Human-in-the-Loop Simulation of Three-Dimensional Path Arrival Management with Trajectory Error

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The Efficient Descent Advisor (EDA) is a prototype ground-based decision support tool (DST) that assists air traffic controllers in efficiently managing arrivals in en route airspace. Currently under development at NASA Ames Research Center, EDA is an extension of the Traffic Management Advisor (TMA) and a component of the Three Dimensional Path Arrival Management (3D PAM) project, a collaborative FAA/NASA/Industry effort. The objective of this study was twofold: one was to investigate the effects of fixed or dynamic turn-out points as part of the path stretch maneuver on EDA operation performance and controller workload. The other was to examine the feasibility of the 3D PAM concept under the presence of uncertainty in aircraft weight, winds, and pilot maneuver conformance. Results indicate that the dynamic start-point configuration caused more corrective advisories to be issued, and made the traffic patterns more complex, though the configuration had little impact on controller workload. Results also demonstrated that the inclusion of uncertainties of the chosen magnitude did not significantly impact either EDA functions or usability for the traffic simulated.

I. Introduction

The Three-Dimensional Path Arrival Management (3D PAM) Project is a joint effort between the Federal Aviation Administration (FAA) and National Aeronautics and Space Administration (NASA) to develop an advanced ground-based automation capability for NextGen. The automation will generate fuel-efficient trajectories incorporating Optimized Profile Descents (OPDs) that aircraft can fly using existing airborne automation.[1] The 3D PAM concept is a near-to-mid-term component of the FAA Next Generation Air Transportation System (NextGen) Implementation Plan, and represents an initial implementation of Trajectory Based Operations (TBOs).[2] In order to minimize required ground or airborne technology changes that might delay deployment, the 3D PAM concept is focused on using existing aircraft capabilities, specifically the lateral and vertical navigation (LNAV/VNAV) functions used in the Flight Management Systems (FMS) of modern transport aircraft. In addition, the initial development and deployment is targeted for use in Air Route Traffic Control Centers (ARTCCs) and will be based on existing ground automation capabilities, specifically the Traffic Management Advisor (TMA).[3] The new ground-based automation capability will generate paths that incorporate a fuel-efficient descent trajectory from cruise to the meter fix closest to the TRACON boundary and present this information as an advisory to the Air Route Traffic Control Center (ARTCC) sector controller. The controller then issues a clearance via voice to the aircraft for entry into the FMS by the pilot. When the clearance is entered into the FMS, the aircraft has all the information it needs to automatically fly an efficient descent while also meeting the TMA-scheduled time of arrival at the meter fix. This significantly reduces the number of controller interactions with each aircraft required to achieve the desired flow of traffic into the Terminal Radar Approach Control (TRACON). The anticipated benefits are fuel savings and reduced emissions due to flying a more efficient vertical profile, and reduced frequency congestion and controller and pilot workload while achieving the desired traffic flow specified by TMA.

The 3D PAM core technology is the Efficient Descent Advisor (EDA), a ground-based decision support tool (DST) currently under development by NASA. Over the past several years, EDA research and development has

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proceeded incrementally through a combination of simulations and field tests and will culminate in an EDA prototype. This prototype will be part of a larger 3D PAM technical transfer package between NASA and the FAA and will enable continued development and eventual deployment of the EDA ground automation capabilities. Recent efforts have relied on a series of high fidelity, human-in-the-loop simulations to develop and evaluate the concept and design of EDA as a decision-support tool for the radar-position (R-side) ARTCC sector controller. The objective is to produce a working prototype as a basis for design and performance specifications. By relying on high fidelity simulations with traffic scenarios and airspace conditions that represent end-state operations, the 3D PAM concept and prototype can be matured to the greatest extent possible prior to pursuing more costly and intrusive field evaluations. A recent paper provides additional details on the 3D PAM EDA operational concept as well as findings from previous simulations and field activities.[4] This current paper presents a brief overview of the 3D PAM concept, followed by details of the fourth human-in-the-loop simulation experiment conducted to investigate the impacts of fixed versus dynamic start-points in path-stretch maneuvers and uncertainty in wind, aircraft weight and turn-out initiation on traffic-flow management performance and controllers' subjective workload. This simulation, completed in December 2010, is part of a planned series of seven EDA Human-In-The-Loop (HITL) simulations and was the first to include active Denver ARTCC (ZDV) controllers. The remainder of the paper is organized as follows: Section II presents an EDA overview, Section III describes EDA phraseology, Section IV describes the simulation environment, Section V presents the simulation's experiment design, Section VI discusses the results of the simulation, and Section VII provides conclusions and next steps.

