ARTCC and its boundary is same as the ARTCC boundary. The second region is a rectangular region that barely encloses the ARTCC.
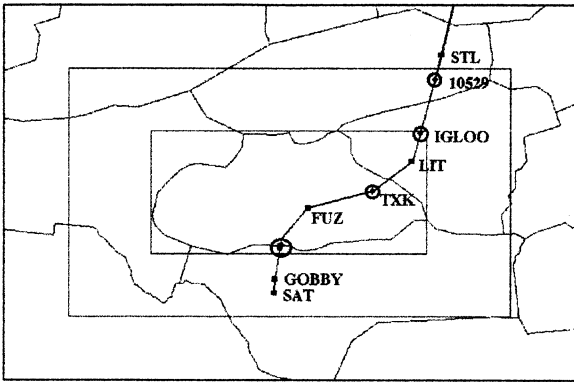
Figure 2: Regions for Fort Worth ARTCC.

Finally, the third box that encloses the ARTCC is about twice as large as the smaller rectangle. The smaller and the larger rectangle shown in this figure are of size 633 × 293 nautical miles and 1000 × 600 nautical miles. The size of the region bounding the fixes to which aircraft will be directly routed impacts the direct routing benefits. For example, consider the flight plan for a flight from San Antonio, Texas (SAT) to Greater Rockford, Illinois (RFD) shown in Figure 2. The planned route for this particular flight is specified in terms of fixes and jet routes as SAT./.GOBBY..FUZ.J131.LIT.J101.STL..BDF..RFD. When the ARTCC boundary is used as the bounding region, the direct routing algorithm sends the aircraft directly to the TXK fix shown in Figure 2. Time savings for the direct-to route is 1.9 minutes. If the choice of the bounding region is the smaller rectangle, the aircraft is sent direct to the IGLOO fix on the jet route J101. The time savings in this case is 3.7 minutes. In the case of the larger bounding box, the aircraft is sent to the intersection 10529 on jet route J101, shown in Figure 2, and the savings increase to 6 minutes. This example suggests that as the box size increases, direct routing benefits increase. To verify that this indeed is the case, time savings per aircraft sent on a direct route and the total time savings were obtained using the 24-hour FACET simulation that had been used earlier for the larger 1000 × 600 nautical miles region. Total time savings for the ARTCC region and that bound by the small rectangle were 7.8 hours and 10.3 hours. Average savings per aircraft on direct routes for these two regions were 4.1 minutes and 4.4 minutes.

4. NUMBER AND NATURE OF CONFLICTS

Important operational issues for direct routing within the existing route and airspace structure are a possible decrease in the air traffic controller's situational awareness and increase in workload. CTAS automation for direct routing is designed with conflict checking and trial planning tools that enhance controller's situational awareness and do not adversely impact workload. One of the ways in which the impact of direct routing on controller workload can be studied is by examining the number of conflicts and the locations where these conflicts occur. Since the primary function of air traffic control is to prevent separation violations, a significant amount of controller workload is attributed to the conflict monitoring and conflict resolution tasks. Controllers expect most conflicts to occur near the intersections of the airways, therefore, their attention is focussed at these regions. The monitoring task may change if the conflicts are dispersed away from the intersections. Due to these concerns, the number of conflicts and their spatial distribution were studied for the Fort Worth ARTCC airspace. Figure 3 shows the time history of the difference between the number of conflicts with the direct routing algorithm and without it. At any given time, the difference between the num-
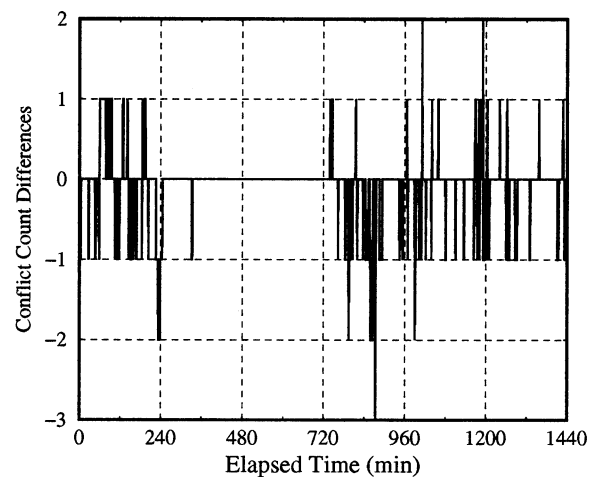

Figure 3: Time history of conflicts.

