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The Efficient Descent Advisor: Technology Validation and Transition

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NASA recently completed the development and testing of the Efficient Descent Advisor (EDA) – a trajectory-based tool for en route air traffic controllers that computes Optimized Profile Descent (OPD) solutions designed to minimize aircraft fuel consumption and associated carbon dioxide emissions while maximizing airspace throughput. EDA was developed and refined through a series of high fidelity Human-in-the-Loop (HITL) simulations, carried out in a three-year effort with the FAA and Boeing known as 3D-Path Arrival Management (3D-PAM). A final simulation was carried out to assess potential benefits using a prototype that reflected a culmination of previous design decisions. The simulation compared EDA against baseline operations in which controllers were provided with scheduling automation alone, representing metering operations today. For added fidelity, the simulation included models of trajectory prediction uncertainty. Results showed that EDA enabled a 92% improvement in the accuracy by which controllers delivered aircraft to the terminal airspace boundary in conformance with metering schedules. In addition, with EDA, controllers were able to accommodate overtake maneuvers en route without adjustments to the optimal arrival sequence. Furthermore, EDA was shown to reduce fuel consumption in transition airspace by 110 lbs per flight, averaged for all aircraft types and traffic scenarios, with substantially more fuel savings observed for busier traffic conditions and larger aircraft types. Reductions in controller workload were also observed along with a 60% reduction in the number of required maneuver instructions between controllers and pilots. Results from this simulation and previous experiments, together with prototype software and design specifications, were delivered to the FAA for transitioning EDA towards operational deployment.

I. Introduction

ACCOMMODATING efficient arrival operations under challenging traffic conditions is a key objective for air-transportation modernization efforts taking place in the United States and throughout the world.[1] Efficient operations can be described as those that maximize system throughput while minimizing fuel consumption, environmental emissions and noise. An arrival trajectory that maximizes efficiency within operational constraints is referred to as an Optimized Profile Descent (OPD). These trajectories, where possible, involve a continuous descent at low engine power from cruise altitude to the final approach fix.

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The ability of pilots to plan and execute continuous descent trajectories through their onboard Flight Management System (FMS) has been well demonstrated in the field. Examples include the CASSIS flight trials at Stockholm[2] and on-going Tailored Arrivals operations at San Francisco and Los Angeles.[3] The challenge, however, is to conduct these operations in the presence of traffic and airspace constraints. Today, continuous descents are typically precluded or disrupted during moderate to heavy traffic conditions by controller actions required to separate, schedule and sequence aircraft for arrival. These frequent, tactical control actions include temporary altitude assignments, speed changes, lateral vectoring, and airborne holding. While such actions serve well to manage throughput and separation, they impede an otherwise continuous descent to the runway. For efficient arrival operations during busy traffic conditions, trajectories must be planned in a manner that considers capacity and airspace constraints.

Scheduling automation for maximizing arrival throughput in the presence of capacity constraints was previously developed by NASA as a component of the Center TRACON Automation System (CTAS) and is now deployed at each Air Route Traffic Control Center (ARTCC) in the United States. This technology – the Traffic Management Advisor (TMA) – computes time-based metering schedules and sequences for aircraft entering terminal airspace over designated meter fixes at the Terminal Radar Approach Control (TRACON) boundary.[4] Today, controllers are provided with TMA scheduling information on their radar display, but they have no automation to assist them in efficiently controlling aircraft to those schedules. Without additional automation, controllers must resort to the aforementioned tactical control techniques for meeting TMA schedules while maintaining separation.

In recent years, research at NASA Ames has combined TMA scheduling at the TRACON boundary with additional, optimized scheduling within the TRACON itself for enabling efficient descents to the runway during capacity-constrained conditions.[5,6] This automation concept, referred to as the Terminal Airspace Precision Scheduling System (TAPSS), requires that ARTCC controllers first deliver aircraft accurately and precisely to meter fixes located at the TRACON boundary in accordance with TMA schedules.

NASA has developed the Efficient Descent Advisor (EDA) to allow ARTCC controllers to perform metering operations while avoiding conflicts and keeping aircraft on efficient arrival trajectories managed through an FMS.[7] This technology was developed with the goal of near-term field deployment through a collaborative government/industry effort known as 3D–Path Arrival Management (3D-PAM). The effort began in 2008 and included NASA, FAA and Boeing as primary members of the research-transition team.

This paper describes results from the final Human-in-the-Loop (HITL) simulation used to validate EDA's benefits potential and ready it for official transfer to the FAA under 3D-PAM. A brief description of the operational concept that resulted from the three-year iterative design and development effort is also presented along with a summary of the products delivered to the FAA in November 2011 to complete the transition of EDA from the research domain towards operational deployment in the Next Generation Air Transportation System (NextGen).

II.   Concept Overview

EDA leverages core elements of CTAS to develop strategic arrival solutions over time horizons of up to 30 minutes to assist radar-side (R-side) sector controllers in ARTCCs. Solutions are sought that allow aircraft to perform fuel-efficient, continuous descents at low engine power while satisfying time-based-metering restrictions at the TRACON boundary. EDA calculates trajectory predictions in search for solutions that conform to Scheduled Time of Arrival (STA) constraints at the meter fix computed by TMA. In searching for these solutions, EDA attempts to avoid conflicts along the arrival path to the meter fix in order to minimize downstream interruptions to an otherwise continuous descent. Trajectories are modeled using an idle-thrust descent for large jet transports and a fixed flight-path-angle descent for regional jets. EDA evolved over the course of 3D-PAM to support operations under all traffic levels. In light traffic, where no delay absorption is required to meet capacity constraints, the TMA STA for an aircraft will match its original Estimated-Time-of-Arrival (ETA). Using EDA for all traffic levels helps to standardize arrival procedures and allows more universal sharing of flight intent between controllers and pilots and their respective automation systems.

Once computed, EDA trajectory solutions are translated into specific maneuver advisories that are presented to controllers upon their request. Advisories involve a combination of cruise-speed, descent-speed and path adjustments, as illustrated in Fig. 1. The advisories become available once aircraft have crossed the TMA *freeze horizon,* when STAs are no longer subject to change through automatic scheduling. The freeze horizon is set within the TMA system to between 130 nmi and 200 nmi upstream of the meter fix, depending on traffic, airspace, and environmental conditions. Once an aircraft has crossed the freeze horizon, controllers are alerted to the availability

of an advisory by the "EDA" symbol that appears at the bottom of the aircraft's flight-data block. This symbol is referred to as the EDA portal.
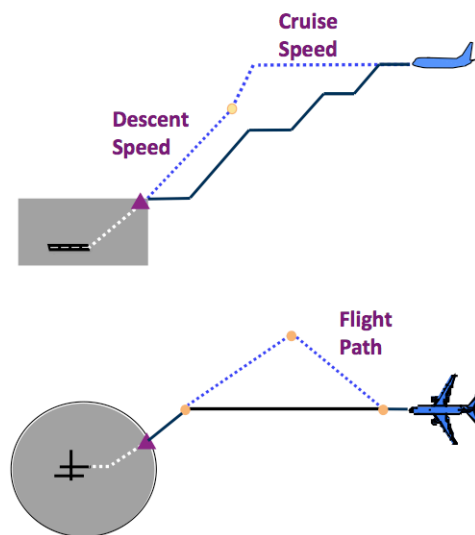
Figure 1. EDA advisory components

Fig. 2 illustrates the primary features of the EDA prototype as they appear on the sector controller's display. In this example, the controller has clicked on the EDA portal for a flight near the center of the screen. Once the portal is clicked, a separate window opens on the display containing the advisory information for the flight. The trial-plan route associated with the advisory is also displayed, which includes the location of the aircraft's predicted top-of-descent (TOD) point (not visible in Fig. 2, since it lies off the map in the sector to the left). In this example, the EDA advisory has cruise speed, descent speed, and path components. Path advisories are issued for conflict avoidance or whenever speed adjustments, i.e., slow downs, are insufficient for absorbing the delay required to meet an STA. Path-stretch advisories are in the form of dogleg maneuvers that have start and end points along the aircraft's nominal flight plan. EDA ensures that path-stretch trajectories do not cross sector boundaries in order to prevent additional inter-sector-coordination workload for controllers.

