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Dynamic Weather Routes: Two Years of Operational Testing at American Airlines

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Abstract - **The Dynamic Weather Routes (DWR) tool continuously analyzes active flights in en route airspace and finds simple route corrections to achieve more time- and fuel-efficient routes around convective weather. A strong partnership between NASA, American Airlines (AA), and the Federal Aviation Administration has enabled testing of DWR in real-world air traffic operations. NASA and AA have been conducting a trial of DWR at AA's Integrated Operations Center in Fort Worth, Texas since July 2012. This paper describes test results based on AA's use of DWR for their flights in and around Fort Worth Center (ZFW). Results indicate an actual savings of 3,290 flying minutes for 526 AA revenue flights from January 2013 through September 2014. Of these, 48 flights each indicate a savings of 15 min or more. Potential savings for all flights in ZFW airspace, corrected for savings flights achieve today through normal pilot requests and controller clearances, is about 100,000 flying minutes for 15,000 flights in 2013. Results indicate that AA flights with DWR in use realize about 20% more savings than non-AA flights. A weather forecast analysis examines the extent to which DWR routes rated acceptable by AA users remain clear of downstream weather. A sector congestion analysis indicates congestion could be reduced 19-38% if all flights fly DWR routes rather than nominal weather-avoidance routes.**

Keywords – weather avoidance routes, trajectory-based automation, en route air traffic management, operational testing.

I. INTRODUCTION

Convective weather cells, or severe thunderstorms, are the leading cause of flight delay in US airspace [1]. Airline Dispatchers are required by Federal Air Regulations (Part 121) to plan flights around known areas of severe thunderstorm activity. Dispatchers submit flight plans 1-2 hours prior to departure utilizing routes that incorporate conservative distances from severe forecast weather. Weather changes as flights progress, and dispatchers and Federal Aviation Administration (FAA) traffic managers and controllers are especially busy during weather events. Workable opportunities for more efficient routes around bad weather are missed, and automation does not exist to help operators determine when nominal weather avoidance routes have become stale and should be updated to reduce delay.

The Dynamic Weather Routes (DWR) tool is a ground-based trajectory automation system that continuously and automatically analyzes active in-flight aircraft in en route airspace to find simple corrections to flight plan routes that can save significant flying time -- at least five minutes wind-corrected -- while avoiding weather and considering traffic conflicts, airspace sector congestion, special use airspace, and FAA routing restrictions [2]. DWR users, including airline Air Traffic Control Coordinators and Flight Dispatchers, and FAA Traffic Managers and Air Traffic Controllers, are alerted when a route correction for a flight can potentially save a user-specified minimum number of flying minutes. The primary inputs to DWR are en route Center radar track and flight plan data, National Oceanic and Atmospheric Administration Rapid Refresh wind, temperature, and pressure data, the Corridor Integrated Weather System (CIWS) convective weather forecast model [3], the Convective Weather Avoidance Model (CWAM) [4], and the Traffic Flow Management System (TFMS) national traffic feed. DWR advisories update every 12 sec as fresh Center radar track and flight plan data are received. The DWR system is currently adapted for Fort Worth Center (ZFW) airspace, and processes all flights in Center airspace, and first tier adjacent Center airspace except arrivals to the Dallas/Fort Worth International Airport (DFW) and Dallas Love Field (DAL). Research is under way to determine how best to handle flights nearing their destination airport [5], but current DWR automation is designed to not interfere with arrival routings near the destination airport, so flights destined for DFW and DAL are not processed.

Stewart [6] describes a concept for tactical reroutes around impacting convective weather that leverages new technologies to automate the necessary coordination between traffic managers and controllers. Taylor and Wanke [7] define an optimization approach to identify operationally acceptable reroute alternatives for flights impacted by weather. The optimization considers acceptability factors such as route track distance savings, consistency of reroutes with historically-flown routes, sector congestion, and other factors important to air traffic operations. To address forecast uncertainty, Matthews and DeLaura [8] define an airspace permeability metric to assess the risk of trajectories passing through a weather impacted airspace regions. Sorensen [9] examined a limited dynamic rerouting concept with airline/ATC collaboration and concluded that distribution of important air traffic and weather data would improve benefits to airspace users. Results from the first three months of testing DWR at American Airlines (AA) are described in [10]. An analysis of execution delays, AA user feedback, and different types of DWRs rated acceptable by AA users is described in [11].

The contribution of this paper is to describe test results from the AA trial over the roughly two-year period from January 2013 through September 2014. The method developed to estimate the actual savings attributed to AA's use of DWR is defined, and an analysis of savings for AA flights where DWR was used vs. AA and non-AA flights where DWR was not used is presented.

The main difference between DWR and other automation for weather avoidance is that route corrections proposed by DWR are triggered by detected opportunities for more efficient time saving routes around weather. In most other related research, route advisories are triggered when automation determines that a flight, or group of flights, must alter their routes to avoid weather on their current route. As shown in Fig. 1, and described in detail in [2], DWR finds reference direct routes that can save 5 min or more, then adds auxiliary waypoints as needed (up to two) to avoid weather along the reference direct route. If a solution is found that can save 5 min or more relative to the current flight plan route, a route advisory is posted to the flight list (upper left in Fig. 1). Weather avoidance is based on probing CIWS/CWAM weather on a 2-hour time horizon. DWR software could be configured to compute minimum-delay routes around weather on the current Center flight plan, but this functionality has not yet been added.

In 2012 NASA partnered with AA and the FAA to conduct an operational trial of the DWR concept and prototype tool at AA's Integrated Operations Center (IOC) in Fort Worth, Texas. The DWR tool has been running 23 hours/day, 7 days/week at the AA IOC from July 2012 to present at a position called the Air Traffic Control (ATC) Desk on the IOC operations floor (Fig. 2). An audible tone (that of an old-fashioned cash register – "ka-ching") alerts AA ATC Coordinators, who are also licensed Dispatchers, whenever a route correction for a new AA flight is first posted to the flight list. A point and click action on the flight list activates a trial planning function enabling users to visualize the proposed route on a traffic display and modify it if necessary using interactive automation. Critical parameters such as weather proximity, wind-corrected flying time savings, traffic conflicts, sector congestion, and special use airspace alerts all update dynamically as the user modifies the trial route using interactive point, click, and drag inputs. If the ATC Coordinator concurs with a DWR advisory, he or she coordinates it with the Dispatcher in charge of the flight. If they both agree, the ATC Coordinator clicks "Accept" on the user display, and the Dispatcher sends a message (via the Aircraft Communications, Addressing, and Reporting System, or ACARS) to the flight crew proposing the route change for time and fuel savings. If the flight crew concurs, they request the route change from air traffic control using normal procedures. The ATC Coordinator may also "Cancel" a trial DWR route for any reason, or "Reject" the route if there is something unacceptable about the proposed route. Clicking "Reject" triggers questionnaires that let users record what factors led to the reject [10]. Testing is limited to AA flights in ZFW airspace, and since adjacent Center processing (see Section VI.B) was installed on May 9, 2014, AA flights in ZFW plus its first tier adjacent Centers (Kansas City, Memphis, Houston, and Albuquerque).