II. EDA Overview

The primary function of the EDA ground automation is to assist the controller in implementing the TMA-derived schedule for arrival aircraft while providing an efficient OPD for the aircraft. The TMA-Scheduled Times of Arrival for aircraft is frozen at the freeze horizon, an arc of radius 130 NM to 200 NM centered at the meter fix. Once the TMA schedule is frozen, if an aircraft is not projected to be at the meter fix within 20 seconds of its scheduled time of arrival, an EDA portal will appear in the flight data block, and, when clicked, the EDA advisory formulation cycle is initiated. Once complete, the controller is presented with an EDA advisory. The EDA advisory provides the required FMS input data for the aircraft to fly a 4D trajectory (cruise speed, descent speed, and lateral path) which will meet the aircraft's STA at the meter-fix. This trajectory is based on a Mach/Calibrated-Airspeed (CAS) transition idle descent that most modern transport aircraft are capable of flying using FMS VNAV capabilities. In addition, EDA employs conflict detection and avoidance in an attempt to formulate advisories that are conflict-free at the time the advisory is generated. If EDA is unable to generate a conflict-free advisory, the controller will be notified through the EDA advisory window which will provide information regarding the potential conflict or conflicts. The controller can use this information to evaluate the advisory and then choose whether or not to accept and issue or to ignore the EDA advisory. A corrective advisory is provided if an aircraft falls out of compliance (20 seconds) with its Scheduled Time of Arrival after its first EDA advisory. Figure 1 shows the EDA advisory formulation process and the four EDA core functions: meet-time automation, conflict detection, conflict avoidance and corrective advisories. Each of these core functions is described in greater detail in the following sections.
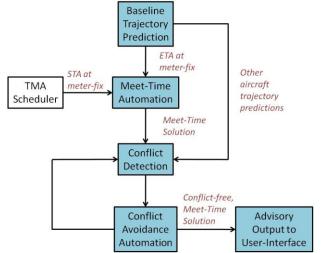

Figure 1. EDA Advisory formulation process

A. Meet-time Automation

A primary goal of the EDA DST is to provide the controllers with advisories that assist them in ensuring that aircraft can meet time restrictions (STAs at the meter fix) generated by the TMA system. In order to specify a 4D trajectory that includes a fuel efficient OPD the following information must be provided to the aircraft FMS: cruise speed (Mach), descent speed (CAS), lateral route, and environmental data such as winds. This assumes that: 1) the trajectory terminates at meter fix with hard altitude / speed constraints; and 2) the aircraft flies a Mach / CAS idle descent with the transition between Mach and CAS taking place where appropriate. If the TMA-derived STAs require an aircraft to be delayed, the EDA meet-time solution cycle first attempts to find a speed advisory to absorb the required amount of delay, a solution from the 'Meet-Time Automation' box in Figure 1. If a speed-advisory is not sufficient, a path stretch advisory is considered. The speed profile associated with a path stretch advisory is typically the slowest advisable cruise and descent speed. This initial meet-time solution is then probed for conflicts in the next stage of the EDA advisory formulation process. Each of the speed and speed/path types of meet-time advisories is illustrated below.