EDA advisories are designed to facilitate clearance delivery by voice using standard FAA phraseology and procedures. For advisories that include path stretching, the controller first issues EDA airspeed clearances to the flight deck followed by saying "advised routing when ready to copy," which prepares pilots for receiving the subsequent path-stretch clearance. Once received on the flight deck, pilots enter the EDA clearances directly into their FMS for guidance and control along the intended arrival trajectory using Required Navigation Performance (RNP) criteria if specified.[8] The TOD point used for flight control is calculated by the FMS using its own trajectory prediction process that incorporates the EDA clearance information. Similar to EDA, the FMS uses a constant Mach/calibrated-airspeed profile in its descent trajectory predictions.

Once controllers receive a readback of the clearance from the flight deck, they update their ground-based automation with EDA flight intent by pressing an *accept* button in the advisory window. At this point, controllers are given the option of including a descent authorization together with the maneuver clearance. If a descent authorization is included, the aircraft can descend at its FMS-computed TOD point without further instruction from the controller. Further details concerning the EDA user interface can be found in Ref. 7.

As a flight progresses along the intended trajectory, EDA continues to monitor conformance to its meter-fix STA by computing new trajectory predictions every 12-second radar cycle. A corrective advisory is generated if an ETA update falls out of conformance with the targeted STA by a set tolerance (20 seconds for simulation described herein). Conformance monitoring provides robustness in the presence of real-world trajectory prediction uncertainty. Controllers are able to manage TOD uncertainty by delaying the authorization to descend until the aircraft is well clear of any traffic that may be of concern at lower altitudes. Separating descent authorization from the primary maneuver clearance is the preferred method of operation during busy traffic conditions.

To monitor for separation assurance along the arrival trajectory once an advisory has been accepted, a strategic conflict probe is included in the concept-of-operations developed for EDA under 3D-PAM. A NASA-developed

conflict-probe[9] was included as a component of the EDA prototype that was evaluated in the final HITL simulation described here.
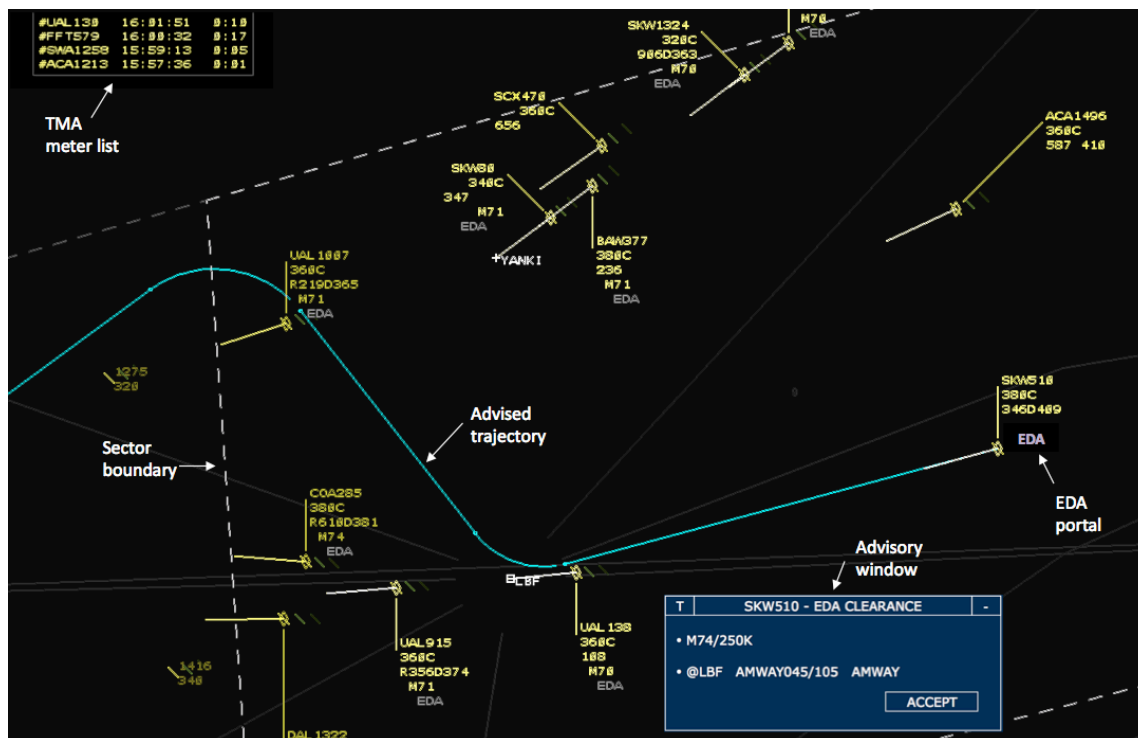

Figure 2. Controller display showing use of EDA in HITL simulation

III. Simulation Approach

A final HITL simulation of EDA in support of 3D-PAM was completed in September 2011. The objective of the simulation was to assess the potential benefits of EDA using a mature research prototype that represented a culmination of design decisions made based on six prior HITL simulation experiments. This simulation also incorporated the latest phraseology and procedures, resulting from prior simulation studies and technical interchange, needed to communicate EDA information and coordinate actions between controllers and pilots. To measure benefits, operations with EDA were compared against baseline operations in which controllers were provided with TMA scheduling automation only, representative of today's environment. The benefits evaluated were potential improvements in time-based metering accuracy, reductions in fuel and emissions, and reductions in controller workload.

The simulation was conducted in the Crew-Vehicle Systems Research Facility (CVSRF) at NASA Ames Research Center. The three controller participants included two active-duty controllers from Denver ARTCC (ZDV) and a recently retired controller from the same facility. The two active-duty controllers were representatives of the National Air Traffic Controllers Association (NATCA). In the simulation, controllers were seated at three separate radar-side sector positions covering northeast ZDV airspace (Fig. 3). Controllers communicated with pseudo pilots that managed simulated flights from a separate location in the CVSRF. Two pseudo pilots were assigned to each airspace sector – one to manage radio communications and the other to make any necessary flight control inputs based on controller instructions. For added fidelity, two simulator cabs flown by airline pilots were included in the simulation. These included a Level-D-compliant B747-400 cab and a specialized research cab that was fitted with a dynamics model so that it behaved as a B737-800. NASA's Multi Aircraft Control System (MACS) was used to provide the user interface for controllers, emulating an ARTCC radar display in the field.[10] MACS also provided the user interface and aircraft dynamics model (target generator) for flights managed by pseudo pilots. The simulation system, as it pertained to EDA operations, is illustrated in Fig. 4.

The independent variables of the simulation involved the automation mode (EDA versus TMA only), traffic scenario, and controller sector assignment. The two traffic scenarios contained a mix of Boeing and Airbus wide-

body and narrow-body jets along with Bombardier regional jets. For both scenarios, the flow-rate constraint at the meter fix was set to 36 aircraft per hour, typical of the rate used in field operations at ZDV. In one scenario, traffic demand exceeded the meter-fix capacity constraint most of the time, while in the other, demand dipped well below the capacity constraint at times. These scenarios were designed to emulate sustained and periodic arrival rushes into Denver. Both scenarios contained numerous conflicts between arrivals and overflights. For the purpose of discussion, the scenario with higher sustained traffic demand is referred to as the *heavy* traffic scenario, while the other is referred to as the *moderate* traffic scenario. The scenarios were designed to challenge controllers without exceeding their ability to manage the airspace alone, i.e., without help from a second controller at a D-side position. Ensuring that traffic scenarios were manageable by R-side controllers alone was found in pretesting to be of particular concern for baseline operations without EDA.