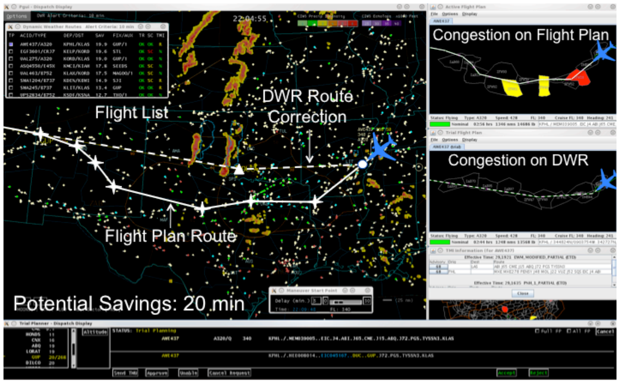

Figure 1. DWR User Display

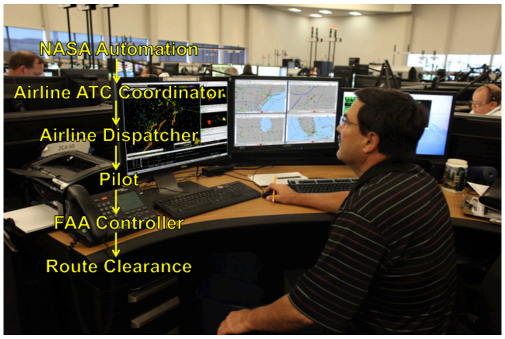

Figure 2. DWR at Air Traffic Control Desk, American Airlines Integrated Operations Center, Fort Worth, Texas

This section has summarized the DWR tool, its operating concept, and the trial operations in place at AA. Section II presents corrected potential savings for all flights in ZFW airspace where corrected savings account for savings realized today, without DWR, through normal pilot requests and controller clearances. The DWR system used for the AA trial identifies and records route correction opportunities for all flights, not just AA flights. Section III describes the automated daily analysis method developed to analyze AA's use of DWR including advisories for AA flights, AA user actions, and estimated actual savings for AA flights. Section III also describes the estimated actual savings analysis method, and compares estimated actual savings for AA flights when DWR was used to that of non-AA flights. Section IV examines the extent to which DWR trajectories rated "Accept" by AA users remain free of weather 1-2 hours beyond the

Accept time. Section V applies the FAA's primary congestion metric, the Monitor Alert Parameter, to compare sector congestion with all flights on DWR routes vs. their nominal weather avoidance routes. Section VI summarizes DWR system improvements and lessons learned based on experience during the AA trial. Section VII provides some concluding remarks.

II. POTENTIAL DWR SAVINGS FOR ALL FORT WORTH CENTER FLIGHTS

In this section potential DWR flying time savings and corrected potential savings are presented for all flights in ZFW airspace in 2013 (except DFW and DAL arrivals). The potential savings for any flight is that which corresponds to the first DWR route advisory for the flight. This is usually the maximum potential savings, since savings decay as flights progress on their current routes. Shown in Fig. 3 are potential savings for all ZFW flights above 10,000 feet for every day in 2013. These data are based on analysis of all ZFW traffic (23 hours/day, 7 days/week) in 2013, and reflect only DWR route corrections with potential savings of 5 min or more. The days with high potential savings correspond well with heavy weather days in and around ZFW airspace. Note that 2,287 flights in 2013 had a potential savings of 10 min or more for a total potential savings of 40,954 or 17.9 min/flight on average.

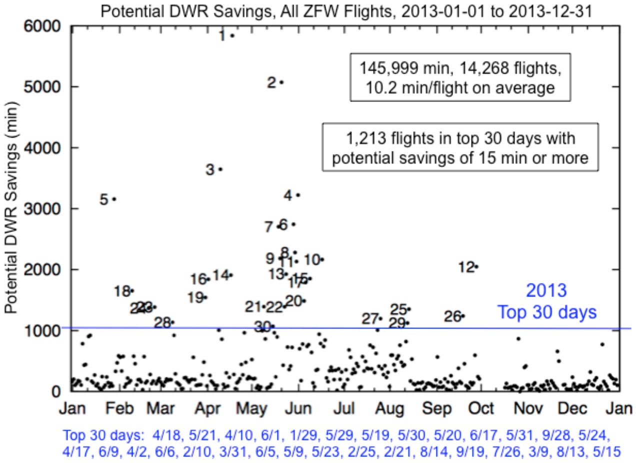

Figure 3. Potential DWR savings for all ZFW flights in 2013.

Corrected potential savings are the potential savings left unrealized after accounting for route amendments that occur as a result of today's normal pilot requests and controller clearances without DWR. The actual Center route amendments that follow the first DWR advisory for any flight are analyzed to estimate the actual flying time savings or delay resulting from these amendments. These savings or delay values are then summed to acquire the estimated actual savings for all flights for which a DWR route advisory was computed. The estimated actual savings analysis method is described in more detail in the next section.

Fig. 4 shows potential DWR savings (dark blue bars) and corrected potential savings (light blue bars) for all ZFW flights in 2013. Results are based on analysis of all ZFW flights (23 hours/day, 7 days/week) in 2013 except arrivals to DFW or DAL. Savings are grouped by airline and ordered in terms of potential DWR savings. The 3-letter airline identifiers are shown, and "N" indicates general aviation flights. The data indicate that under today's operations, flights achieve about 32% of potential DWR savings on average without using DWR. The corrected potential DWR savings in ZFW airspace is about 100,000 min for 15,000 flights, or about 6.7 min per flight on average. Assuming an operating cost of $3,585/flight-hour ($59.75/min) for a B737NG aircraft [12], this equates to about $6 million per year potential savings in airline operating costs in one en route Center.