1. EDA Speed-Only Advisory:

An EDA speed-only advisory will specify a new cruise speed (Mach) and descent speed (CAS). The aircraft is expected to maintain its existing lateral routing, terminating at the meter fix and complying with crossing restrictions. An example advisory presented on the controller's display may take the form of **M70/260K, TELLR1 PROF,** indicating the aircraft should cruise at Mach 0.70 and transition to 260 knots CAS in the descent and descend via the published TELLR1 profile (the TELLR1 profile clearance portion clears for an OPD). Figure 2 is an illustration of the vertical profile for an aircraft that is issued an EDA speed-only advisory. Note that all EDA advisories are issued well before the EDA-estimated Top-Of-Descent (TOD) for the aircraft. The position of the TOD will shift depending on whether the advisory provides an increased or decreased descent CAS. This initial meet-time cycle advisory is then probed for conflicts and modified in the conflict avoidance automation section of the cycle.
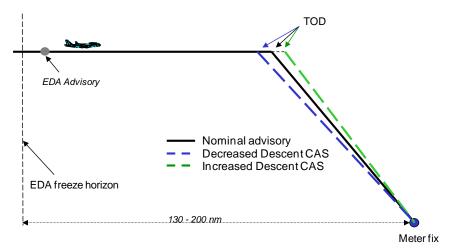

Figure 2. EDA speed-only advisory vertical profile

2. EDA Speed and Path Stretch Advisories

If a speed advisory is insufficient to absorb the required amount of delay, an EDA path stretch advisory is generated. EDA path stretch advisories, in addition to cruise speed and descent speed, include modifications in the aircraft's lateral path. The lateral path consists of three or four main points. These are: turnout, place-bearing-distance (PBD) point based on a fixed return point, the fixed return point and the meter fix (see Figure 3). Typically, a fixed start point is used in the initial meet-time cycle, but a dynamic start point can also be used, as was done in this HITL simulation. An example advisory may be: **M70/260K, @LBF..AMWAY067@32..AMWAY, TELLR1 PROF**. This information indicates that the aircraft should cruise at Mach 0.70 and transition to 260 knots CAS in the descent, then, proceed directly to LBF (turnout point) then to the PBD defined to be on the 067 radial, 32 NM from AMWAY, then direct to AMWAY (fixed return point) and then onto the meter fix. The aircraft is also cleared on

the published TELLR1 profile. Once the initial meet-time advisory has been formulated, conflict detection and avoidance is performed on the route, and if conflicts are detected, the advisory is modified as necessary.
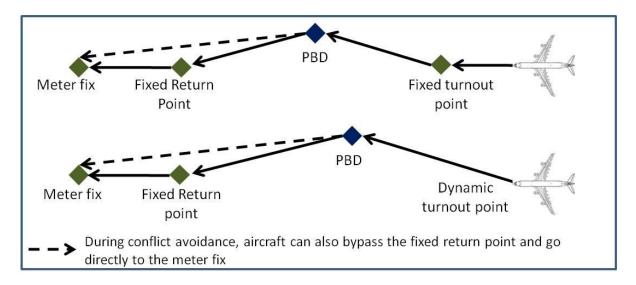

Figure 3. EDA path stretch advisories with fixed and dynamic turnout points

B. EDA Conflict Detection and Avoidance (CD&A)

Once an initial meet-time solution has been found (speed or path-stretch advisory), it is probed for conflicts by the EDA conflict detection algorithms. These algorithms, using the selectable detection settings in Table 1, probe the entire trajectory for potential of Loss of Separation (LOS) with other aircraft, from the point of EDA acceptance down to the meter-fix encompassing both the cruise and descent segments. The selectable buffers can be set according to controller preference. For example, some controllers may want to add a larger buffer than others to allow the algorithms to be more conservative when detecting conflicts.

Table 1. EDA Lateral and Vertical Separation Tolerances

Phase of Flight	Lateral Separation	Vertical Separation
Cruise vs. Cruise	e.g., 5 nm + selectable buffer	900 ft.
Cruise vs. climbing/descending	e.g., 5 nm + selectable buffer	2000 ft.
Climbing/descending vs. climbing/descending	e.g., 5 nm + selectable buffer	2000 ft.

