

STRATEGIC AIRSPACE CONSTRAINT ANALYSIS AND ENVIRONMENTAL IMPACT OF DYNAMIC WEATHER ROUTES

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Abstract

This paper presents analyses of the strategic airspace constraints and the environmental impact of Dynamic Weather Routes automation. The Dynamic Weather Routes are flight plans along which an aircraft can save a user-specified amount of wind-corrected flying time compared to the currently active flight plan. The strategic airspace constraints address sector congestion and Special Activity Area traversal along the two flight plans. The environmental impact considers fuel burn and emissions (e.g., hydrocarbons, carbon dioxide, etc.) along the two flight plans. A comparison of airspace constraints and emission values between the as-flown tracks of the aircraft and the suggested Dynamic Weather Route is presented. The results are for August 1 through October 31, 2012, when NASA's Dynamic Weather Routes software was running continuously at the American Airlines System Operations Center in Ft. Worth, TX. The results indicate that Dynamic Weather Routes not only save flying time and fuel, but help reduce traffic congestion and harmful emissions as well.

Introduction

The Air traffic management system in the United States often incurs weather related delays. During convective weather season, flight delays of one or more hours are common. To avoid convective weather, the FAA often uses weather avoidance routes to manage traffic. The air traffic managers and flight dispatchers are busy handling flight schedules during those events, and sometimes the required avoidance routes are not removed resulting in unnecessarily long travel times. In order to assist the operators during such events, NASA has developed the Dynamic Weather Routes (DWR) system [1 and 2]. DWR is an automated search engine, which continuously evaluates time saving opportunities for aircraft and presents these in a list to the user as an alternate route advisory. The user can

then choose to evaluate, accept or reject that advisory. If an airline's Air Traffic Control (ATC) Coordinator and flight dispatcher accept it, the advisory could be uploaded to the pilot, who in turn could request that route clearance from a controller. Currently, the ATC Coordinators or dispatchers at major airlines in the United States do not have automation that continuously evaluates such time and fuel saving opportunities, while checking against airspace constraints and environmental emissions.

Several other efforts are reported in literature to provide support for airborne rerouting around airspace constraints. Taylor and Wanke [3] presented operationally acceptable routes for rerouting around airspace constraints using a simulated annealing method. Wanke, et al. [4] reported on using previously flown routes for flight option generation for the en route phase. Their simulations indicate that the flight option generation process can produce alternative routes that are suitable for use by an automated en route congestion management system. However, these approaches are applicable for rerouting groups of aircraft and are not from an individual flight perspective. These approaches serve more of an airspace service provider purpose, and are focused on situations where aircraft must deviate to avoid weather. DWR finds opportunities for efficient weather-avoidance routes even when the current route of flight is clear of weather. Mayhew and Manikonda [5] presented a Constrained Airspace Rerouting Planner (CARP), which provides users several capabilities needed to model and simulate strategic and tactical rerouting algorithms for time varying constrained regions in the en route airspace for the purpose of studying and evaluating future concepts. CARP does not operate in real-time and has not been tested in an operational environment.

The DWR system developed at NASA Ames Research Center operates in real-time on individual flights for airline operations. This paper presents the results of aircraft flying time savings for airspace

congestion and Special Activity Airspace (SAA) constraints, along with the fuel and emissions values of operationally accepted DWR advisories by American Airlines ATC Coordinators and dispatchers [6] over three months of evaluation. The Center TRACON Automation System (CTAS) [7] and the Future ATM Concepts Evaluation Tool (FACET) [8] were integrated together for this purpose. CTAS continuously evaluates routes for wind-corrected flight-time savings and proposes alternate weather-avoiding routes. FACET computes the airspace constraints, fuel usage, and emissions for those routes. Sridhar, et al. [9] presented the modeling and simulation of the impact of air traffic operations on the environment. The analysis of DWR advisories for fuel burn and emissions was conducted using the approach described in that research. For their computations, the authors used the Aviation Environmental Design Tool (AEDT), the International Civil Aviation Organization (ICAO) data bank, and the Boeing Fuel Flow Method 2 (BFFM2).

The paper first summarizes the method of generating DWR advisories next. The analysis and results for strategic airspace constraints is presented after that. The details of the fuel burn/emissions model and the consequent results are presented in the environmental impact section. The paper ends with concluding remarks.