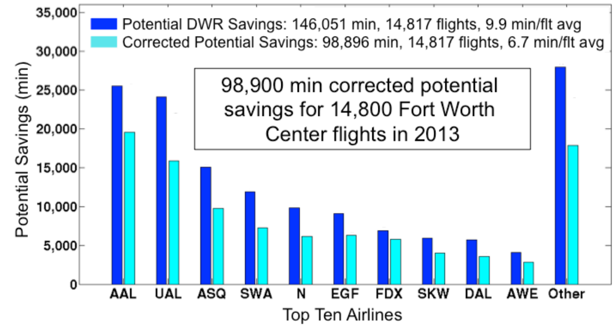

Figure 4. Corrected potential DWR savings for all ZFW flights in 2013.

III. ESTIMATED ACTUAL SAVINGS DURING DWR OPERATIONS AT AMERICAN AIRLINES

In this section a method is defined to estimate the actual flight time savings due to observed Center route amendments that follow DWR advisories. This estimate of actual flight time saved is referred to herein as estimated actual savings. The method is first applied to AA flights where DWR was used. Then we compare estimated actual savings for AA flights where DWR was used to that of AA and non-AA flights where DWR was not used. The sample flights in this section illustrate the potential benefit of air/ground datalink for DWR operations.

A. Estimated Actual Savings Analysis Method

The principal assumption in the estimated actual savings analysis is that if one or more Center route amendments are observed within a certain elapsed time following the point at which an AA user clicks "Accept" on the DWR display, then those route amendments are assumed correlated with AA's use of DWR. This assumption is necessary because the ACARS messages sent by AA dispatchers to flight crews are not available for analysis nor are controller/pilot voice communications. Under the trial procedures the ATC Coordinator clicks "Accept" only after he or she and the Dispatcher have agreed to send an ACARS message to the flight crew. Anecdotal reports from users indicate that in approximately 85-95% of cases, if the Accept button is clicked, an ACARS message with a DWR route proposal is sent to the flight.

A few important observations have been consistent throughout the trial. Observed route amendments that follow the Accept time often do not exactly match the DWR route sent to the flight crew. This is an expected finding. Once the pilot and controller evaluate a proposed route change, the resulting route amendment, or amendments, may be different from what was proposed by the dispatcher. In some cases flights achieve more savings than what was proposed by the dispatcher. Results show that AA flights often receive multiple route amendments following the Accept time, and there is a wide variation in elapsed time between Accept time and observed route amendments. Multiple route amendments are also an expected finding as it is common for flights to receive multiple route updates to rejoin preferred routes during weather events.

Several factors could contribute to the observed variation in elapsed time between Accept time and observed route amendments. The maneuver start point (MSP) is nominally set to 5 min downstream of the present position. MSP is usually more than 5 min for climbing flights because the minimum MSP altitude is FL240 so that DWR routes for climbing flights start in high-altitude airspace. There could be delays in sending the ACARS message to the flight crew, and the crew needs time to review the proposed route. Controllers may have to delay clearance delivery for workload, traffic, or other factors. Sometimes, to simplify inter-sector or inter-Center coordination, controllers ask pilots to hold their route change request until they reach the next sector or Center.

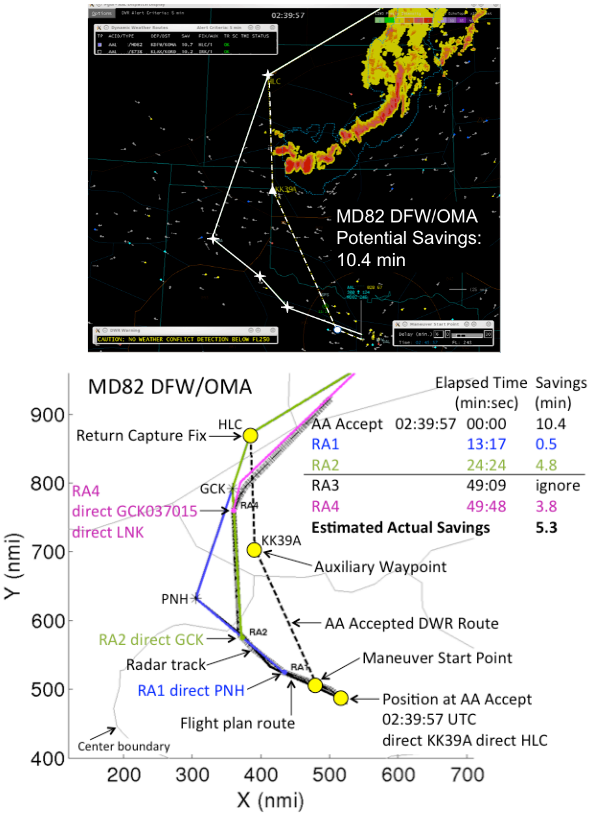

Figure 5. (top) Screen capture of DWR accepted by dispatcher, (bottom) plot showing accepted DWR, observed route amendments, and actual aircraft track.

To account for these factors we compute the flying time savings, or delay, associated with each route amendment observed up to 30 min after the Accept time. The savings or delay values associated with each amendment are summed to estimate the actual savings for the flight. Visual inspection of a sampling of AA flights with accepted DWR routes suggests that amendments beyond 30 min are likely not related to DWR. Though we select 30 min as the nominal limit, later in this section estimated savings are grouped by elapsed time (10, 20, and 30 min) to observed route amendments.

Two sample flights are used to illustrate the estimated actual savings analysis method. Fig. 5 shows a flight from Dallas, TX to Omaha, NB. The screen capture (top) shows the original flight plan (solid line), the DWR route accepted by AA users (dashed line), and the impacting weather. The plot (bottom) shows the original flight plan route, the accepted DWR route, the observed route amendments, and the actual radar track data. At 02:39:57 UTC the user accepted the DWR route going from the maneuver start point direct to fix KK39A then direct HLC with the rest of route unchanged. The first observed amendment (RA1) occurs 13 min after Accept time and is a simple direct to a downstream fix (PNH) for a savings of 0.5 min. The second amendment (RA2) occurs 24 min after Accept time and is a more significant direct to another downstream fix (GCK) for a savings of 4.8 min. The third amendment (RA3) is ignored because it occurs less than one min prior to the fourth amendment (RA4). RA4 is not factored into the estimated actual savings result because it occurs 49 min after the Accept time. The estimated actual savings for the flight is the sum of savings due to RA1 and RA2 or 5.3 min.