The conflict prediction is deterministic and is based on data including aircraft flight plan, current speed / altitude, and descent speed. The conflict detection logic is only active when assessing a potential EDA advisory. It evaluates conflicts between the aircraft receiving the EDA provisional trajectories and all other active aircraft trajectories. It uses detailed information regarding airspace geometry and considers sector boundaries (ensuring airspace containment of advisories) when evaluating conflicts and path stretch advisories. If an LOS is detected, EDA conflict avoidance logic attempts to regenerate another EDA advisory which meets time and resolves the conflict within the selected vertical and lateral separation parameters. The CD&A logic uses speed, route changes or a combination of both to avoid conflicts; altitude is not used as a degree of freedom[5]. Path stretches used in conflict avoidance maneuvers can incorporate a fixed or dynamic start point for primary path stretch advisories, and only a dynamic start point for corrective path stretch advisories, but can terminate at the fixed return waypoint or at the meter fix for both types of path stretch advisories, see Figure 3. This new solution is probed once again for any LOS by the conflict detection algorithms and if an LOS is detected, the cycle continues till a conflict free, meet-time compliant solution is found or the solution space has been exhausted, i.e., all possible advisories, speed-only and speed and path stretch, have been exhausted. If the solution space is exhausted, a meet-time trajectory with the minimum number of conflicts, along with a list of conflicting aircraft, is presented to the controller. If a solution with a conflict is accepted by a controller, controllers are reminded of this fact by an indication in the Flight Data Block (FDB).

The EDA's CD&A functionality is intended to provide a strategic Conflict Avoidance capability to the controller and is active only in support of generating an advisory to solve a meet-time problem based on the TMA sequence and schedule. The strategic conflict prediction capability probes the entire EDA advisory trajectory for conflicts, from the aircraft receiving the EDA advisory's (the EDA aircraft) position to the meter-fix, which could be at least 30 minutes away from the aircraft's current position, i.e., a long time horizon. At the time of execution, the algorithms take into account flight plans of all aircraft currently in the airspace and compare them with the EDA aircraft's provisional route to determine any LOS situations. In contrast, a tactical conflict prediction capability typically uses dead-reckoning projections for all aircraft to determine LOS situations within a short time horizon. By attempting to avoid conflicts in a strategic manner while solving the meet-time problem, EDA decreases the chance that a controller will have to interrupt an OPD trajectory to manage separation downstream. In looking for conflict-free solutions, EDA only considers adjusting the trajectory of EDA aircraft in order to meet its TMA schedule; it does not look into adjusting the trajectories of other flights. Because of this inherent constraint and the requirement to meet a precise arrival time at the meter fix, EDA cannot always compute a conflict-free solution. It is important to note that when using EDA, the controller still retains full responsibility for separation assurance. Furthermore, EDA is intended to work with, rather than replace automation for general conflict detection and resolution such as the User Request Evaluation Tool (URET)[4,6] and does not currently provide an active conflict probe capability.

C. Corrective Advisories

Because of real-world uncertainties, the EDA tool needs the ability to generate corrective advisories after an EDA advisory has been issued. Uncertainties and other factors, such as an incorrect entry of speeds or path stretch waypoint into FMS, incorrect/different winds/weights in the ground-based system or aircraft, or delay in FMS execution, could cause an aircraft to fall out of meet-time compliance after the initial advisory has been issued and accepted. In such cases, EDA will issue a new corrective advisory (i.e., an amendment) which should bring the aircraft back into meet-time compliance at the meter fix. As with the primary advisory, the corrective advisory or amendment can be comprised of a speed-only advisory, or a combination of speed and path. EDA will recalculate the ETA for each aircraft based on 12-second radar updates and check for meet-time compliance. If the difference between the ETA and STA is greater than the compliance threshold (20 seconds), then the controller will be prompted to open and deliver a new EDA advisory. Corrective advisories are not issued earlier than 120 seconds after the primary advisory, or if the aircraft is within 120 seconds of its estimated TOD.