ber of conflicts was obtained by subtracting the number of conflicts that occurred when all the aircraft flew on their flight plans from the number of conflicts that occurred when the direct routing algorithm was used for routing aircraft with more than one minute of time savings. The figure shows that at some time instants the number of conflicts in the direct routing case is more than the nominal flight plan case. At other instants, the behavior is opposite. The histogram of the difference between the number of conflicts is shown in Figure 4. This figure shows that during 88% of the 24-hour period there were no differences in the number of conflicts on the direct and flight plan routes. During 9% of the time, there were fewer conflicts with direct routing. The number of conflicts increased by one during 3% of the time. Only about 0.1% of the time there was an increase of two or more conflicts. The overall time history shown in Figure 3 and the histogram in Figure 4 lead to the conclusion that direct routing does not
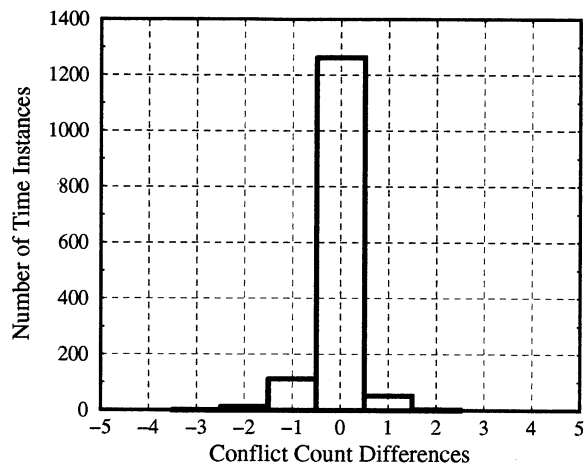
Figure 4: Histogram of difference between number of of conflicts.

significantly alter the total number of conflicts.

The spatial distribution of all the conflicts that occurred in the 24-hour period when aircraft flew on their flight plans is shown in Figure 5. A similar distribution when aircraft were sent on direct routes is shown in Figure 6. By comparing these two figures it is easily seen that the conflict locations are fewer and slightly dispersed with direct routing. Overall change is insignificant. Observe that these figures do not show the conflict locations at any one time but the composite of all times within the 24-hour period. This fact along with the conflict count shown in Figure 3 suggest that direct routing may not have a significant adverse effect on the controller's workload.
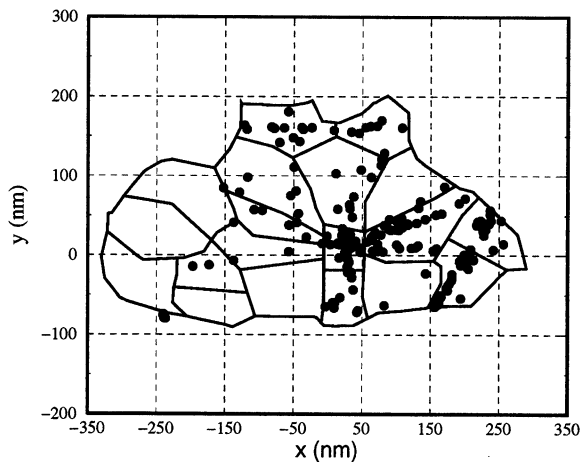

Figure 5: Spatial distribution of conflicts without direct routing.

5. BENEFITS IN NAS

Having studied the benefits of the direct routing algorithm and the nature of conflicts in the Fort Worth

ARTCC, the benefits study was extended to the 19 additional ARTCCs in the continental United States. The boundary of each of these ARTCCs is shown in Figure 7. The average time savings per aircraft sent on a direct route and the total time savings were obtained for regions surrounding each of the 19 additional ARTCCs, using the 24-hour traffic simulation in FACET. Like the Fort Worth case, three regions around each ARTCC were used.

Results for regions that exactly enclose these ARTCCs are summarized in Table 1. The first column of this table shows the name of the ARTCC.
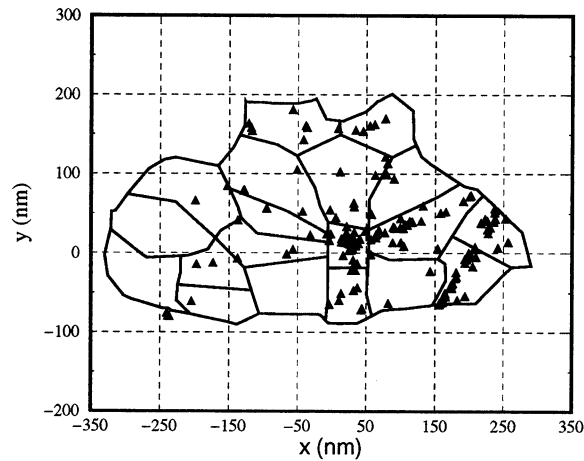

Figure 6: Spatial distribution of conflicts with direct routing.