DWR Generation

As mentioned before, CTAS and FACET are integrated together to create the Dynamic Weather Routes system. CTAS is a real-time Air Traffic Control Decision Support Tool that generates trajectories using the real-time en-route 12-second data and constantly searches for direct routes for flights, which would benefit more than a user-specified number of minutes (e.g., 5 minutes) of flying time by removing dog-legs in its flight plan. The Convective Weather Avoidance Model (CWAM) [10] provides weather avoidance fields generated by MIT Lincoln Labs through research initiated by

NASA. It provides probability polygons that are used for representing the convective weather regions (including intensity and storm heights) that pilots tend to avoid. The conflict resolution algorithm, within the Automation Airspace Concept (AAC) developed at NASA is used for generating lateral routes around the CWAM polygons. If the time-saving direct route intersects one or more CWAM polygons, the AAC algorithm generates a reroute around the weather with one or two auxiliary waypoints. This newly generated flight plan becomes the DWR advisory. The currently active flight plan and the suggested DWR advisories are both presented to the ATC Coordinator. If they find it acceptable, they suggest it to the airline flight dispatcher handling the flight, who can send a message to the pilot to request clearance using today's standard procedure.

In Figure 1, the display used by American Airlines ATC Coordinators is shown. The display is split mainly in three parts. The big window on the left is the CTAS Plan-view Graphical User Interface. In this window, a flight's 'Current flight plan route' is shown in a solid-white line and the proposed 'DWR' advisory is shown in dashed-white line. The downstream 'Capture fix' used to compute the direct route and the 'Auxiliary waypoint' used to find the route around CWAM polygons, are displayed as well. The flights that have sufficient user-adjustable flight-time savings are displayed in the 'DWR list' on the top-left part of the big window. The long window at the bottom shows the current flight plan route and DWR advisory, along with time-savings for various downstream fixes at left. This is labeled as the 'Capture fix menu & flying time saving' in the figure. The two windows on the right show the sector congestion for the current flight plan route (top) and the DWR advisory (bottom). The corresponding sector congestion values (as red or yellow sectors) for those routes are shown within. Red sectors are those where the congestion is caused by all aircraft are currently airborne, while yellow sectors have proposed departure aircraft causing predicted congestion.