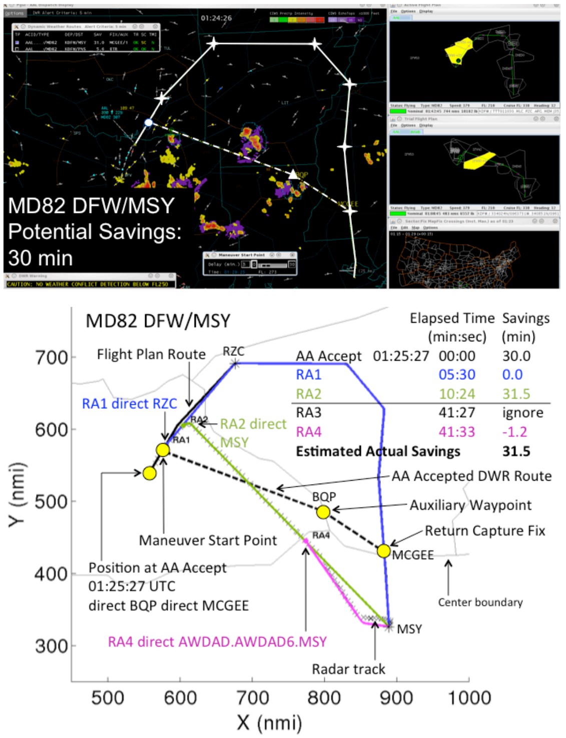

Figure 6. (top) Screen capture of DWR accepted by dispatcher, (bottom) plot showing accepted DWR, observed route amendments, and actual aircraft track.

Fig. 6 shows a flight from Dallas, TX to New Orleans, LA where the AA dispatcher accepted the route as shown to the capture fix (MCGEE) via one auxiliary waypoint (BQP) for a savings of 30.0 min. In this case the flight was cleared direct MSY, then later cleared to the AWDAD6 arrival to MSY.

The example in Fig. 5 illustrates how air/ground datalink, communication and/or automation enabling a sector controller to auto-load a route change request into their trial planning function, could greatly simplify the coordination process and likely result in significantly more savings. Today's FANS-1/A with Controller/Pilot Datalink Communication (CPDLC) equipage enables pilots to load an uplinked ACARS message into the Flight Management System with one button click and see a graphic display of the proposed route change on a cockpit display that also shows weather radar. CPDLC is operational in parts of Europe [13], and some operations have been conducted in the US [14, 15]. Weather avoidance in a CPDLC datalink environment has been effectively demonstrated in pilot and controller in-the-loop simulations [16]. Any other means for the pilot to see a graphic display of the proposed route change with relevant weather and traffic, via Electronic Flight Bag automation for example, would likely help the flight crew and streamline the process [17]. If controllers could click a button to activate the same trial plan that the dispatchers and/or pilots are requesting, they could quickly see the proposed route with relevant weather and traffic, and, as in the Fig. 5 sample, wouldn't have to search for the auxiliary waypoint KK39A. In this case, the controller would also easily see that the proposed route does not interfere with the sparse flow of DFW/DAL arrivals to the northwest arrival meter fix, and likely issue the clearance as requested for a full savings of 10.4 min.

Thirty percent of the potential DWR savings in the top 30 days of 2013 are due to DWR advisories where at least one auxiliary waypoint was inserted to avoid weather (DWRs with two auxiliary waypoints are rare; only 3% of savings result from DWRs with two auxiliary waypoints). For the direct route DWRs, where no auxiliary waypoints were needed to avoid weather, insertion of an auxiliary waypoint is an easy way to add more buffer to weather, avoid a congested sector, or insert a fix on a long direct route segment.

B. Estimated Actual Savings for American Airlines Flights

Fig. 7 summarizes DWR advisories, AA user actions, and estimated actual savings for AA flights over the period January 1, 2013 through September 30, 2014. Route corrections for 8,993 AA flights were proposed, and of those, 2,011 were evaluated by AA users. "Evaluated" means the user responded to the audible alert and activated the DWR trial planner to evaluate the proposed route. Staffing was the principal reason for not all advisories being evaluated by AA users. For various reasons, including the fact that DWR is configured for a trial and not completely integrated with other dispatcher tools, the DWR tool was not always staffed. For example, during very severe weather events impacting AA operations (e.g., diversions, airport closures, extensive ATC delays) DWR may not be staffed. Note that DWR routes for 1,311 flights, 65% of those evaluated, were rated "Accept" by AA users for a total accepted potential savings of 8,866 flying minutes. The estimated actual flying time savings attributed to AA's use of DWR is 3,290 wind-corrected flying minutes for 526 revenue flights or 6.2 min per flight on average. Assuming the B737NG operating cost per flight hour, this equates to about $196,000 savings in airline operating costs.

Note that estimated actual savings (3,290 min) is 37% of accepted savings (8,866 min). If we limit the results in Fig. 7 to start on May 9, 2014, the day adjacent Center processing (described later) was first activated, estimated actual savings rises to 49% of accepted savings. The estimated actual savings analysis is more accurate with adjacent Center data since some relevant route amendments occur after flights have crossed into the next Center.

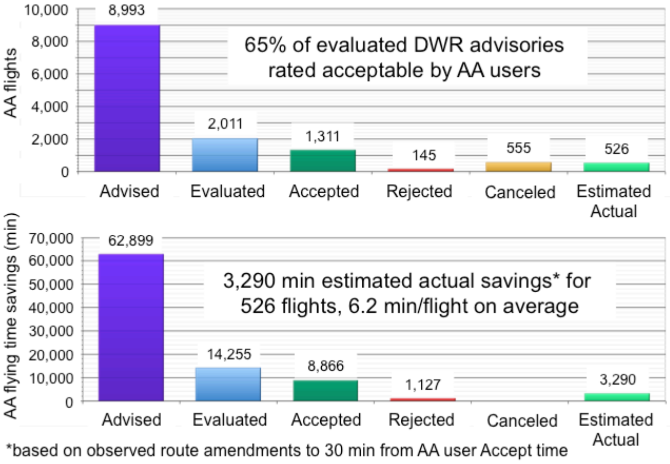

Fig. 7. DWR advisories, AA user actions, and estimated actual savings for AA revenue flights from Jan 1, 2013 to Sept 30, 2014.

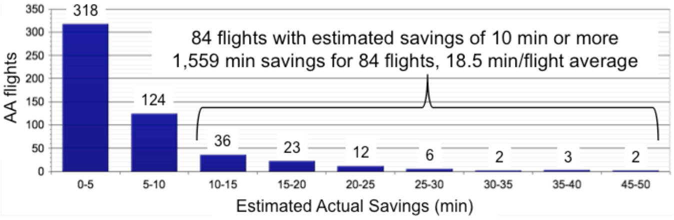

Figure 8. Distribution of AA flights by magnitude of estimated actual savings.