A wind field provided by a Rapid Update Cycle (RUC) forecast model was included in each simulation run.[11] The wind forecast corresponded to the time and date (July 21, 2011) at which traffic was captured from live data to provide input to the simulation. Winds were from the southwest with an average magnitude of approximately 60 kts at 36,000 ft. The winds, along with atmospheric temperature and pressure data included in the RUC forecast, were incorporated into both EDA and FMS trajectory predictions.

Controllers were rotated through each sector position using three unique seating arrangements designed to study the effect of controllers on EDA benefits. The three controller stations were arranged from right to left corresponding to ZDV Sectors 9, 16 and 15, shown in Fig. 5. Sectors 9 and 16 are adjacent high-altitude sectors, and Sector 15 is the low-altitude sector (below 24,000 ft) that feeds arrival traffic to the meter fix (SAYGE). The two parallel arrival routes shown in Fig. 5 served as 'backbones' for EDA path-stretch maneuvers. The combination of independent variables resulted in the 12-run test matrix shown in Table 1, with runs arranged to minimize learning effects that might confound results.

In the TMA-only baseline runs, controllers were provided with functions and displays representative of what they have available today in the field. This included a meter list showing TMA-computed ETA, STA and predicted arrival time error (STA – ETA) rounded to the nearest minute. In the TMA-only runs, controllers attempted to deliver aircraft to the meter fix with zero minutes of error displayed in the meter list, i.e., within ±30 sec of TMA-computed STAs, accounting for rounding. In the EDA runs, controllers attempted to deliver aircraft within ±20 seconds of STAs, consistent with the corrective-advisory error tolerance previously described.

In all simulation runs, controllers were asked to maintain current separation standards for aircraft in en route airspace: 5 nmi horizontal and 1,000 ft vertical. In EDA runs, controllers were provided with a strategic conflict probe with a 25-minute look-ahead time to assist with separation assurance. In TMA-only runs, controllers were provided with a conflict-alert capability similar to that available in the field today, implemented using the EDA conflict probe but with a look-ahead time set to 3 minutes.

In all simulation runs – with and without EDA – trajectory-prediction uncertainty was added to better represent real-world performance. Errors in forecast winds and aircraft weight estimates were modeled to produce TOD and meter-fix ETA errors similar to those observed in field tests at Denver ARTCC.[12] In addition, the variance in the onset of heading changes associated with EDA path-stretch clearances requiring immediate turnout maneuvers was modeled using flight-deck simulation results provided by Boeing. Wind errors had an RMS of 3.8 m/s; weight errors for each flight were randomly selected from a uniform distribution with bounds at approximately ±15% of the aircraft's nominal landing weight; variance in the onset of heading changes from the flight deck was ±8 s (σ); and resulting TOD errors were ±8 nmi (2σ).

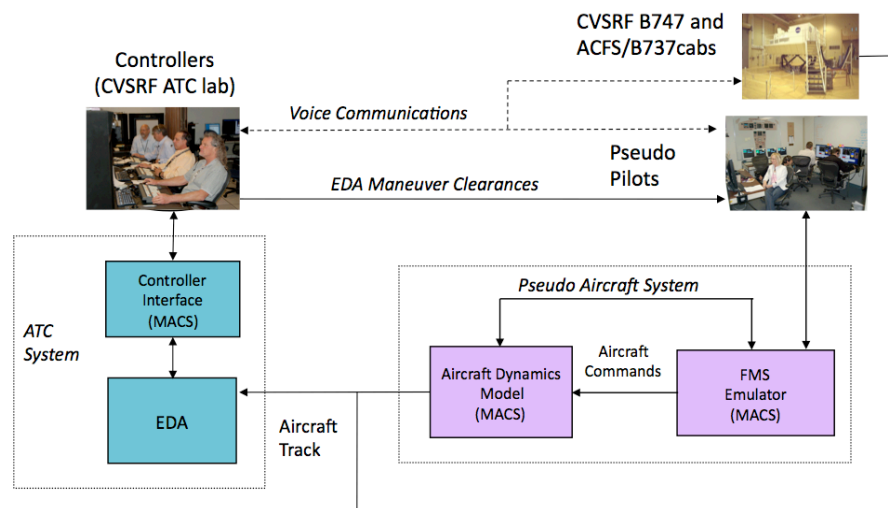**Figure 3. Controllers participating in HITL simulation of EDA**
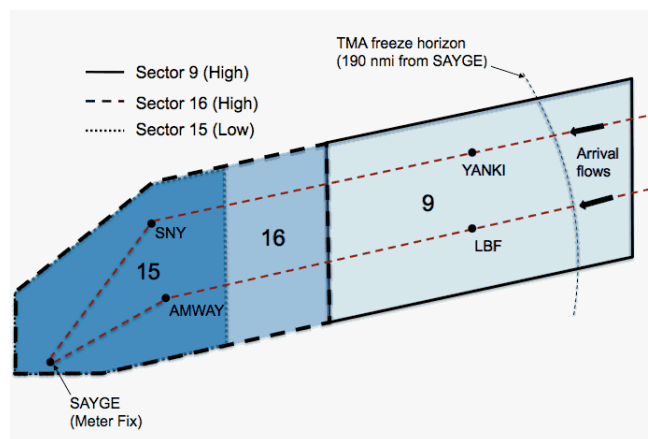

Figure 4. HITL simulation environment

Figure 5. Airspace sectors and arrival flows

Table 1. Simulation Test matrix

Run #	Condition		Sector 9 Controller	Sector 16 Controller	Sector 15 Controller
	Automation Mode	Traffic Scenario			
1	TMA	Heavy	C1	C2	C3
2	TMA	Moderate	C2	C3	C1
3	TMA + EDA	Heavy	C3	C1	C2
4	TMA + EDA	Moderate	C1	C2	C3
5	TMA + EDA	Heavy	C2	C3	C1
6	TMA	Moderate	C3	C1	C2
7	TMA + EDA	Heavy	C1	C2	C3
8	TMA + EDA	Moderate	C2	C3	C1
9	TMA	Heavy	C3	C1	C2
10	TMA	Moderate	C1	C2	C3
11	TMA	Heavy	C2	C3	C1
12	TMA + EDA	Moderate	C3	C1	C2

IV. Simulation Results and Discussion

A. Metering Performance

TMA schedules aircraft in order to maximize landing rate without exceeding capacity constraints stipulated at the runway threshold and/or designated points along the arrival route. As described previously, the capacity constraint for the simulation was set to 36 aircraft per hour over the meter fix SAYGE for both traffic scenarios. Since EDA computed advisories to conform to TMA arrival times at the meter fix, it was not expected to directly increase the volume of aircraft delivered to the meter fix in comparison with TMA-only operations. EDA did, however, substantially improve the ability of controllers to conform to the TMA-assigned arrival sequence and schedule at the meter fix, which can improve overall arrival efficiency by reducing the need for delay buffers and corrective control actions within the TRACON.