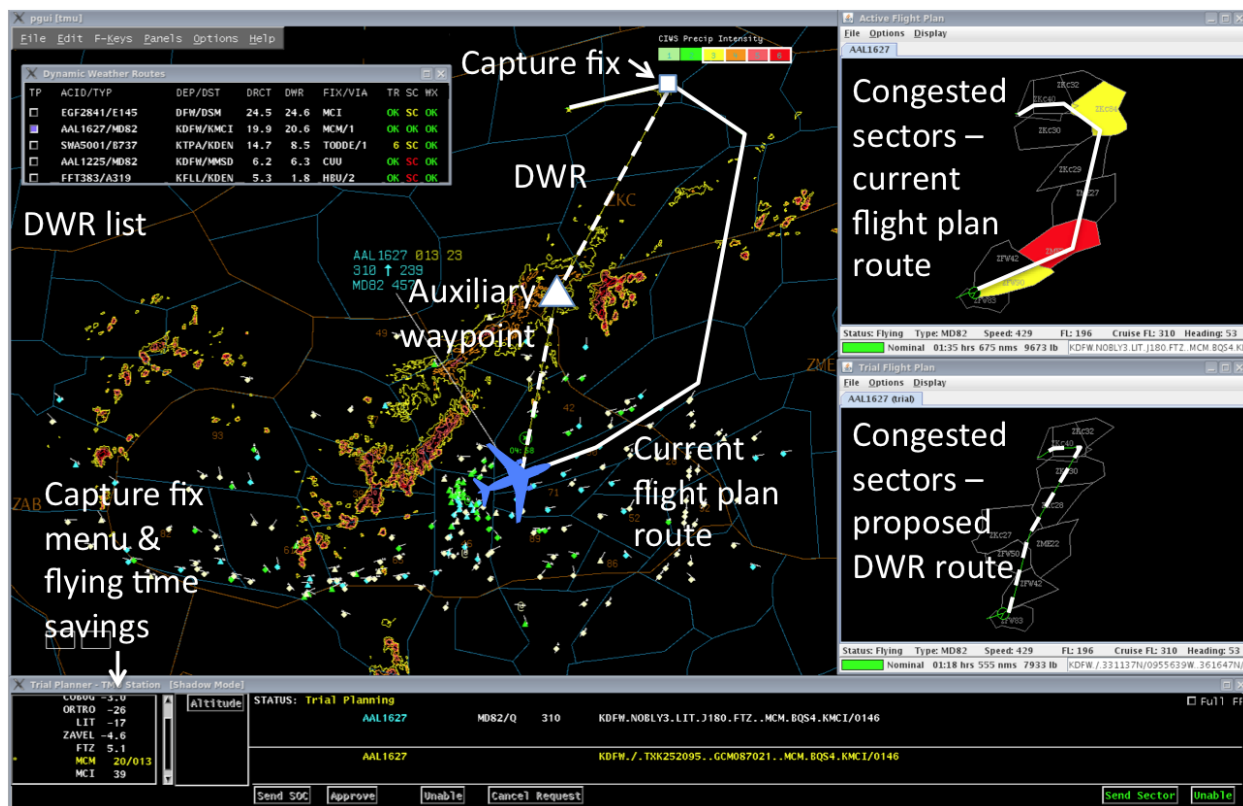


Figure 1. The Dynamic Weather Routes Display

The DWR system has been running continuously at American Airlines (AA) SOC in Ft. Worth, TX since August 2012. The discussion presented in subsequent sections pertains to a period of time between August 1 and October 31, 2012. During that time period, 637 DWR advisories were proposed, 156 were evaluated by AA personnel, and 83 were rated acceptable by AA personnel. A description of operational testing of DWR and analysis of time savings is presented in [6]. The analysis of airspace constraints, fuel burn, and emissions is described next. It should be noted that for all results presented, the as-flown and simulated DWR tracks were compared from the aircraft track position in Center airspace at which the AA user rated the advisory acceptable until the aircraft reached its destination.

Strategic Airspace Constraints

This section presents the violation of airspace constraints by DWRs. The metrics considered are airspace sector congestion and the Special Activity Airspace (SAA) traversal. In the following subsections, first the sector congestion is examined, from an air traffic manager's perspective. Then, the sector congestion is presented as seen by individual flights and relevant for an airline operator. The SAA traversal is discussed last in this section.

Sector Congestion

When DWR advisories are computed for flights, sector congestion is not included as a constraint but is presented for the ATC Coordinator's consideration. The sector congestion information is obtained using the predictive capability of FACET. In [2], a sector congestion analysis was presented for one week's data. Here, all DWR advisories proposed to AA

personnel were analyzed from a sector congestion perspective. A congested sector is defined as one that is at or above its Monitor Alert Parameter, a nominal number of aircraft that an air traffic controller working the sector can safely handle.

In Figure 2, all sectors are shown that were congested when a flight track (as-flown in red bars and DWR in blue) traversed through it. In all, there were 57 such sectors accounting for all the 637 proposed DWR advisories during the evaluation period of Aug. 1 through Oct. 31, 2012. Out of those

57 sectors, there were 14 sectors (25%) which had more as-flown tracks fly through them and there were 3 sectors (5%) which had more DWR track traversals. All other sectors had no difference between the two situations. Overall, the as-flown tracks traversed congested sectors for 167 one-minute instances (almost three hours) more than DWR tracks. The reason for reduced congestion is that DWR advisories take flights out of nominally congested areas and fly them through openly available airspace.

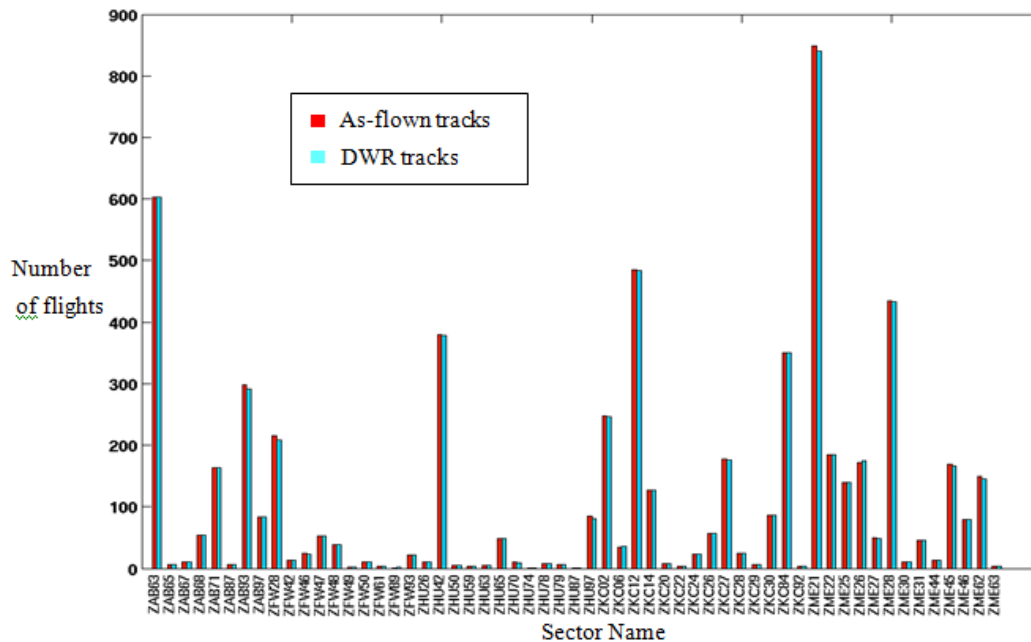


Figure 2. Congested Sectors Traversal for All Flights

Flight Impact

During the evaluation, 71 of the DWR advisories shown on the DWR list were accepted by AA users either as with or with some modifications. There were 12 additional flights for which AA users created and accepted reroutes starting from the active flight plan, e.g., without a DWR advisory. The discussion presented next is for these 83 flights. An analysis of user comments and Center Host flight plan amendments suggests that 11 of these flights were cleared to fly the DWR advisory route from air traffic controllers [6].