III. EDA Phraseology

The operational assumption for 3D PAM EDA is that advisories are issued via voice by controllers to the flight deck. Pilots will then enter and execute the EDA advisories in the FMS through the Control Display Unit (CDU). In the simulation environment, the controller will issue the advisory via voice to the pseudo-pilot participants (qualified private or commercial pilots who monitor the desktop aircraft simulators used in the HITL). After the pseudo-pilot correctly reads back the EDA advisory, the controller will accept the EDA advisory through the EDA window, and the advisory is automatically loaded and executed in the simulated aircraft's FMS. The prototype Computer-Human Interface (CHI) and phraseology for the EDA advisories have been developed by FAA Denver ARTCC personnel and NASA Ames researchers. The phraseology is intended to enable the controllers to issue the EDA advisories via voice with minimal impact to controller workload while ensuring compliance with the ATC handbook[7] and all associated regulations including ZDV Letters of Agreement (LOA) and Standard Operating Procedures (SOPs). Controllers have some flexibility in how they can issue the advisories. For example, an EDA advisory that contains both speed and path components can be issued in two different ways. In the following hypothetical case, the speed-only advisory for flight United 123 is issued as follows:

- Advisory:
    o M70/250K TELLR1 PROFILE

- ATC Clearance:
    o "United 123, EDA clearance, maintain mach point seven slant two five zero knots, descend via the TELLR1 profile"

A hypothetical speed/path advisory is issued to flight United 123 as follows:

- Advisory:

- o M70/250K
- o @LBF..AMWAY067@032..AMWAY TELLR1 PROFILE
- ATC Clearance:
  - o "United 123, EDA clearance, maintain mach point seven slant 250 knots, revised routing when ready to copy"
  - o "United 123, at North Platte, proceed direct to the AMWAY zero six seven at zero three two, then direct AMWAY, descend via the TELLR1 profile"

Alternatively, the controller may choose to issue the descent clearance as a separate clearance.

IV. Simulation Environment

A. Simulation Infrastructure

The simulation study was performed in the Crew-Vehicle Systems Research Laboratory at NASA Ames Research Center. Referring to Figure 4, the simulation infrastructure included: the Center-TRACON Automation System (CTAS)[8]; the Multi Aircraft Control System (MACS) which served as both desktop aircraft simulators (also referred to as the pseudo-pilot system), and as ARTCC Display System Replacement (DSR) emulators; and the Aeronautical Datalink and Radar Simulator (ADRS), a data bridge between the CTAS system (through the Input Source Manager, (ISM)) and the pseudo-pilot system. A basic TMA system was emulated with the STAs calculated by the Dynamic Planner (DP) and the ETAs calculated by the Route Analyzer (RA) utilizing the built-in Trajectory Synthesizer (TS). The JTGUI was used to set the operating parameters for the TMA system. The main EDA algorithms including conflict detection and avoidance are a part of the Profile Selector-Enroute (PFS-E) and interface with the TS. All these components are connected using the Communication Manager (CM). Three human-controlled pseudo-pilot consoles and DSRs were used to control aircraft in three simulated sectors, as explained in the next section. The National Oceanic and Atmospheric Administration's (NOAA) Rapid Update Cycle (RUC) weather was also used in both the pseudo-pilot system and CTAS for trajectory and FMS predictions as well as environment winds.
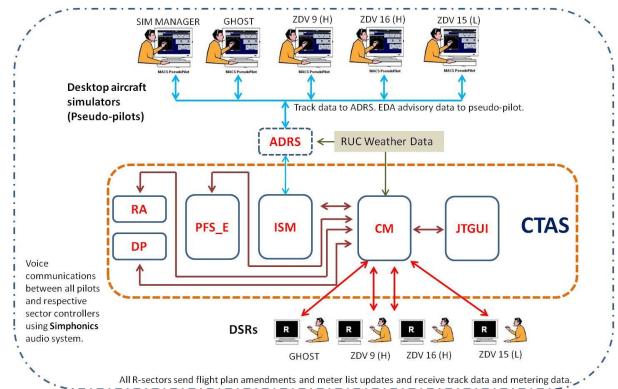