In TMA operations today, controllers often manually change the TMA-assigned aircraft sequence at the meter fix without affecting overall flow rate by performing what is know as a swap. In a swap, the STAs assigned to a pair of aircraft are switched with one another, resulting in a sequence change in the displayed meter list. This is typically performed in order to prevent an aircraft with a faster original cruise speed from having to pass another in order to meet its TMA-assigned STA. Such maneuvers – which result from the *first-come-first-serve* algorithm that TMA applies to initial ETA predictions to the meter fix, described in Ref. 4 – often increase controller workload due to the closer monitoring of separation needed as one aircraft passes another. Although such swaps do not usually affect throughput into the TRACON, they potentially decrease runway throughput by requiring additional spacing buffers on final approach to compensate for a large aircraft being inadvertently sequenced ahead of a smaller aircraft prior to TRACON entry, as illustrated in Fig. 6. Manual sequence adjustments in en route airspace are more likely to disrupt terminal airspace operations and affect inter-arrival spacing at the runway for flights on continuous descents, which are less tolerant to maneuvering after TOD.
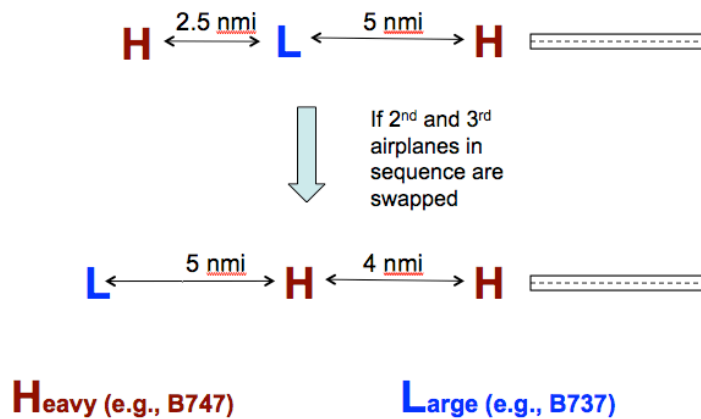
Figure 6. Possible effect of sequence change on final approach spacing requirements

Table 2.   Number of aircraft sequence swaps per run

Controller Seating Order	Traffic Scenario	Run Number	Automation Mode	Number of Swaps
1	Heavy	1	TMA	4
		7	TMA + EDA	0
2	Moderate	2	TMA	3
		8	TMA + EDA	0
3	Heavy	9	TMA	6
		3	TMA + EDA	0
1	Moderate	10	TMA	0
		4	TMA + EDA	0
2	Heavy	11	TMA	9
		5	TMA + EDA	0
3	Moderate	6	TMA	7
		12	TMA + EDA	0

Table 2 shows the number of manual sequence swaps performed by controllers during each simulation run, grouped by controller seating order and traffic scenario. Although controllers were allowed to perform swaps in both TMA-only and EDA runs, no swaps were found necessary by controllers when using EDA. In contrast, the average number of swaps per run with TMA-only was 3.33 and 6.33 for the moderate and heavy traffic scenarios respectively. Based on controller commentary and observations, EDA appears to have reduced the need for sequence swaps partially due to a wider utilization of the airspace through automated path stretching for delay absorption. With aircraft on substantially different horizontal paths, controllers were able to assure separation during overtake maneuvers with less effort had aircraft been on the similar routes.

The ability of controllers using EDA to more accurately and precisely deliver aircraft to the meter fix in conformance with TMA schedules was also studied in the simulation. Better schedule conformance reduces the possibility of missed arrival slots. With fewer missed slots, controllers can maximum runway throughput with less compensatory delay reserved for the terminal airspace, known as TRACON delay buffer. Reducing the intentional TRACON delay buffer minimizes average TRACON transit time, thereby accommodating a continuous descent to the runway with reduced overall flight delay and fuel consumption.[13,14]

Simulation results showed substantial improvement in arrival-time accuracy and precision at the meter fix with the use of EDA, as shown by the error histograms in Figs. 7 and 8. Fig. 7 compares actual meter-fix crossing times with original scheduled times of arrival assigned by TMA prior to any swapping of aircraft pairs. Fig. 8 makes the same comparison, but against scheduled times of arrival that account for swapped aircraft pairs.

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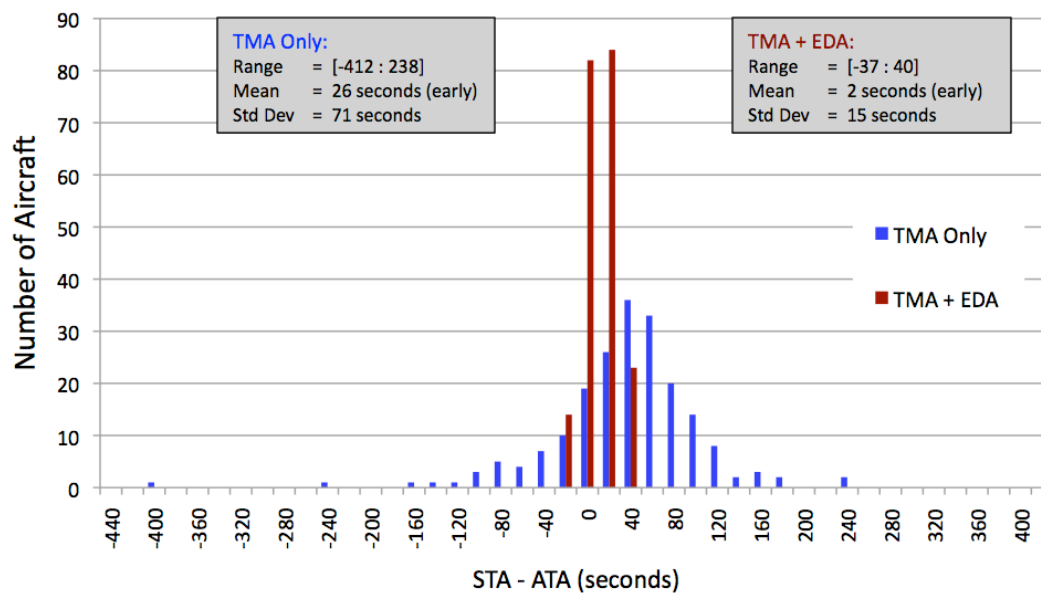
Figure 7. Actual meter fix crossing time versus original TMA schedule
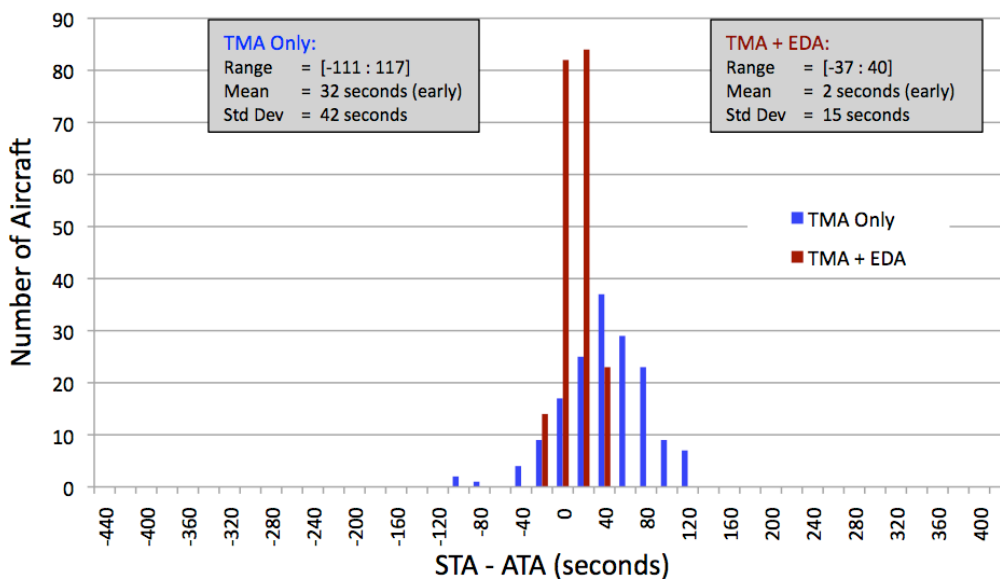
Figure 8. Actual meter fix crossing time versus TMA schedule with swaps

The results in Fig. 7 characterize the total metering performance over all simulation runs, capturing how well controllers matched the TMA-optimized sequence and schedule with and without the use of EDA. As indicated by summary statistics in the figure, the results show a 92% reduction in mean arrival-time error (from 26 s to 2 s) over the meter fix with a corresponding reduction in the standard deviation of arrival-time error of 79% (from 71 s to 15 s) when using EDA to conform to the original TMA sequence and schedule, i.e., without controller-initiated swaps.