Out of the total 83 flight routes considered for congestion analysis, there were 8 flights which were rated green, 10 flights were rated red, and the rest, 65 flights, were rated blue. These are shown in Figure 3. An accepted DWR advisory for a flight is given a green rating if the DWR advisory is predicted to go through no congested sectors but the flight’s as-flown tracks went through congestion (likely along its active flight plan). On the other hand, if the accepted DWR advisory is predicted to go through one or more congested sector(s), while the as-flown flight tracks did not go through any congestion, the DWR advisory is given a red rating. If a flight’s as-flown track did not go through congestion nor was the

accepted DWR predicted to, the flight's DWR advisory is rated blue. Alternately, if the as-flown track went through congestion, and the DWR was predicted to go through that congestion, the flight's DWR advisory is rated blue as well. Since this rating requires the congestion information for the as-flown tracks, it can be computed in post-operations only. Out of the 10 flights rated red, two flights were currently in a congested sector. One flight was predicted to be in a congested sector 18 minutes later. The other seven flights had congestion predicted 30 minutes or later. It should be noted that AA operators were advised to accept DWR advisories for flights that had no congestion predicted or congestion predicted 30 minutes or later only. This was to prevent a controller being asked for requests when he/she was already working high traffic density. On the other hand, as-flown tracks of eight green-rated flights went through congested sectors, but were predicted to be free of congestion if they had traveled along the DWR advisory. Thus, DWR suggested flights could have saved time, and helped the traffic manager and controller by reducing excessive traffic through their sectors. The majority of the other flights did not encounter congestion in as-flown tracks nor would have traversed congested sectors along accepted DWR advisories.

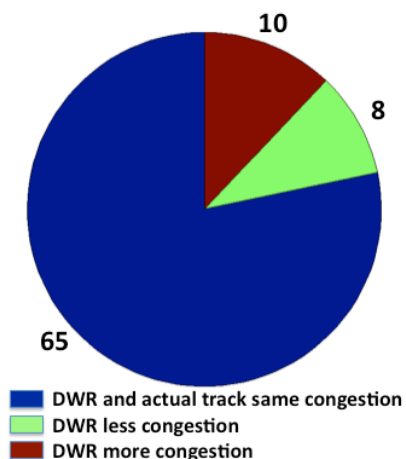


Figure 3. Congestion Encounters for 83 DWR Advisories

Special Activity Airspace (SAA) Traversal

SAA are regions of airspace that the FAA blocks off for special use (e.g., military operations,

etc.) Among the 83 flights, there were no as-flown tracks that traversed through any SAA. There were two DWR flights that were proposed to go through one SAA each. These traversals were predicted 61-minutes ahead for a 2-minute traversal and 63-minutes ahead for a 3-minute traversal. Considering the brief traversal interval, this was not an issue.

The next section presents the environmental impact assessment of the proposed DWR advisories.

Environmental Impact

From [6], DWR advisories that were accepted by AA represented a potential savings of 483 minutes of flying time for the same 83 flights over a 3-month period. The environmental impact of those 83 flights is presented in this section.

Time and Fuel Burn

In order to assess the environmental impact, the modeling described by Sridhar, et al. [9] was employed for this research. This modeling is embedded within the FACET software and was used for analysis of DWR advisories.

The Base of Aircraft Data (BADA) [11], which is used by FACET for obtaining speed and climb/descent rates, also contains the fuel burn model. It uses the aircraft parameters, including aircraft type, mass, altitude, and speed to compute the fuel burn. Based on the flight altitude and speed, the climb, cruise, descent-idle, descent-approach, and descent-landing stages are determined.

The following equation is used to calculate the fuel burn (FB in kilograms) for climb, descent-approach and descent-landing stages.

$$FB = SFC * T * t, \tag{1}$$

where, SFC is the thrust specific fuel consumption in kg/min*kN,

T is the thrust in Newtons, and

t is the elapsed time in minutes.

For the cruise phase, the fuel burn is

$$FB = SFC * T * C_{fc} * t, \tag{2}$$

where, C_{fc} is the cruise fuel flow factor. For the descent-idle phase, the fuel burn is

$$FB = C_{f3} (1 - h/C_{f4}), \quad (3)$$

where, C_{f3} and C_{f4} are descent fuel flow coefficients, and h is the altitude in meters. The details of thrust specific fuel consumption for jets and turboprops, as well as the C_f coefficients are provided in [9].