Figure 4. EDA and Simulation Environment Architecture

B. ZDV Simulated Operating Environment

The operating environment for the current simulator study included three sectors representing the northeast arrival corridor at Denver ARTCC (Figure 5):

- Sector 9, a high-altitude sector that the arrival aircraft initially enter. There are two primary arrival streams – a North flow through the YANKI waypoint, and a South flow through the LBF (North Platte) waypoint.
- Sector 16, a high-altitude sector adjacent to Sector 9. This sector contains two primary waypoints: SNY (Sidney) on the North arrival stream, and AMWAY on the South arrival stream.
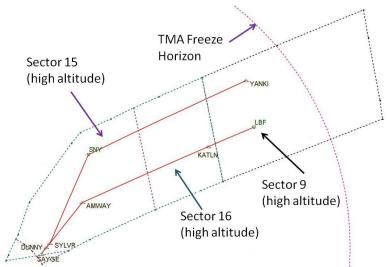- Sector 15, a low-altitude sector that merges the two flows and transitions aircraft to the meter fix (SAYGE).

Figure 5: Northeast Arrival Corridor in ZDV

Although this configuration does not include all of the arrival flows in the northeast corridor in ZDV, it was decided that the three-sector version and chosen arrival flows would provide a reasonable operating environment to emulate EDA operations.

V. Experimental Design

A. Simulation Objectives

The specific objectives of the current study included the evaluation and comparison of controller acceptance of alternative EDA configurations. The two configurations reflect differences in the logic for the construction of path stretch advisories: 1) preferred use of fixed turn-out points for path stretch advisories, and 2) sole use of dynamic turn-out points for path stretch advisories. In addition, the impact of trajectory prediction uncertainty on EDA usability and controller acceptance was evaluated. Accurate and precise trajectory predictions are essential to the success of EDA. Ground-based trajectory predictions must adequately model trajectories resulting from FMS guidance and control, including any compensating pilot inputs. The accuracy of EDA trajectory predictions is limited by uncertainty in inputs such as forecast winds, aircraft weight and aircraft aerodynamic and propulsive performance models.[4] The trajectory prediction errors were based on field test data and were introduced into the simulation through variations in winds, aircraft weights, as well as variations in turn-out execution times for dynamic turn-out point path stretch advisories. This represented a crucial step in the design and evaluation of the 3D PAM concept and the EDA prototype.

B. EDA Configurations

In the first EDA configuration, the software would attempt to utilize fixed turn-out points for path stretches. However, in cases where: 1) the aircraft had passed the fixed turn-out point, 2) the aircraft was too close to the fixed turn-out point, or 3) conflict avoidance maneuvers were required, an advisory with a dynamic turn-out point would be generated. In the second EDA configuration, path stretches using dynamic turn-out points were used in all cases where a path stretch was required. One motivation for considering the use of dynamic turn-out points is that they might simplify future airspace adaptation where fixed turn-out points are not available.

Note that path stretches could still end at either a fixed return point or the meter fix for both design configurations. Speed advisories still were issued in both configurations if the amount of delay to be absorbed was minimal. The evaluation of the two configurations included examination as to whether the use of either type of turn-out point for path stretches significantly impacted the EDA performance, such as the number of corrective advisories generated in each of the configurations, and the controller's perceived workload.

C. Modeling of Uncertainties in the Simulation Environment

One of the main goals of this simulation was to determine the effect of real-world trajectory prediction uncertainty factors on EDA performance and controller workload. Three sources of uncertainty were included in the HITL simulation environment: 1) a difference between actual aircraft weight and the aircraft weight as modeled by EDA, 2) a difference in pseudo-pilot winds and EDA trajectory prediction winds, and 3) differences between the time the aircraft would turn out compared to when EDA predicted the aircraft would turn out during dynamic turn-out path stretches. These variations would induce differences in the predicted aircraft state in the ground automation (i.e., EDA) and the predicted state in airborne automation (i.e., FMS) and actual aircraft state. In this way, the impact of real-world trajectory prediction uncertainty on the usability and performance of the EDA tool could be evaluated. The variations in weight, winds, and turnout initiation were selected to approximate distributions of the TOD locations of OPD operations and their meter-fix-crossing time prediction errors observed in the ZDV field trial in 2009[9].