Figure 7: Boundaries of 20 ARTCCs.

The second column shows the average time savings μ in minutes, while the third column shows the standard deviation of the time savings σ in minutes. Observe from Figure 1 that time savings can be less than μ, but is always greater than zero. Assuming a gaussian distribution, the maximum time savings for an aircraft in the ARTCC can be estimated to be $\mu + 3\sigma$. Using this rule, and the μ and σ values in Table 1, the upper bound of the time savings for an aircraft within the

Fort Worth ARTCC can be estimated to be 12.5 minutes. The fourth column presents the number of aircraft that were sent on the direct route in the 24-hour period. Finally, the fifth column lists the total time savings in hours for the 24-hour period for each bounding region. Total savings were obtained by adding the savings of individual aircraft sent direct using the direct routing algorithm.

Table 1: ARTCC region results

ARTCC	μ (min.)	σ (min.)	# Ac.	Total (hrs.)
Boston	2.6	1.6	378	16.5
Fort Worth	4.1	2.8	113	7.8
Indianapolis	2.6	1.8	210	9.1
Jacksonville	2.6	1.7	491	21.3
Miami	2.6	1.6	127	5.4
New York	2.4	2.0	128	5.0
Atlanta	2.6	1.8	184	7.9
Houston	2.7	1.9	96	4.4
Memphis	2.9	2.4	84	4.1
Kansas City	2.7	2.2	76	3.4
Cleveland	2.3	1.5	305	11.5
Minneapolis	2.6	1.6	63	2.7
Chicago	2.8	1.5	196	9.3
Albuquerque	2.5	1.8	193	7.9
Denver	3.5	2.8	158	9.1
Salt Lake City	2.7	1.7	80	3.6
Seattle	3.8	2.7	73	4.7
Oakland	3.5	2.3	223	12.9
Los Angeles	2.7	1.8	230	10.2
Washington	2.5	1.5	301	12.6

Time savings results were also obtained for small rectangular regions that barely enclosed the 20 ARTCCs. These results are given in Table 2. The length and width of the rectangular region closely bounding the Fort Worth ARTCC are 622 nautical miles and 293 nautical miles. For the Fort Worth ARTCC study described in the previous section, a 1000 × 600 nautical miles rectangular box had been used as the larger region. These dimensions result in the length scale factor of 1.61 and width scale factor of 2.05. Larger regions bounding each of the ARTCCs were obtained by scaling the length and width by the same scale factor as the Fort Worth ARTCC. Results for the large rectangular bounding regions are summarized in Table 3.

The average time savings and the total time savings results shown in Table 1 through Table 3 are plotted as bar charts in Figure 8 and Figure 9. In the set of three bars for each ARTCC, the first bar from the left represents the savings in the ARTCC region. The middle bar represents the savings in the small rectan-

Table 2: Small bounding region results

ARTCC	μ (min.)	σ (min.)	# Ac.	Total (hrs.)
Boston	2.7	1.7	415	18.4
Fort Worth	4.4	2.9	139	10.3
Indianapolis	2.8	1.8	248	11.6
Jacksonville	2.7	1.8	558	25.4
Miami	2.7	1.7	517	7.6
New York	2.5	1.9	292	12.2
Atlanta	2.6	1.9	179	7.8
Houston	3.0	1.9	118	5.9
Memphis	2.8	2.0	167	7.8
Kansas City	2.6	2.0	110	4.7
Cleveland	2.3	1.6	394	15.4
Minneapolis	2.3	1.5	266	10.3
Chicago	2.9	1.3	197	9.5
Albuquerque	2.4	1.7	273	11.1
Denver	3.0	2.4	226	11.5
Salt Lake City	2.4	1.5	130	5.3
Seattle	3.0	2.3	99	5.0
Oakland	3.2	2.2	263	14.1
Los Angeles	2.4	1.8	414	16.6
Washington	2.6	1.7	394	17.1