The results in Fig. 8 characterize metering performance while accounting for the sequence swaps that occurred in the TMA-only runs. Results show a 94% reduction in mean arrival-time error (from 32 s to 2 s) over the meter fix with a reduction in the standard deviation of arrival-time error of 64% (from 42 s to 15 s) when using EDA to conform to the final TMA schedule. The results show that even when manual sequence adjustments by the controller are accounted for, the improvement in metering accuracy with EDA is substantial. According to subject matter

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experts, metering accuracy achieved in the field with TMA-only is even lower than that observed in the simulation with TMA-only. In real-world operations at Denver ARTCC, meter-fix delivery accuracy is typically between 1 and 2 minutes.

B. Fuel and Emissions

A direct benefit mechanism of EDA is its potential to improve flight-path efficiency in ARTCC airspace. In general, descent trajectories that are flown at low engine power and avoid level-off segments are most fuel efficient. For the typical problem that EDA addresses, however, where aircraft are subjected to metering constraints that require delay absorption, maximizing fuel efficiency is more complicated than simply avoiding level-off segments altogether. Indeed, leveling an aircraft off at lower altitudes is an effective means by which controllers absorb delay, since it reduces an aircraft's groundspeed without changing its airspeed. Studies show that maximum fuel efficiency under a fixed arrival-time constraint is achieved by slowing the aircraft in cruise flight towards its maximum-endurance airspeed while planning a continuous descent that is initiated as early as possible upstream of the meter fix.[15] This strategy – employed by EDA unless speed adjustments are needed for conflict resolution – theoretically maximizes fuel efficiency for any magnitude of required delay absorption. For large delays that require path stretching, EDA first ensures that the aircraft's descent- and cruise-airspeed profile has been minimized (in that order). Once the airspeed has been minimized, fuel consumption is largely invariant to the horizontal path that the aircraft flies to absorb any remaining delay in the fixed-flight-time problem.

A first-order indication of flight-path efficiency improvements can be made by comparing the number of level-off segments with and without the use of EDA. Fig. 9 shows the vertical tracks resulting from the simulation under the heavy-traffic scenario for each of the three rotations by which controllers were assigned to the airspace sectors. By reducing unnecessary level-off maneuvers, EDA not only offers to save fuel, but it also frees up more altitudes for controllers to perform separation assurance and accommodate overflights. The reduction in the number of level-off segments with EDA is further shown in Fig. 10, which counts the number of level-off segments observed during descent over the entire simulation. With TMA only, the majority of flights received at least one level-off instruction from the controller. With EDA, the majority of flights – almost four times as many than with TMA-only – were able to execute an uninterrupted descent to the meter fix from cruise altitude.
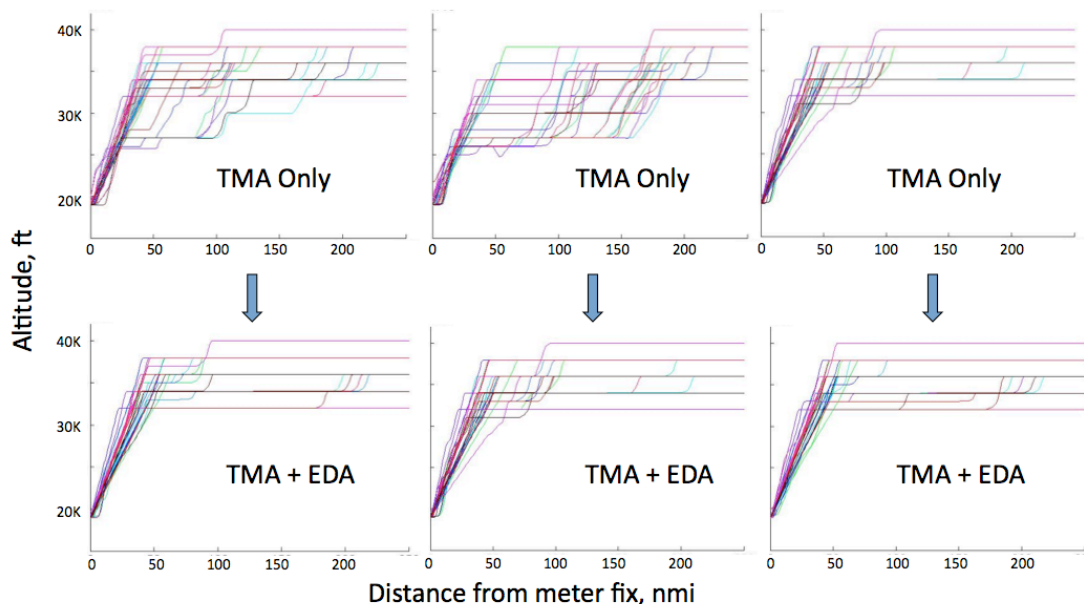
Figure 9. Vertical Flight Tracks in Heavy-Traffic Simulation Scenario
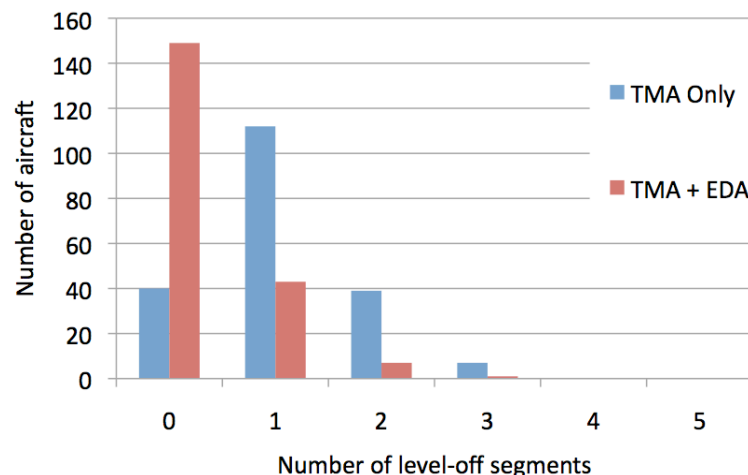
Figure 10.   Number of level-off segments in descent

To measure efficiency directly, the fuel consumed along the arrival trajectory was compared across flights managed with and without EDA for the same traffic scenario and controller-sector rotation. Two different methods were used to compute fuel burn estimates. The first used the aerodynamic and propulsion models intrinsic to CTAS, upon which EDA's trajectory predictions themselves are based. Since a real-time fuel depletion model was not available within either the MACS dynamics model or CTAS, this approach required using piecewise trajectory predictions to recreate flown horizontal and vertical paths.[16] The second method used a technique developed by Chatterji[17] that relied on state estimation together with Eurocontrol's Base of Aircraft Data (BADA) version 3.9 to estimate fuel burn for a given flight track input consisting three-dimensional position versus time. These two techniques are referred to respectively as *CTAS* and *BADA* in the results that follow.

Using both the CTAS and BADA methods, the fuel consumed by each flight was estimated from the ARTCC boundary to the meter fix in order to reflect every action taken by the controller team for metering and separation assurance. Because controllers were allowed to swap aircraft at their discretion as previously described, fuel burn comparisons between flights managed with EDA versus TMA only were grouped depending on whether either flight in a pairwise comparison was swapped or not.