Figure 4 shows the flow chart for computing fuel burn and emissions (to be discussed in the next section) computations in FACET software. The aircraft information is ingested in the Aviation Environmental Design Tool (AEDT) components embedded within FACET. The fuel burn rate from the model is provided for each trajectory update step to FACET, which then computes the incremental and total fuel burn for each trajectory.

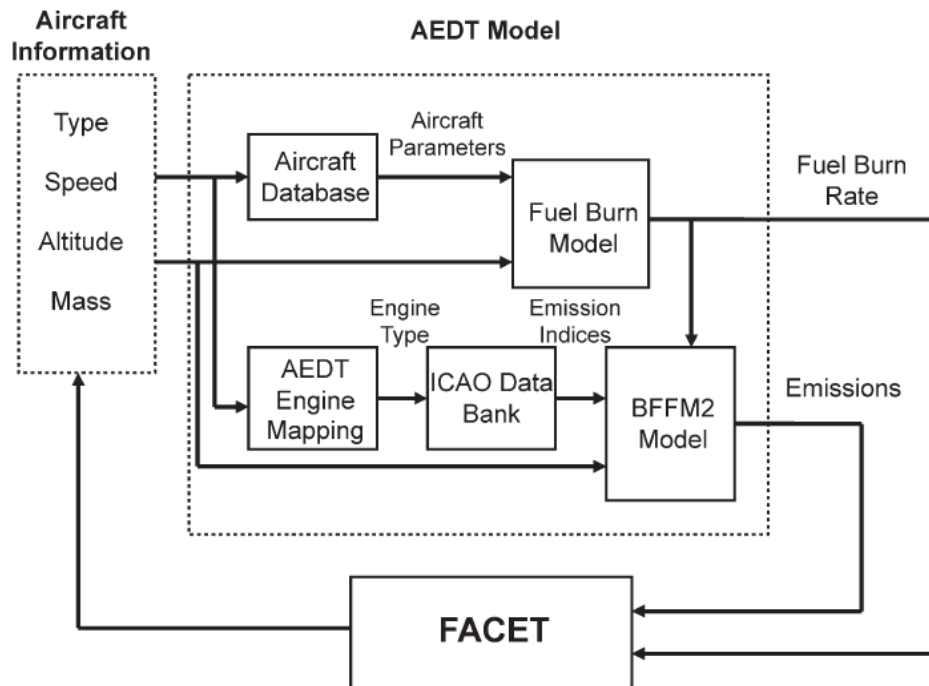


Figure 4. Fuel Burn and Emission Computation Flow Chart

The initial results of fuel burn and emissions computations showed significant differences in the flight altitude and ground speed between as-flown tracks and DWR simulated tracks in FACET. These resulted in differences in descent profiles as well as emission coefficients. The differences prompted improvements in trajectory modeling for this analysis so the time, fuel burn, and emissions computations were in closer agreement between the DWR simulated and as-flown trajectories. The modifications are reported in the Modeling Improvements sub-section below and were incorporated in results presented here.

The time savings are calculated using recorded air traffic data in FACET. The National Oceanography and Atmospheric Administration provided Rapid Refresh wind data were used for all results presented here. In Figure 5, the percent reduction in time (black) and fuel burnt (blue) with DWR advisories is shown as a function of each of the 83 AA-acceptable trajectory flights. The graph has been ordered first as decreasing % reduction in time, and then the fuel burn savings are plotted for the same aircraft list (along x-axis). One would expect that the fuel burn savings would vary linearly with time savings, small modeling variations of DWR trajectories (variations in observed wind) reflect a non-monotonic reduction. It is seen that for aircraft numbers 66, 71, and 83, the

fuel burn savings are negative. For the first two cases, differences in airspeed computation were responsible, presumably a higher headwind. The last aircraft (#83) was cleared for another direct, downstream of the DWR capture fix. For all 83 flights, the average time and fuel savings were 6% (441 minutes) and 8% (448 kgs), respectively.

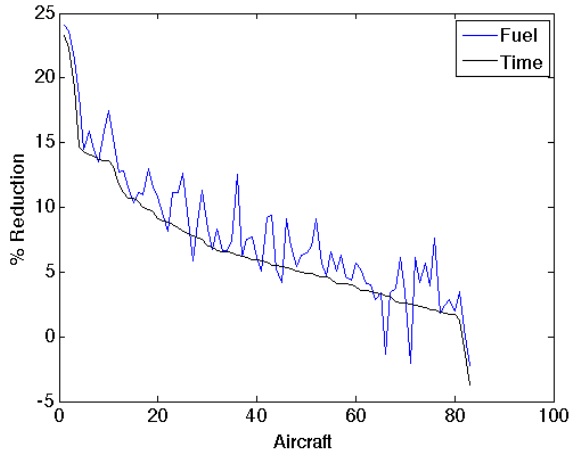


Figure 5. Time and Fuel Burn Savings for Each Aircraft

Emissions

In order to analyze the reduction of aircraft emissions, the AEDT Engine Mapping, International Civil Aviation Organization (ICAO) data bank, and Boeing Fuel Flow Method 2 (BFFM2) were used, as shown in Figure 4. For the purpose of this research, the emissions computed are carbon dioxide (CO₂), water (H₂O), nitrogen oxide (NO_x), sulphur dioxide (SO₂), carbon monoxide (CO), and hydrocarbons (HC). Once the fuel burn (FB) values are computed based on Equations (1), (2), and (3), the emissions can be computed using the equation set (4) as follows:

$$\begin{aligned}
 E_{CO_2} &= 3155 * FB \\
 E_{H_2O} &= 1237 * FB \\
 E_{SO_2} &= 0.8 * FB \\
 E_{NO_x} &= E_{INO_x} * FB \\
 E_{CO} &= E_{ICO} * FB \\
 E_{HC} &= E_{IHC} * FB
 \end{aligned}
 \tag{4}$$

The first three equations for CO₂, H₂O, and SO₂ are directly proportional to fuel burn values. The emissions for NO_x, CO, and HC are functions of emissions indices (EI). Reference 9 provides a description of these indices and equations to compute their values. Figure 6 shows the % reduction in the first four parameters. Note that since CO₂, H₂O, and SO₂ are directly proportional, the % reduction shows them overlapped and are shown in green color in Figure 6. The NO_x values are shown in yellow color, while time savings are shown in black for reference. Again, aircraft numbers 66, 71, and 83 show up with negative reduction values due to same reasons mentioned above for fuel burn values. The average savings for CO₂, H₂O, SO₂, and NO_x were all 8%. The values for these savings were 1412 kgs, 554 kgs, 358 gms, and 6.6 kgs, respectively.

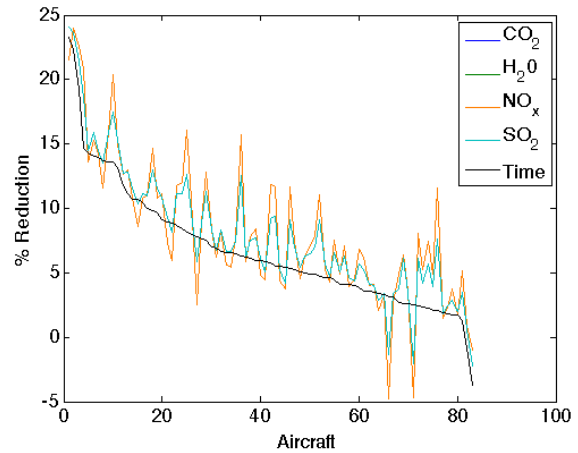


Figure 6. Fuel Emissions % Reduction for Each Aircraft

The non-linear nature of the emission indices (EIs) for CO and HC is due to its dependence on the fuel burn, temperature and pressure conditions, Mach number, and reference emission indices. The CO and HC reduction values were computed for each of the 83 flights and are shown in Figure 7 in blue and green, respectively. It is interesting to note that the two aircraft numbered 66 and 71 do not show up with negative % reduction values. It was observed that those two aircraft had higher headwinds close to their destination and the CO/HC emission coefficients are very sensitive to descent rates. The only outlier is aircraft #83, and as explained earlier as receiving another shortcut downstream of DWR capture fix, which aided the efficiency of the as-flown tracks.

The average savings for CO were 7% (914 gms) and for HC were 6% (184 gms).

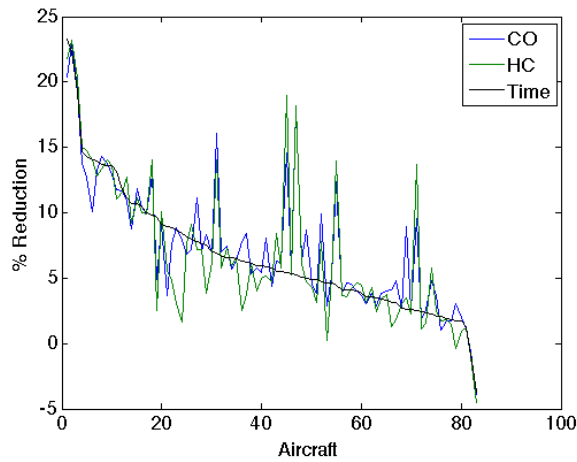


Figure 7. CO/HC Emissions % Reduction for Each Aircraft

Modeling Improvements

As mentioned earlier, considering the large differences of time, fuel burn, and all six emissions

observed in earlier research, the simulated tracks for DWR advisories in FACET were investigated. It was observed that the as-flown tracks (altitude and ground speed) of flights varied significantly over time. The altitude and ground speed variations from the as-flown tracks were used to make the modeling of the simulated DWR track profiles more representative of what the aircraft would have flown (shown in Figure 8 and described later).