Table 3: Large bounding region results

ARTCC	μ (min.)	σ (min.)	# Ac.	Total (hrs.)
Boston	2.7	1.7	593	26.7
Fort Worth	3.5	2.8	349	20.6
Indianapolis	2.8	1.9	503	23.2
Jacksonville	3.1	1.9	720	37.6
Miami	2.7	1.7	517	27.0
New York	2.3	1.7	542	20.7
Atlanta	2.5	1.7	513	21.5
Houston	2.8	1.9	363	17.1
Memphis	2.7	2.0	383	17.4
Kansas City	2.4	1.7	376	14.9
Cleveland	2.5	1.9	678	28.5
Minneapolis	2.5	1.8	452	18.9
Chicago	3.7	2.4	370	22.6
Albuquerque	2.5	1.8	489	20.6
Denver	3.0	2.2	370	18.3
Salt Lake City	2.2	1.4	278	10.4
Seattle	2.8	2.0	182	8.5
Oakland	3.2	2.2	415	21.9
Los Angeles	2.3	1.7	570	22.1
Washington	3.0	1.8	825	40.6

gular bounding region. The bar on the right shows the savings in the large rectangular region surrounding the ARTCC airspace. Figure 8 does not show a definitive trend in the average time savings as a function of size of the bounding region. It is interesting to note that the mean of the average time savings is 2.8 minutes irrespective of the size of the bounding region. The total time savings, shown in Figure 9, lead to the conclusion that total time savings increase with the increasing size of the bounding regions. The main reason, as can be seen from an examination of Tables 1, 2 and 3, is that the number of aircraft within an ARTCC eligible for direct routing increases monotonically with the size of the bounding region. Total time savings in just the

jurisdiction over their airspace hence they can send aircraft direct to any location within their airspace. When larger regions which are beyond the ARTCC boundary are used, letters of agreements with neighboring ARTCCs determine the extent of privileges they have in their neighbors airspace. No matter whether the ARTCC regions, small rectangular regions, large rectangular regions, or combinations of them are used, the time savings for each direct route segment as the aircraft are handed off from one bounding region to the next will need to be summed up to obtain NAS wide savings. An estimate of NAS wide savings of 439 hours, obtained by summing up the fifth column of Table 3, is an optimistic one in this context. A similar estimate of 169 hours for the ARTCC regions in Table 1 is a conservative one. The estimate of 228 hours obtained via Table 2 represents a compromise between the two extremes.
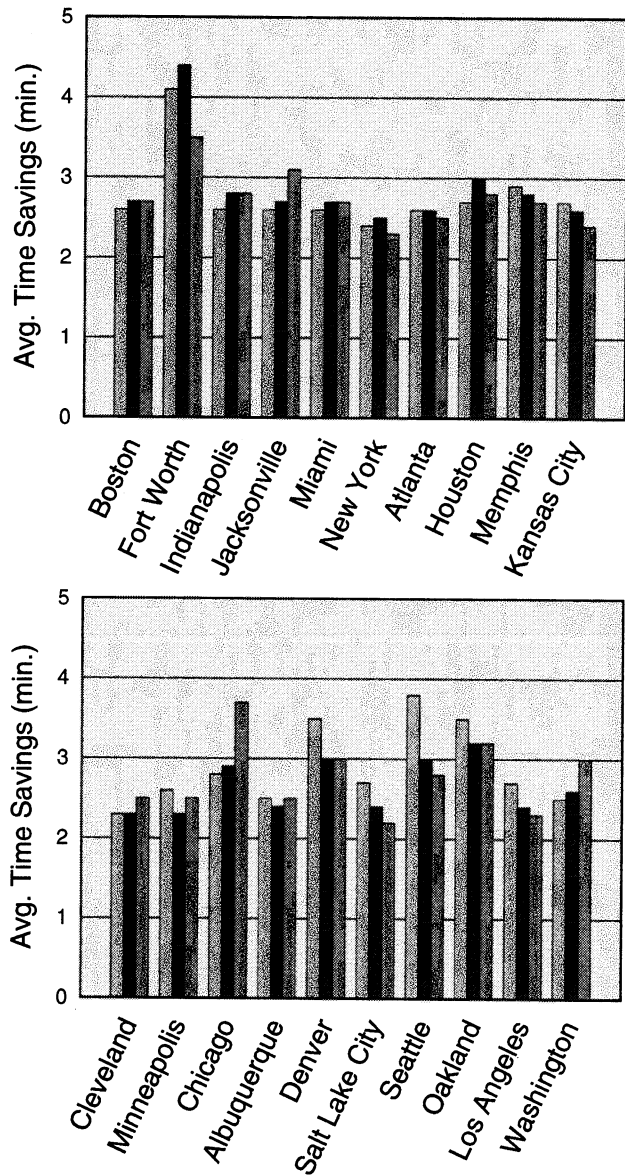

Figure 8: Average time savings for the 20 ARTCCs.

Figure 9: Total time savings for the 20 ARTCCs.