Fig. 8 groups the 526 AA flights with estimated savings attributed to DWR by the magnitude of their savings. This distribution illustrates the relatively high estimated savings for some flights. Such high savings for a flight could potentially prevent much more costly outcomes such as missed connections, flight cancellations, crews exceeding their crew-time limits, diversions, and customer inconvenience and dissatisfaction. Note that 84 flights realized an estimated actual savings of 10 min or more. The total estimated actual savings for these 84 flights is 1,559 min or 18.5 min/flight on average.

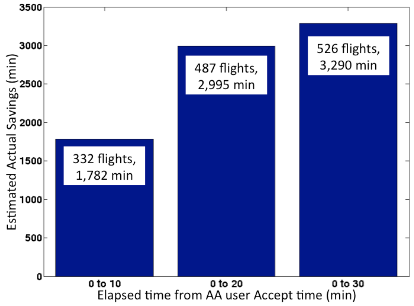

Figure 9. Estimated actual savings vs. elapsed time since AA user accept.

Fig. 9 breaks out estimated savings by elapsed time from Accept time to observed amendment time. Note that 91% of estimated actual savings for AA flights is attributed to route amendments that occur within 20 min of Accept time.

C. Estimated Actual Savings for AA Flights & non-AA Flights

In this section the estimated actual savings for AA flights is compared to that of non-AA flights using data from common traffic and weather samples. As discussed above, it is known that flights get some portion of savings opportunities identified by DWR through normal pilot requests and controller clearances. With DWR in use at AA we expect shorter elapsed times between DWR advisories and observed route amendments, and a greater percentage of advised savings for AA flights.

Each day, the DWR system stores route advisories computed for all flights (AA and non-AA). The post-run analysis then computes the flying time savings, or delay, associated with each observed route amendment that follows the first DWR advisory for every flight. Here the time of the first DWR advisory is the reference time, since we are comparing results for AA and non-AA flights, and non-AA flights do not have Accept times. Three parameters are of particular interest for this analysis: 1) elapsed time between the first DWR advisory and any observed route amendment for the flight, 2) savings (or delay) associated with each observed route amendment, and 3) ratio of observed amendment savings (or delay) to the potential savings for the first DWR advisory. This savings ratio seems more suitable for comparative analysis since flights are on different routes and impacted by weather differently.

Accepted AA flights and non-AA flights during the period May 9, 2014 to September 30, 2014 are analyzed. Adjacent Center processing started on 5/9/14, and the estimated actual savings analysis is more accurate with adjacent Center processing since some relevant route amendments (ones that occur within 30 min of the DWR advisory) do not occur until the flight crosses into an adjacent Center. Days selected for analysis are those where total potential savings for AA flights is high (greater than 200 min), and AA's use of DWR is at least moderate (5% or more of advised DWRs are accepted); 29 days[1] in 2014 meet these criteria. The 5% accept criteria ensures we compare AA and non-AA savings on days when DWR is being used, and high potential savings days correlate well with the presence of impacting convective weather.

Fig. 10 groups the savings ratios for all observed amendments by elapsed time from the first DWR advisory for the flight with separate groupings for Accepted AA flights and non-AA flights. For example, the first group includes amendments for Accepted AA flights that occur within 5 min from the first DWR advisory. The red bars (inside boxes) indicate the median savings ratio in the group, and the boxes indicate the variation of the 50% of savings ratio points closest to the median value (25% of points are above the median and 25% of points are below the median). Note in the 0-5 min elapsed time bin the median savings ratio for AA flights is about 1, and 25% of AA flights have higher savings ratios between 1 and about 1.2. For non-AA flights the median ratio is quite a bit lower, about 0.5, and 25% of savings ratios fall between about 0.5 and 1. These trends are similar out to 15-20 min elapsed time. The results in Fig. 10 show that AA flights where DWR was used generally get more savings sooner compared to non-AA flights.

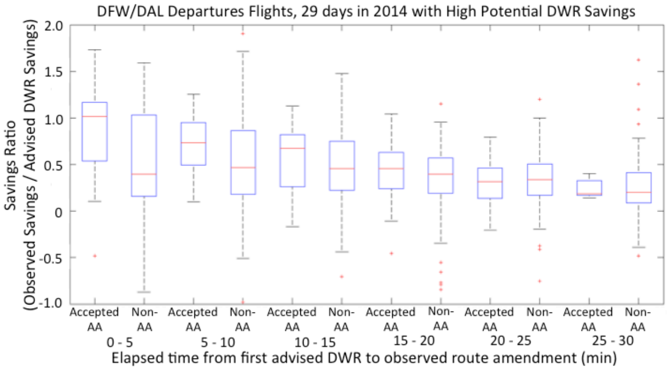

Figure 10. DWR savings ratio (observed/advised) for Accepted AA flights and non-AA flights over 11 common traffic and weather days.

Fig. 11 shows the overall average savings ratio (total observed savings / total advised savings) for Accepted AA flights, non-Evaluated AA flights, and non-AA flights. Savings are categorized by elapsed time from the first DWR advisory to observed amendments. Results are based on analysis of 1,118 AA and non-AA flights for which DWR advisories were computed over the 29 high potential savings days. The data show that AA flights where DWR was used realized about 20% more savings than other flights.

However, non-AA flights on routes similar those of AA flights where DWR is used likely realize some benefit from AA's use of DWR. For flights on similar routings, it is common for Center controllers to issue clearances to following flights that are similar to those previously issued to leading flights. An analysis this effect might reveal interesting results but is beyond the scope of this paper.

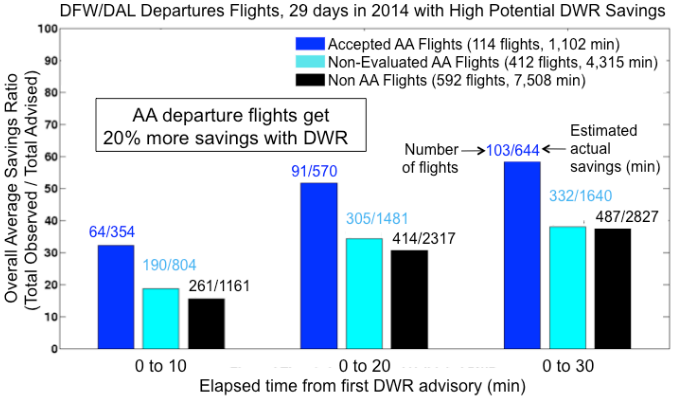

Figure 11. Overall average savings ratio for Accepted AA flights, non-Evaluated AA flights, non-AA flights over 29 high value days in 2014

IV. WEATHER MODELING AND ROUTE SELECTION PERFORMANCE

In this section we examine DWR system performance by measuring the extent to which proposed DWR routes rated Accept by AA users remain clear of weather beyond the point at which the user clicks Accept and the dispatcher sends an ACARS message to the flight crew. Since DWR accounts for the growth, decay, and movement of weather over time,

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[1] May 9, 12, 22, 23, and 24; June 1, 9, 10, 12, 19, 22, 23, 24, 25, 27, and 28; July 2, 3, 9, 10, 17, and 23; Aug 29; Sept 2, 6, 10, 12, 26, and 30.

proposed routes are predicted to remain clear of weather out to the two-hour CIWS/CWAM forecast horizon. In addition, the DWR user interface provides strong warnings if a user modifies a DWR route such that its trial trajectory conflicts with forecast weather.