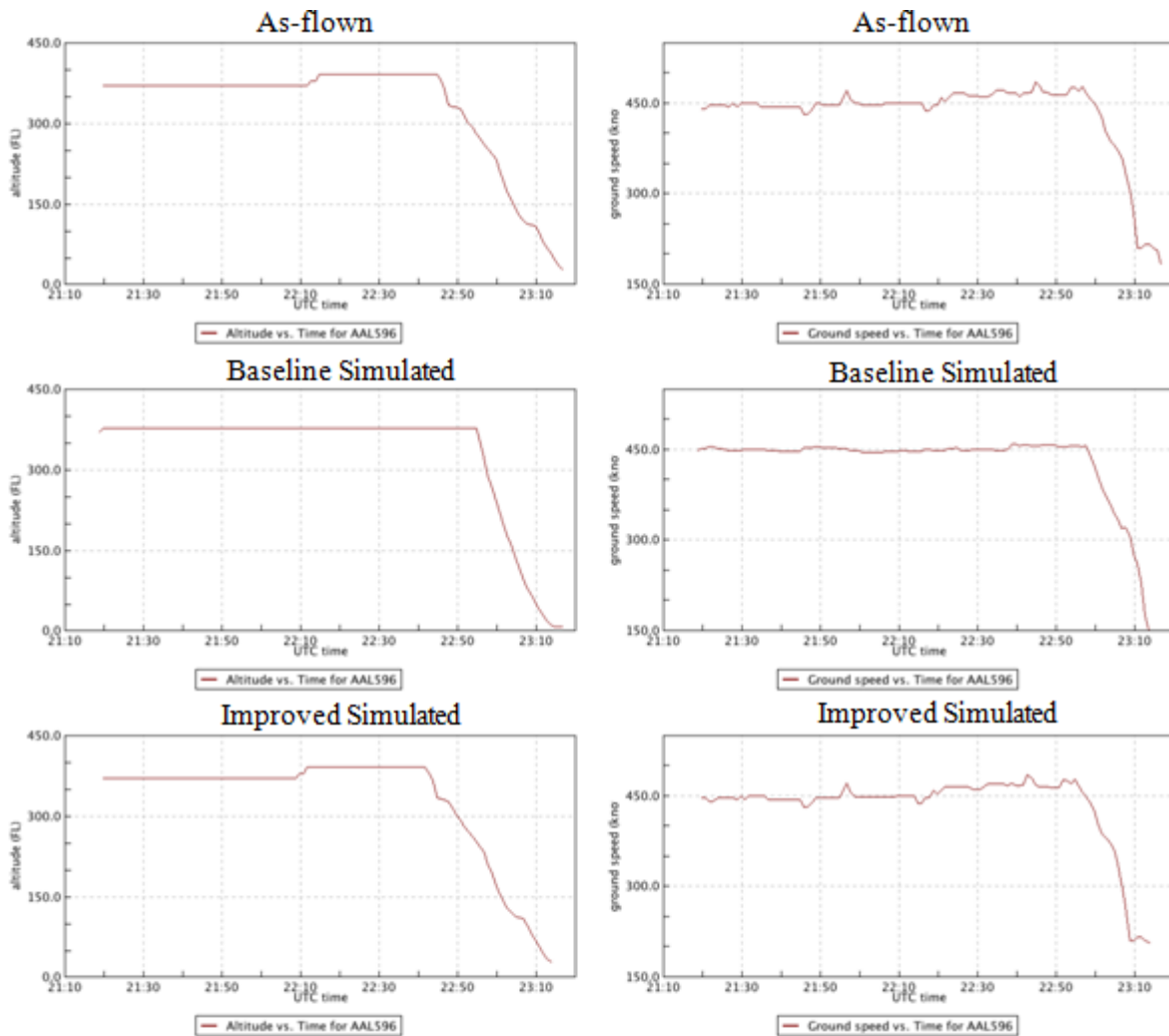


Figure 8. Comparison of Altitude and Speed Profiles

The fuel burn and emissions results from the modeling were found to be highly sensitive to variations in altitude and ground speed profiles, and these profiles of the simulated aircraft flying the DWR advisories differed significantly from the as-flown profile. The emission results for the DWR advisories were improved by simulating the flight of the aircraft at the altitudes and ground speeds of the actual or as-flown tracks.

Figure 8 presents this improvement for one of the 83 flights. On the left side, the altitude profiles are shown and on the right side, the ground speed profiles are presented. The top, middle, and bottom plot shows the as-flown, baseline simulated in FACET, and improved FACET simulation tracks. As

can be seen from the altitude and ground speed plots (compare top and bottom plots), the matching described above works well for improved simulation where the times, along with descent profiles look very similar to the top profiles.