The average fuel savings afforded by EDA for flights that did not include swaps are shown in Fig. 11. The fuel savings, on average, were found to be higher using the BADA method than the CTAS method. More importantly, the estimated fuel savings with EDA were dependent on controller-seating order and traffic scenario. The dependence of seating order indicates that fuel benefits are a function of how each controller uses EDA relative to baseline automation; some controllers will benefit from EDA more than others, depending on how proficiently they manage arrivals using TMA-only. Furthermore, fuel benefits were generally higher in the heavy traffic scenario than the moderate scenario. This indicates that controllers benefited more from strategic EDA solutions during complex traffic conditions. In such conditions, controllers were less likely to resolve combined metering and separation problems efficiently using their more tactical, legacy techniques. This same trend is observed in the results shown in Fig. 12, which includes flights that received a sequence swap when managed using TMA only. During such swaps, some flights received a fuel penalty, as they were re-sequenced to a later slot in the TMA schedule requiring more delay absorption, while others received fuel benefits as they were moved to an earlier slot that allowed more direct routing to the meter fix. Since it includes flights with schedule swaps, Fig.12 contains substantially more pairwise fuel-burn comparisons than Fig. 11 (198 vs. 94).

Results from the CTAS and BADA methods were averaged for the remaining fuel-burn analyses presented in this paper,

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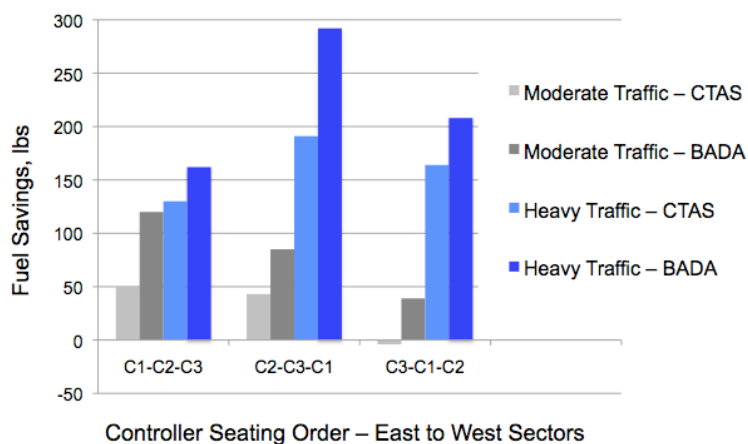
Figure 11.   Average fuel savings per flight with EDA, not including swaps
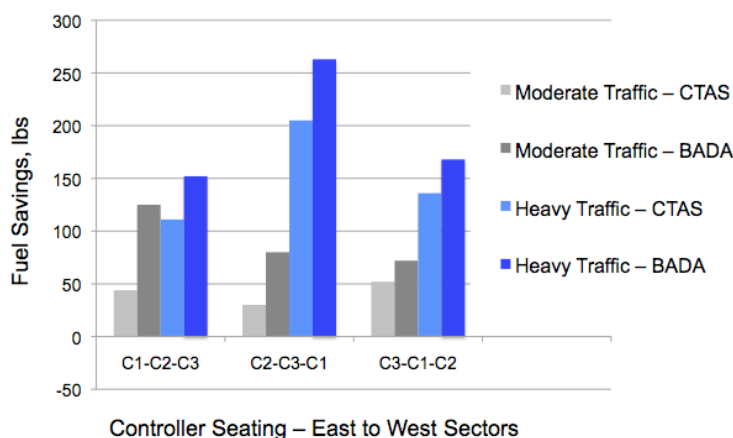
Figure 12.   Average fuel savings per flight with EDA, including swaps

As expected, the mean and range of fuel savings with EDA tended to increase with aircraft size. Figs. 13 and 14 show the difference in fuel burn for each flight in the simulation managed with EDA vs. TMA-only, excluding and including swaps, respectively. It can be seen here that maximum fuel savings from EDA are particularly large for the small sample of B747 and B777 flights in the simulation.

Average per-flight fuel savings, over the entire simulation, are shown in Table 3 along with corresponding estimates of the reduction in carbon dioxide and nitrogen compounds. These greenhouse gas emissions scale directly with fuel burn and represent the primary pollutants from jet-engine combustion.[18]
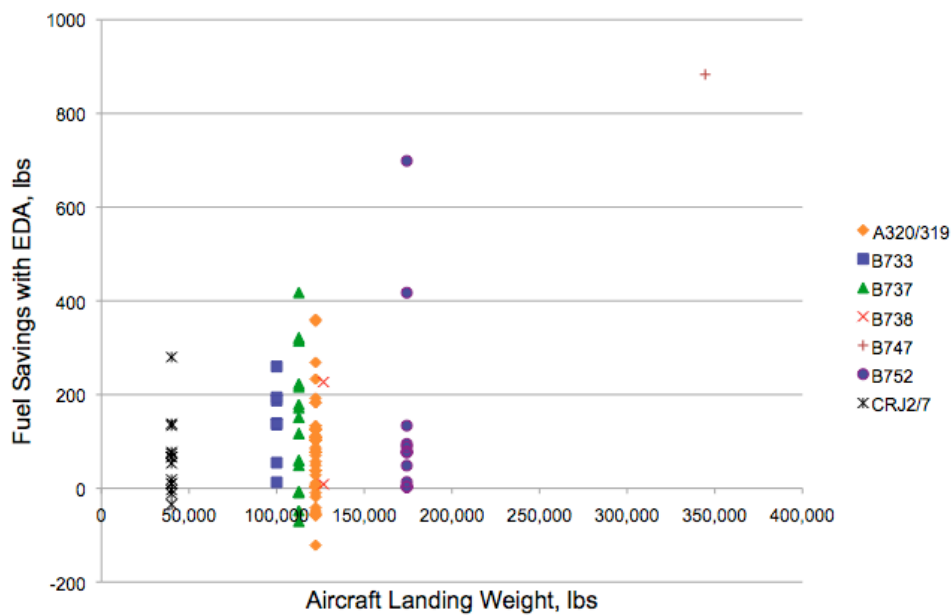
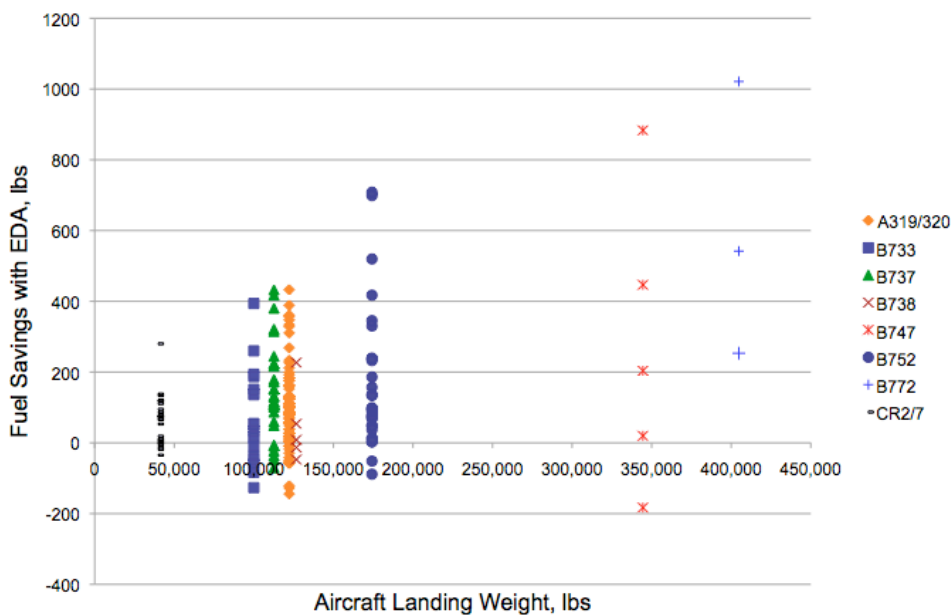**Figure 13.** **Fuel savings per flight from EDA versus landing weight – without swaps**

Figure 14. **Fuel savings per flight from EDA versus landing weight – with swaps**

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Table 3. Average per-flight reduction in fuel and emissions from EDA over entire simulation

Per-Flight Reductions, lbs	Moderate Traffic	Heavy Traffic	All Traffic
Fuel	60	191	110
CO_2	189	595	346
NO_x	1.2	3.9	2.2

## C. Controller Workload, Acceptability, and Communications

By providing advisories designed to implement metering and conflict avoidance through a single, comprehensive arrival instruction, EDA potentially reduces controller workload and the number of communications required between controllers and pilots to maneuver aircraft in busy arrival airspace. These direct benefits to controllers were evaluated in the simulation together with the overall acceptance of EDA automation by the controller team.