The nowcast weather methodology described below evaluates DWR system performance by analyzing how well accepted DWR trajectories (predicted to avoid forecasted weather) remain clear of current weather if the aircraft were to fly the trajectories exactly as predicted by the system and accepted by AA users. The CIWS and CWAM weather models used by DWR update every 5 min and contain the current "nowcast" weather along with a 2-hour forecast at 5 min time steps. For the purposes of this analysis nowcast weather is assumed to be true weather. Since DWR automation uses the 70% forecast CWAM polygons as the basis for weather avoidance [2], the 70% nowcast polygons are used as the basis for detecting weather along accepted DWR routes. Only the trajectories associated with accepted DWR routes are analyzed for system performance because it was these accepted DWR routes that dispatchers sent to AA flight crews as route change proposals.

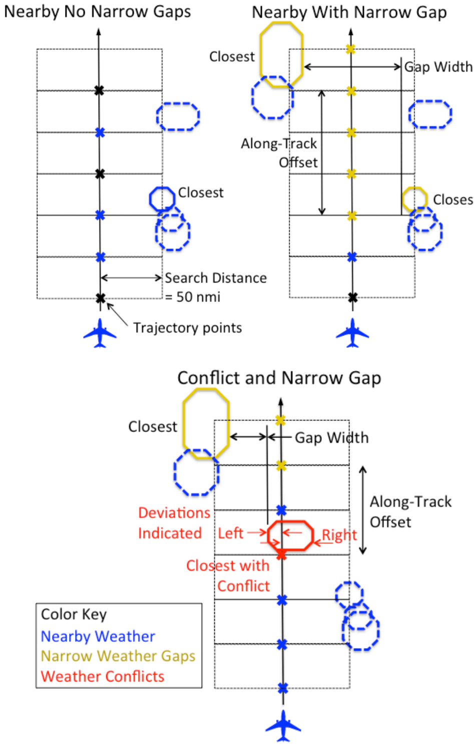

Figure 12. Analysis of nowcast weather on AA accepted DWR routes.

A number of weather factors are considered in the nowcast analysis. As illustrated in Fig. 12, metrics include: a) narrow gaps between nowcast weather cells where the Gap Width <= 50 nmi and the associated Along-Track Offset <= 50 nmi, b) conflicts with nowcast weather, c) minimum deviation from the DWR trajectory required to avoid a detected weather conflict, and d) forecast look-ahead time to narrow gaps and conflicts.

At each trajectory point from the Accept point to two hours downstream the analysis searches for nowcast polygons within 50 nmi on the left and right sides of the trajectory point. Close weather on one side of a trajectory without close weather on the other side (blue polygons in Fig. 12) is generally not considered an operational problem. However, close weather on both sides at the same or nearby trajectory points indicates a potentially narrow weather gap that should be avoided. A narrow gap is defined as a condition where nowcast polygons are detected on both sides of the trajectory at points within an along-track offset distance of one another (pair of yellow polygons in Fig. 12). In the common case where multiple gaps made up of different polygon pairs are detected within an along-track offset distance of one another, the minimum gap width is the basis for this analysis. Also note that in the nowcast analysis, a gap could be due to a conflict polygon and a nearby polygon (yellow and red polygons in Fig. 12).

In the operational trial system gap and offset parameters were initially set to 25 nmi and 50 nmi respectively. After a few DWR advisories that seemed a little too close to weather were observed, on July 24, 2014 the gap parameters were changed to 50 nmi width and 75 nmi offset.

To scope the analysis we choose data from that subset of days in 2014 where potential DWR savings for AA flights was high: greater than 200 flying minutes total, and AA's use of DWR was high: 50% or more of advised DWR routes were evaluated by AA users. Nine days in 2014 meet these criteria[2]. During these days, DWR routes for 180 flights were accepted by AA users.

Shown in Fig. 13 are (a) plots of gap width for detected nowcast weather gaps of width <= 50 nmi and (b) minimum indicated deviation needed to avoid a detected nowcast weather conflict. Both are plotted vs. elapsed time from AA user Accept time. Note if the weather forecast model was perfect, we would expect no points in Fig. 13a with detected nowcast gap width under 50 nmi (for cases where the trial system had its minimum gap parameter set to 50 nmi), and no nowcast weather conflicts (Fig. 13b). As expected, increasing the minimum allowable gap width and along-track offset parameters reduces the number of nowcast gaps detected.

Inspection of cases in Fig. 13a where gaps are detected shortly after Accept time (e.g., less than 10 min) suggests the weather cells are so close to the flight, and usually predominantly to one side of the flight trajectory, that the pilot would certainly ensure safe separation from weather. Note in Fig. 13b that most of the indicated deviations around nowcast conflicts are 10 nmi or less which is considered an acceptable level of deviation.

Fig. 14 shows a sample flight from Dallas, TX to Tampa, FL (circled Fig. 13a), and includes a screen shot of the accepted DWR route, and the associated nowcast analysis. The nowcast graph shows conflict polygons (red), gaps of less than 50 nmi (between orange polygons) and polygons within 50 nmi, but with no gaps (grey). For detected gaps, the minimum gap width and offset are indicated (text in nowcast

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[2] 3/28, 4/6, 4/13, 4/21, 5/22, 5/24, 6/1, 9/6, & 9/12/14.

plot). For detected conflicts, the right and left deviations required to avoid the conflict polygon are indicated. The 9.2 nmi gap is between a relatively large polygon to the North and a relatively small polygon to the South. The gaps in Fig. 14 suggest the potential utility of a gap deviation parameter used to determine if a small deviation could clear a gap completely, and/or use of the permeability metric [8] as a secondary check on a proposed DWR route. Note that the weather conflicts in Fig. 14 indicate minor deviations (0.2 nmi and 3.4 nmi) to the South. Fig. 14 (and Fig. 5) also shows how impacting weather polygons within parameter nmi (default = 25 nmi) of an active trial plan trajectory are shown in dashed blue on the DWR user interface.