The as-flown track times are mostly longer than the DWR track times. The length of the DWR flight plan is determined in FACET. An improved profile was simulated to replicate the as-flown tracks but along the DWR advisory and with the DWR advisory route travel time. The longest time intervals of constant altitude and ground speed in as-flown tracks were noted. The aircraft were flown along the DWR advisories simulated with those altitude rates and

ground speeds used in FACET, but with shorter durations to accommodate the difference in lengths.

Ordinate values in Figure 9 show the improvement due to this modified modeling on the HC and CO profiles. Again, the top, middle, and bottom plots are for the same tracks as the altitude and ground speed profiles shown in Figure 8. It can be seen that the top profile (for as-flown trajectory), and the bottom profile (for simulated tracks on the DWR advisory flight plan route), appear very similar.

Concluding Remarks

Dynamic Weather Routes (DWR) is a system that identifies reroute opportunities for shorter time- and fuel-efficient routes around weather. Integrating the Center-TRACON Automation System and the Future ATM Concepts Evaluation Tool, and utilizing the Convective Weather Avoidance Model polygons, the DWR system proposed 637 reroutes for a total potential savings of 5274 minutes of flying time. Of those, American Airlines (AA) Air Traffic Control Coordinators evaluated 156 flights and found 83 flights with acceptable DWR reroutes, for a total potential savings of 483 minutes. These results are for three months of data from August 1 through October 31, 2012 when the DWR system was running continuously at AA System Operations Center in Ft. Worth, TX. This paper presented a flight traversal comparison of the sector congestion, Special Activity Airspace (SAA), fuel burned, and emissions data between the as-flown tracks and DWR simulated tracks in FACET.

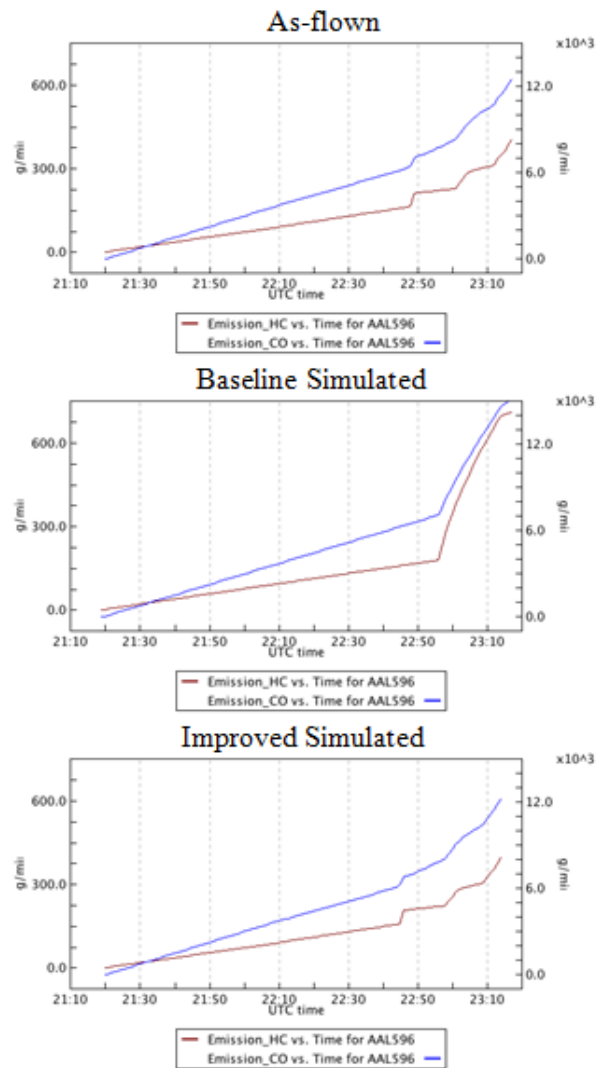


Figure 9. Comparison of HC and CO Profiles

It was found that if all of the AA accepted routes were to be cleared to fly on proposed DWR advisories, the sector congestion would have been at the same level as what happened in reality or lower, in 95% cases. Only two out of 83 flights were suggested routes that would have taken the flight into Special Activity Airspace, each for less than three minutes, and the traversal predicted more than an hour out. Also, Dynamic Weather Routes are generally shorter than their active flight plans, therefore they result in fuel and emissions savings as well. Generally, the emissions are related to the fuel burn rate. For all 83 flights, the analysis presented that more than 448 kgs, roughly, 8%, of fuel could have been saved. Corresponding numbers are

available for reduced emissions of CO, CO₂, HC, NO_x, and SO_x. Each of these are reported to be between 6% and 8% for the 83 AA accepted DWR advisories for the three-month period.

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