For uncertainty in weight, a random aircraft-specific weight was assigned to each aircraft flown in the scenario by the pseudo-pilot system, ranging from 75% and 110% of the nominal descent aircraft weight used in EDA trajectory predictions. This resulted in a rough range of the empty weight + 5000 lbs to the maximum landing weight for each aircraft type. To aid controllers in determining where an aircraft may descend and to account for the added uncertainty, uncertainty bars, 5NM on either side of the predicted TOD, were shown on the DSR when the aircraft's active route was shown.

For the wind uncertainty, two different Rapid Update Cycle (RUC) wind files were input to EDA and the pseudo-pilot system. The files were chosen such that the difference between the two files reflected real-world differences as found by comparing predicted wind files with the actual recorded wind speeds and directions as detailed in a study by Schwartz et. al.[10]

For the uncertainty in dynamic turn-out path-stretch initiation, we used data from Boeing Flight Deck HITL[11] simulations. This data indicated how long it took pilots to enter EDA advisory data which incorporated a path stretch with a dynamic turn-out, into the FMS. The mean value used was 11.6 seconds with a standard deviation of 8 seconds. A random value within this distribution was assigned to each aircraft in the simulation.

D. Simulation Traffic Scenarios

Three distinct traffic scenarios representing heavy arrival rushes from the northeast arrival corridor were used to evaluate EDA performance. The traffic scenarios were derived from historical recorded traffic provided by NASA. Traffic files were processed and filtered to include only jet transport arrivals traversing the ZDV Northeast sectors to Denver TRACON and overflights in the ZDV Northeast sectors. The three traffic scenarios varied in the distribution of traffic and delay magnitudes, but all scenarios represented a nominal arrival rate of 36 aircraft per hour, a typical rate during peak-traffic time, and 7 nautical mile separation at the SAYGE meter fix based on two flows merging at the meter fix. Each aircraft in each scenario was randomly assigned an aircraft specific weight along with a randomly chosen turn-out initiation delay. The same wind files were used in each scenario and data run, but the combination in which they were used differed. In this HITL, two combinations were used. For two of the scenarios, weather file A was used in EDA trajectory predictions and weather file B in the pseudo-pilot system. In the third scenario, weather file B was used in EDA trajectory predictions and weather file A was used in the pseudo-pilot system. The two different combinations resulted in all aircraft being late at the meter fix or all aircraft being early at the meter-fix.

A total of 18 simulation runs were conducted in a counterbalanced order (2 Configurations × 3 Scenarios × 3 Sectors = 18 Runs). The run schedule was structured so that controllers would rotate through the sector positions to evaluate each combination of configuration and traffic scenario. No data-position (i.e., D-side) functions were simulated, and each controller performed both D- and R-side functions.

E. Metrics and Data Collection

In order to capture feedback in real time, observers monitored each controller station during the simulation runs and noted feedback from the controllers as well as non-EDA controller actions such as issuing heading, speed, and altitude changes for sequencing or spacing. After each simulation run, controllers were given questionnaires to

evaluate their maximum and average workload during the simulation run based on the Modified Bedford Workload Scale.[12] After each simulation run, a debrief session was held to discuss operational, design, CHI, and other relevant issues identified by the controllers. Additional data including radar track data, EDA advisory information and TMA meter list data were collected for further analysis.

VI.   Results and Discussion

In this section we discuss the analytical results including: 1) the evaluation of the two alternative EDA design configurations, 2) controller feedback on perceived workload, 3) controller feedback on the use of the EDA automation, and 4) the impact of uncertainty on EDA trajectory prediction performance.