To evaluate controller workload, subjective measurements were taken during and after each simulation run. During each run, controllers were asked to rate their workload on a scale from 1 to 6, from easiest to hardest according to the scale shown in Table 4. These real-time workload ratings were obtained from each controller at the three sector positions every five minutes over the course of each simulation run. In addition to these real-time workload ratings, each controller was asked to rate their overall workload at the end of each run on a questionnaire based on a modified version of the NASA Task Load Index (TLX) rating procedure.[19] The post-run TLX questionnaire asked controllers to rate their level of *mental demand, temporal demand, performance* and *frustration* on an analog scale from low to high, as shown by the example in Fig. 15. Ratings for each workload element were then converted to a numerical scale of 1 (low) to 10 (high) and then used to compute a composite workload rating. This composite rating was a weighted-sum average of the TLX ratings based on controller responses to questions regarding the importance of each workload element relative to the others.

Table 4. Real-time workload scale

| Workload descriptions	Sub categories	Scale
Hard (Reactive)	High	6
	Low	5
Medium (Moderately alerted)	High	4
	Low	3
Easy (Extra time at hand)	High	2
	Low	1

Analysis of the real-time ratings found a slight reduction in workload with EDA in comparison with TMA-only over both traffic scenarios. The average workload rating across all controllers and traffic scenarios with EDA was rated as 1.39 versus 1.63 with TMA-only. The standard deviation in both cases was small (<0.06). The low, absolute workload ratings under both automation conditions indicated that controllers found the traffic scenarios easier to manage than expected by the designers of the experiment. Albeit small, the workload reduction with EDA was found to be statistically significant ($p < 0.05$) based on a repeated-measures Generalized Linear Model (GLM) analysis that examined the causal effects of the independent variables in the simulation and their interactions. GLM analysis of the real-time workload ratings also revealed that controllers found the *heavy* traffic scenario somewhat more difficult to manage than the *moderate* traffic scenario on a statistically significant basis, as expected. GLM analysis of the post-run TLX ratings also indicated that the *heavy* scenario was more challenging than the *moderate* scenario in terms the *frustration* workload element and the overall composite TLX workload score. Interestingly, GLM analysis revealed no statistically significant effect of the automation condition – EDA versus TMA only – on TLX workload ratings. This contrasted with the statistically significant effect of automation mode on real-time workload ratings and informal post-run and post-simulation controller comments that suggested workload was lower with EDA.
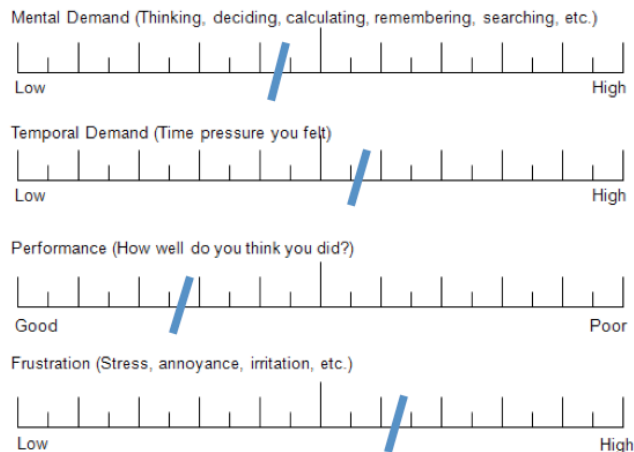
Figure 15.   Example of a completed post-run TLX workload questionnaire

To evaluate controller acceptance of the EDA automation, a series of Likert-scale[20] questions were asked following each simulation run, focusing on operational safety and perceived automation benefits. GLM analysis of responses showed that all controllers found traffic operations with EDA highly acceptable, while the majority of controllers (2 of 3) found traffic operations with TMA alone only moderately acceptable. Similarly, all controllers considered operations with EDA to be very safe, with the majority of controllers feeling that EDA improved their ability to assure separation in comparison to using TMA-only.

The reduced number of communications required between controllers and pilots to meter and separate aircraft with EDA was a likely contributor to the favorable workload and acceptability ratings given by controllers for EDA. The number of required maneuver clearances – i.e., those that directly affected the trajectory of aircraft – was found to decrease on average by 60% in EDA operations compared to those with TMA-only over all simulation runs. An example of this reduction is shown Fig. 16, which maps the location of aircraft at times when maneuver clearances were issued during the heavy traffic scenario using TMA-only (run 11) vs. EDA (run 5). A histogram showing the number of maneuver clearances with and without EDA for all simulation runs is shown in Figure 17. These data show that with TMA-only it was most common for aircraft to require six maneuver instructions from controllers in ARTCC airspace for metering and separation. With EDA, however, it was most common for aircraft to receive just a single, comprehensive maneuver instruction.
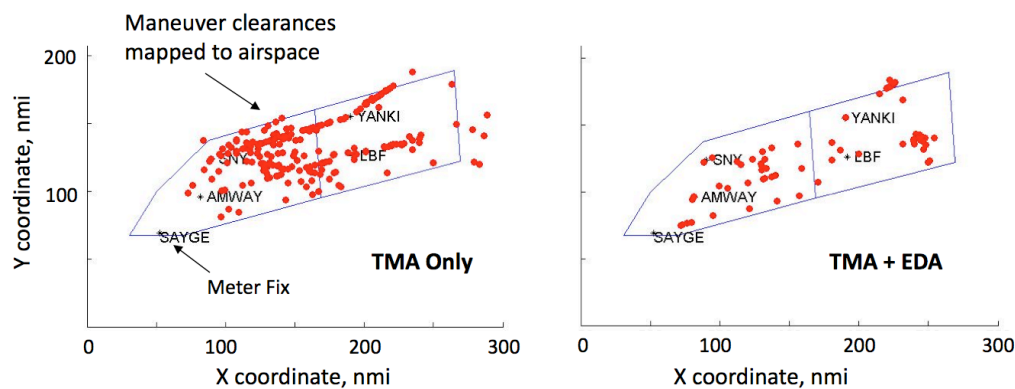
Figure 16.   Example of reduction in maneuver clearances with EDA
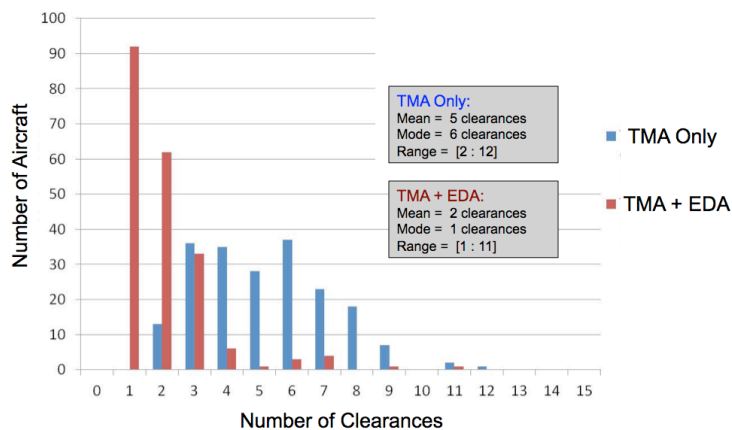
Figure 17. Number of maneuver clearances per flight

V.   Technology Transition

The results described above were reported to the FAA to help complete the transition of EDA towards operational deployment. Official technology transfer of EDA under 3D-PAM included the items listed and described in Table 5. The primary deliverable was a functional-design specification of the final EDA research prototype used to support the simulation described herein. The research prototype itself was also included as a deliverable in order to provide a reference for how specified functions were implemented in software. Items described in Table 5 are specific to those delivered by NASA. Additional deliverables from the 3D-PAM partners included a concept-of-use document developed by the FAA with input from NASA and Boeing, reports of Boeing-led simulations that focused on pilot operations, and a NAS-wide cost and benefits assessment. A NASA technical report providing a compendium of the items described in Table 5 is being prepared for future publication.