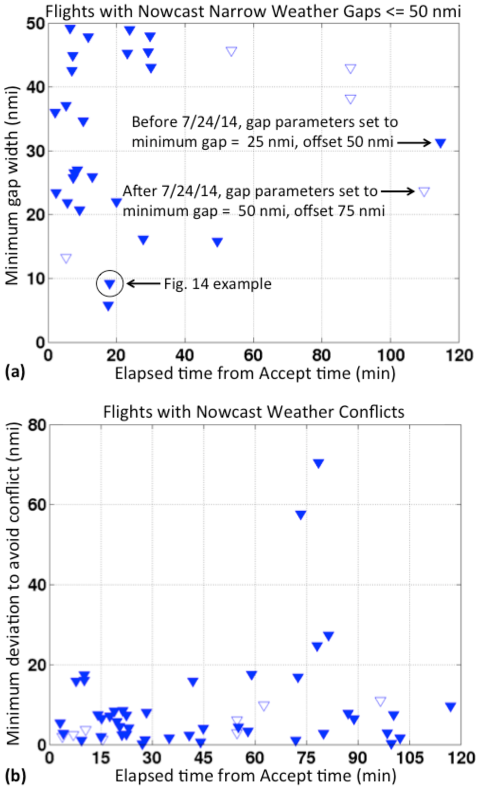
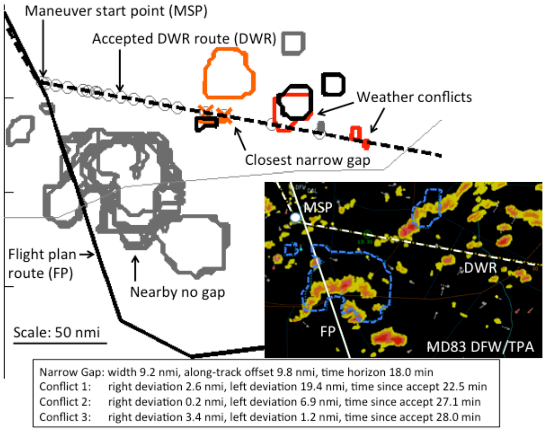


Figure 13. (a) Nowcast gaps width <= 50 nmi, (b) minimum deviation to avoid nowcast weather conflict, AA accepted DWR routes for 180 flights.



Narrow Gap: width 9.2 nmi, along-track offset 9.8 nmi, time horizon 18.0 min
Conflict 1: right deviation 2.6 nmi, left deviation 19.4 nmi, time since accept 22.5 min
Conflict 2: right deviation 0.2 nmi, left deviation 6.9 nmi, time since accept 27.1 min
Conflict 3: right deviation 3.4 nmi, left deviation 1.2 nmi, time since accept 28.0 min

Figure 14. Sample flight (DFW/TPA) showing screen capture of accepted DWR route and results of nowcast gap and weather conflict analysis.

The four conflict cases in Fig. 13b with large minimum deviations (about 25, 60, 70 nmi) all occurred on June 1, 2014. A playback of the traffic and weather data confirms that DWR routes were correctly computed in playback such that these conflicts do not occur. An analysis of the weather files computed in real-time on 6/1/2014 does not indicate any weather data processing delays. It is possible that the weather conflict detection processing slowed for some reason on this day. This will be investigated. In none of these cases were flights routed along erroneous routes.

V. SECTOR CONGESTION ANALYSIS

In this section we compare traffic congestion for the case where all flights fly the first DWR route advisory computed for the flight vs. the case where all DWR flights stay on their nominal flight plan routes. The metric used for comparison is the Monitor Alert Parameter, or MAP value, the FAA's primary sector congestion metric. Every sector in US airspace is assigned a MAP value which is the nominal number of aircraft controllers can safely handle at one time in the sector.

Red sectors are those predicted to be over capacity based only on trajectory predictions for in-flight aircraft. Yellow sectors are those predicted over capacity based in part on trajectory predictions for aircraft that have not yet departed. Red congestion predictions are more reliable since there is less uncertainly in predictions based on in-flight aircraft.

The traffic samples selected for this analysis are the top 30 days in terms of potential DWR savings for all ZFW flights over the period July 31, 2012 through September 30, 2014. Fig. 15 shows time spent in congested (red or yellow) sectors for 7,098 DWR flights flying their first advised DWR route vs. the same flights flying their Center flight plan routes that were current at the time the first DWR was advised. The results show that DWR trajectories spend 38% fewer minutes in red sectors and 20% fewer minutes in yellow sectors.

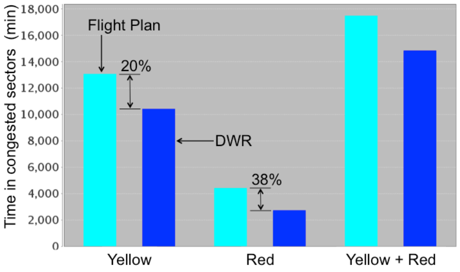


Figure 15. Time spent in congested sectors, DWR vs. Flight Plan trajectories.

In order to measure the effect of all flights flying their DWR routes, two FACET [18] simulation runs were conducted for each of the 30 traffic samples. In the first set of runs, the DWR runs, all flights with DWR route advisories were flown on the DWR route that was first identified for the flight. All non-DWR flights were flown on their actual observed Center flight plan routes. In the second set of runs, the baseline runs, all flights with DWR route advisories were flown on the Center flight plan route that was in effect at the time the first DWR route advisory was computed. For both sets of runs sector congestion was measured in the home Center (ZFW) sectors and in the first tier adjacent Center sectors, e.g., sectors in Kansas City, Memphis, Houston, and Albuquerque Centers. The metric for this analysis is the amount of time any sector spends in red or yellow Monitor Alert congestion status. The analysis uses all traffic in five Centers over 30 days including 7,098 flights for which DWR advisories were computed. Results show that the total time all sectors spend in congestion status is reduced by 19% with flights on DWR routes vs. nominal weather-avoidance routes.

Fig. 16 shows the Houston Center (ZHU) sectors that are in congested status for at least 5 min over the 30 days. Note ZHU sectors 95 and 97 are congested significantly longer with flights on their flight plan routes vs. their DWR routes. The largest difference in congested status for these sectors occurred on 5/12/2014. On this day the difference was due to a Command Center reroute for transcontinental flights (LEV East) that routed traffic directly through these two relatively large sectors on the South side of ZHU airspace. The DWR routes take the traffic completely out of these sectors.