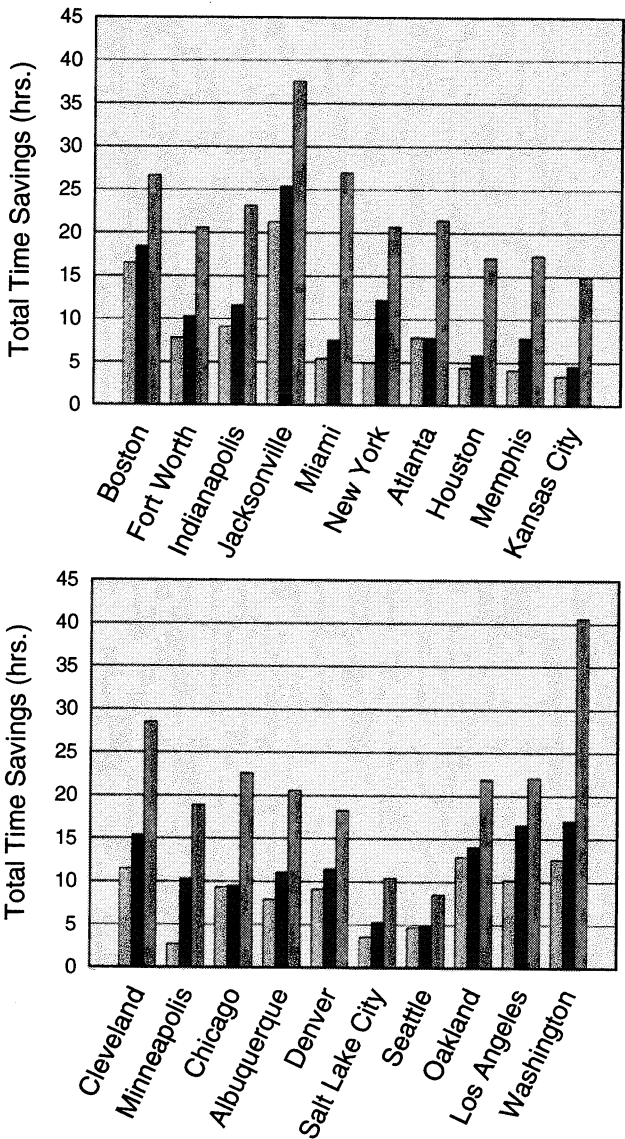ARTCC regions represents the conservative but realizable estimates. This is because ARTCCs have a clear

6. CONCLUSIONS

The potential benefits of the Direct-To tool for en-route controllers, developed by the National Aeronautics and Space Administration, was the subject of this study. The benefits of the direct routing algorithm were estimated for the Fort Worth air route traffic control center airspace in terms of average time savings per aircraft sent on direct routes and the total time savings within the 24-hour period. Benefits were assessed for three different regions bounding the airspace. The total time savings in the first region that exactly bounds the air route traffic control center airspace was found to be 7.8 hours/day. Time savings for the second region, which is the smallest rectangular region bounding the airspace, was found to be 10.3 hours/day. Time savings for the third region was found to be 20.6 hours/day. This region was twice as large as the small rectangular region. Assuming an operational cost of $29 per minute, the time savings in these three regions translate into an annual cost savings of $5 million, $6.5 million and $13 million, respectively. The time savings in the larger region results in a savings of $16 million based on a cost of $35 per minute, which compares very well with the savings of $18 million predicted using the Center TRACON Automation System implementation of Direct-To tool. The spatial distribution of the conflicts was also studied for the first region with direct routing in contrast with the spatial distribution of conflicts that occurred as the aircraft flew according to their flight plans. It was found that the number of conflicts at any given time do not change significantly which suggests that the controller's workload may not be adversely impacted by the direct routing procedure. The benefits study was extended from the Fort Worth Center to the 19 additional air route traffic control centers. Total time savings results obtained for the three regions bounding each of these 20 air route traffic control centers show that significant time savings, ranging from 169 hours/day to 439 hours/day, are possible. These time savings translate into annual cost savings ranging from $107 million to $279 million, based on an assumed operational cost of $29 per minute. These results are in agreement with an earlier Delta airline study which forecast annual cost savings ranging from $42 million to $92 million based on 2000 flights/day with an average time savings of two minutes. Scaling the baseline benefit of $42 million for the 2000 flight per day with the number of aircraft sent on direct routes per day in the three regions amounts to annual savings ranging from $78 million to $214 million.

The benefit results presented in this study provide valuable data to make decisions about different ways a direct routing tool can be implemented in the National Airspace System. To our knowledge, it is the first study which estimates the savings from direct routing, Center by Center, based on a tool which can be implemented in the near future.

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