Table 5.   Deliverables from NASA to FAA for EDA technology transfer

Deliverables	Description
Functional design specification	Description of the functions and algorithms of the final EDA prototype that support trajectory prediction, metering conformance, conflict resolution, and controller interface.
Post HITL simulation reports	Findings from each of the seven HITL simulations used to iterate on EDA concept and functions and assess potential benefits.
Post field-test reports	Findings from two field tests conducted at Denver ARTCC involving commercial flights operated by United/Continental and SkyWest and test flights conducted by the FAA. Tests were to assess the accuracy of EDA trajectory predictions. The first test (2009) focused on large jets capable of idle-thrust FMS vertical navigation. The second test focused on regional jets that use fixed flight path angles for FMS vertical navigation.
Prototype build reports	Description of the key functions and features of the EDA software builds that supported each HITL simulation. These reports detail the iterative design and development of EDA based on prior simulation results and input from subject-matter experts.
Prototype software	The EDA prototype software (source code and executable) used in the final, benefits-oriented simulation.

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VI. Conclusion

The Efficient Descent Advisor was iteratively designed and developed through a series of HITL simulations that included trajectory-prediction uncertainty models based on field-test data. Results from initial simulations were used to refine the concept, algorithms, user-interface and procedures behind the automation. Having developed a mature research prototype that reflected a culmination of design decisions, a final simulation was carried out to measure EDA benefits. Results showed that EDA allowed controllers to perform time-based metering operations in busy traffic with substantially improved accuracy and precision. In comparison with scheduling automation only (i.e., the Traffic Management Advisor), EDA improved meter-fix delivery accuracy by 92% and reduced the standard deviation of arrival error by 79%. EDA also substantially improved vertical flight-path efficiency, providing a four-fold increase in the number of aircraft able to fly an FMS-guided continuous descent to the meter fix. Results showed that EDA saved an average of 110 lbs of fuel per flight in ARTCC arrival airspace, with significantly greater fuel savings for larger aircraft types. Although dependent on how each controller used the EDA automation, average fuel savings and corresponding emission reductions were shown to increase significantly as traffic complexity increased. EDA was also found to reduce controller workload, likely due in part to a 60% reduction in the number of maneuver instructions required between controllers and pilots with EDA in comparison with TMA-only baseline operations. Findings from this simulation capped a three-year collaborative effort between government and industry to successfully transition EDA from the research domain towards operational deployment.

Acknowledgments

References

[1]Brooker, P. "SESAR and NextGen: Investing in New Paradigms," The Journal of Navigation (2008), 61, pp 195-208.

[2]Klooster, J., Amo. A., and Manzi, P., "Controlled Time of Arrival Flight Trials," 8th USA/Europe Air Traffic Management Research and Development Seminar, Napa, CA, July 2009.

[3]Coppenbarger, R., Mead, R., Sweet, D., "Field Evaluation of the Tailored Arrivals Concept for Datalink-Enabled Continuous Descent Approach," Journal of Aircraft, Vol. 46, No. 4, 2009, pp 1200-1209.

[4]Swenson, H., Hoang, T., Engelland, S., Vincent, D., Sanders, T., et al., "Design and Operational Evaluation of the Traffic Management Advisor at the Fort Worth Air Route Traffic Control Center," 1st USA/Europe Air Traffic Management R&D Seminar, Saclay, France, June, 1997.

[5]Swenson, H.N., Thipphavong, J., Sadovsky, A., Chen, L., Sullivan, C., and Martin, L., "Design and Evaluation of the Terminal Area Precision Scheduling and Spacing System," 9th USA/Europe ATM R&D Seminar (ATM2011), Berlin, Germany, 14-17 June 2011.

[6]Robinson, III, J. E., and Kamgarpour, M., "Benefits of Continuous Descent Operations in High-Density Terminal Airspace Under Scheduling Constraints," 10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Fort Worth, TX, 13-15 Sep. 2010.

[7]Coppenbarger, R., Dyer, G., Hayashi, M., Lanier, R., Stell, L., Sweet, D., "Development and Testing of Automation for Efficient Arrivals in Constrained Airspace," 27th International Congress of the Aeronautical Sciences (ICAS), Nice, France, 19-24 Sep. 2010.

[8]Haraldsdottir, A., Scharl, J., Berge, M., Schoemig, E., and Coats, M. (2007). *Arrival Management with Required Navigation Performance and 3D Paths.* 7th USA/Europe Air Traffic Management R&D Seminar. Barcelona.

[9]McNally, B. D., Bach, R. E., and Chan, W., "Field Test Evaluation of the CTAS Conflict Prediction and Trial Planning Capability," AIAA Guidance, Navigation, and Control Conference, Boston, MA, 10-12 Aug. 1998.

[10] Prevot, T., and Mercer, J., "MACS: A Simulation Platform for Today's and Tomorrow's Air Traffic Operations," AIAA Modeling and Simulation Technologies Conference, Hilton Head, SC, 20-23 Aug. 2007.

[11]Schwartz, B.E., S.G. Benjamin, S.M. Green, and M.R. Jardin, 2000: Accuracy of RUC-1 and RUC-2 wind and aircraft trajectory forecasts by comparison with ACARS observations. *Weather. Forecasting*, 15, 313-326.

[12]Stell, L., "Prediction of Top of Descent Location for Idle-thrust Descents," 9th USA/Europe ATM R&D Seminar (ATM2011), Berlin, Germany, 14-17 June 2011.

[13]Erzberger, H. (1995). *Design Principles and Algorithms for Automated Air Traffic Management.* Mission Systems Panel of AGARD and the Consultant and Exchange Program of AGARD (p. 31). Madrid, Chantillon, Moffet Field: AGARD.

[14]Thipphavong, J., and Mulfinger, D., "Design Considerations for a New Terminal Area Arrival Scheduler," 10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Fort Worth, TX, 13-15 Sep. 2010.

[15]Nikoleris, T., Chatterji, G., and Coppenbarger, R., "Comparison of Fuel Consumption of Descent Trajectories under Arrival Metering," AIAA Guidance, Navigation, and Control Conference, Minneapolis, MN, 13-16 Aug. 2012.

[16]Nagle, N., Trapani, A., Sweet, D., Carr. G., "Determining Trajectory Change Points from Simulation Radar Data for Use in a Trajectory Modeler, with an Application to Efficient Descent Advisor Benefits Assessment," AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Indianapolis, IN, 17-20, Sep. 2012 (submitted for publication).

[17]Chatterji, G.B., "Fuel Burn Estimation Using Real Track Data," AIAA-2011-6881, 11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Virginia Beach, VA, 20-22 Sep. 2011.

[18]Aviation & Emissions - A Primer, FAA Office of Environment and Energy, Jan. 2005

[19]Hart, S., "NASA-Task Load Index (NASA-TLX); 20 Years Later," Proceedings of the Human Factors and Ergonomics Society (HFES) 50th Annual Meeting, San Francisco, CA, 16-20, Oct. 2006.

[20] Likert, Renis, "A Technique for the Measurement of Attitudes," Archives of Psychology, 140, pp 1-55, 1932.

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