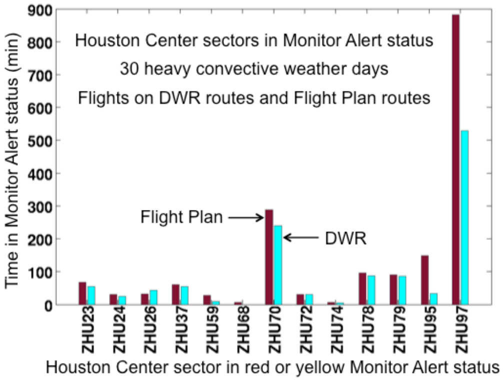


Figure 16. Time Houston Center sectors in congestion status over 30 heavy weather days, all flights on DWR routes vs. all flights on flight plan routes.

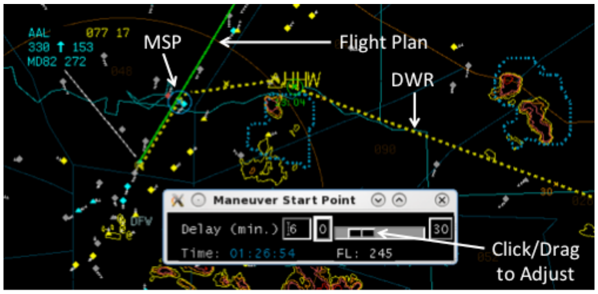
Flight plan vs. DWR congestion data, like that shown in Fig. 16, but for the other four Centers, looks much like that for most sectors in Fig. 16 (ZHU23, ZHU24, etc). There is little difference between flight plan and DWR congestion, and time in congestion status is around 50 min or less over the 30 days.

VI. IMPROVEMENTS AND LESSONS LEARNED

In this section we describe some of the more significant improvements that were incorporated into the DWR system based on feedback during the trial.

A. *Maneuver Start Point*

Early in the testing AA users identified the need for a maneuver start point (MSP) in the DWR trajectory modeling. Depending on dispatcher workload and other factors, the ATC Coordinator may need several minutes of coordination time before an ACARS message can be sent to the flight crew. A MSP (Fig. 17) located an adjustable number of minutes downstream of present position on the current flight plan trajectory enables users to see the effect of coordination delay on trajectory status parameters like weather proximity, flying time savings, traffic conflicts, and level flight status, which is particularly important for climbing DFW departures that may not have reached the high altitude airspace. An adjustable default MSP value is nominally set to 5 min downstream of present position, or for climbing flights, the first point beyond 5 min downstream at which the flight is predicted at or above FL240, the bottom of ZFW's high altitude airspace. All DWR advisories incorporate the default MSP. Once in trial planning, the user may adjust the MSP using click and drag inputs and assess the effect on status parameters. If the MSP is within 10 nmi of a flight plan fix, the MSP snaps to the flight plan fix.



Delay (min.) 6 0 30

Time: 01:26:54 FL: 245

Figure 17. Maneuver Start Point.

B. *Adjacent Center Traffic*

The need for adjacent Center traffic to supplement the home Center traffic was also identified early in the project. If FAA traffic managers are going to consider a large reroute for a flight through their Center, they need to start looking at the proposed reroute well before the flight reaches the Center boundary. Processing adjacent Center traffic also increases potential savings because for many flights the inefficient portion of the route segment spans multiple Centers, and starting the reroute sooner results in higher potential savings. Adjacent Center processing was installed on the AA DWR system on May 9, 2014. The limit region for return capture fix selection was not changed from that used for single Center operations [2], but eligible DWR flights must have either their flight plan route or their DWR route pass through the home Center (ZFW) airspace. Table 1 shows potential savings for over-flight traffic for a period in 2014 with adjacent Center processing and the same period in 2013 without adjacent Center processing. Over-flights, i.e., flights not landing or departing from home Center airspace, stand to gain the most potential benefit from adjacent Center processing.

Table 1. Potential DWR savings, over-flight traffic, adjacent & single Center

Adjacent Center or Single Center	Potential Savings (min)	Number of Flights	Average Savings (min/flt)	Flights with Potential Savings >=15 min
Adjacent 5/9 - 9/30/14	134,413	13,885	9.7	1,642
Single 5/9 - 9/30/13	50,486	5,262	9.6	643

C. *Narrow Weather Gap Detection*

A narrow weather gap detection function similar to that described in Section IV was added to the DWR software. The function includes two adjustable parameters, the minimum gap width and along-track offset (see Fig. 12). Any potential DWR solutions with gap and offset under these values are rejected. As discussed earlier, the gap and offset parameters are currently set to 50 nmi and 75 nmi respectively.

D. Command Center Reroutes and Special Use Airspace

Functionality to determine if a flight with a DWR advisory is impacted by an FAA Air Traffic Control System Command Center issued reroute, and to determine if a proposed, or modified, DWR route crosses Special Use Airspace (SUA) was added to the DWR software. First, using the Traffic Flow Management Data to Industry data [19], based on origin airport/Center and destination airport/Center pairs, each DWR flight is checked for the presence of an FAA imposed reroute. If a DWR flight is impacted, an alert is included in the DWR flight list, and the corresponding reroute information, including its published time, is presented on the user display. Many cases were noted where the published time was about 2 hours prior to the current time.

Second, if a current flight plan or proposed DWR crosses a scheduled SUA (e.g., Military Operation Area, Restricted Area, etc.), the corresponding SUA is highlighted on the sector congestion window(s). The user can obtain additional information about the SUA (e.g., in/out times, schedule time, altitude range). The SUA schedule is obtained from the FAA's website (http://sua.faa.gov).

VII. CONCLUDING REMARKS

The most important benefit of the DWR concept is to let automation continuously and automatically analyze active flights to find simple route corrections that can save significant time and fuel. Airline and FAA operators are especially busy during weather events. It's more effective to let automation find high-value route correction opportunities.

A strong partnership between NASA, American Airlines, and the FAA has enabled timely testing and validation of the DWR concept and prototype in real air traffic operations. Several other US airlines and US aerospace companies have expressed strong interest in the DWR tool. NASA has licensed the DWR software (non-exclusively) to one large aerospace company and other licenses are pending.

Feedback from American Airlines managers and dispatchers has been very favorable. The two most prevalent and consistent suggestions have been to have DWR advisories posted directly to dispatcher displays, and to incorporate DWR trajectory analysis methods into FAA automation for selecting and correcting weather avoidance routes for all flights.

Potential DWR savings are significant, about 100,000 wind-corrected flying minutes for 15,000 flights in 2013, or about \$6 million in airline operating costs in one en route Center. Trial results indicate an actual savings of 3,290 flying minutes for 526 AA revenue flights over the period January 1, 2013 to September 30, 2014.

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