A. Alternative EDA Design Configurations

As previously mentioned, one of the primary functions of EDA is to provide meet-time advisories to controllers. The meet-time advisories can include both primary and corrective advisories. In theory, EDA automation could generate primary meet-time advisories that would enable all EDA aircraft to successfully meet their required sequence and schedule at the meter fix. In practice, because of uncertainties in trajectory prediction, variability in aircraft performance, and controller actions such as heading, speed or altitude changes, EDA will need to provide corrective advisories as well. The number of EDA advisories generated can have an impact on the usability of the EDA automation because each advisory will impact controller workload.

We compared the number of advisories generated for each of the two EDA configurations. Figure 6 shows the number of aircraft that received 0, 1, 2, 3 or 4 EDA advisories, parsed by scenario, controller combination, and EDA configuration. Although the resulting traffic pattern in each run was unique, the initialization parameters and amount of delay each aircraft needed to absorb was constant within scenarios. Because the same controller was sitting at the same position in both the EDA configurations, it was possible to directly compare the number of EDA advisories issued to the aircraft across the scenarios. Results show for the entire experiment, 87 aircraft received two or more EDA advisories in the Dynamic configuration, compared with 48 aircraft in the Fixed configuration. This is likely due to the delayed turnout initiation introduced into the runs involving a dynamic turn-out point of the path stretch advisory. Even though the EDA logic incorporated a nominal "look-ahead time" to account for the time to deliver the advisory and for the pilot to enter the advisory parameters into the FMS, in reality, the aircraft could start its turn earlier or later than this nominal look-ahead time. If the aircraft started its turn later, it would not be able to absorb as much delay as needed to meet the TMA-derived STA, resulting in a corrective advisory to once again delay the aircraft. If it started its turn earlier than what the EDA logic predicted, it may be on a path to absorb an excess amount of delay, so EDA would issue a corrective advisory to increase the aircraft speed.
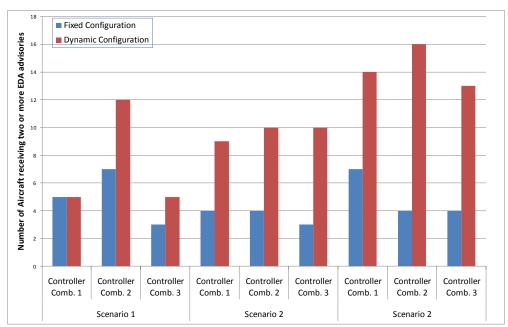

Figure 6.   Number of aircraft receiving two or more EDA advisories

Over the course of the experiment, controllers noted that there seemed to be an increase in north-south traffic near the sector 9 and 16 boundary during the runs in which EDA issued path stretch advisories with only dynamic turn-out points (Dynamic configuration). The controllers indicated that this might increase the difficulty in managing the traffic situation. However, this result could be airspace specific due to the distance between the freeze horizon and sectors 9/16 boundary. In the Northeast Denver airspace, the distance between the freeze horizon and the sector 9/16 boundary is about 55 NM, which, if an aircraft is flying a ground speed of 350 knots, gives the controller and pilot 9.5 minutes to deliver and enter the EDA advisory into the FMS. With the dynamic turn-out point, turns could easily occur close to or even on the sector 9/16 boundary. Aircraft turning north or south to absorb delay at sector boundaries can be confusing to controllers and can impact situational awareness. Figure 7 depicts the traffic in two runs at the sector 9/16 boundary for the same scenario and controller group: path stretches using a predominantly fixed or turn-out point (plot on left), and path stretches using only a dynamic turn-out point (plot on right). It can be seen that with path stretches using the predominantly fixed turn-out point, traffic is concentrated on a set number of paths, while with path stretches using only dynamic turn-out points, the tracks seemed to be less predictable and more diffuse. In addition, controllers had to cope with the additional uncertainty of turn-out initiation time during the path stretches with dynamic turn-out points, further increasing complexity.
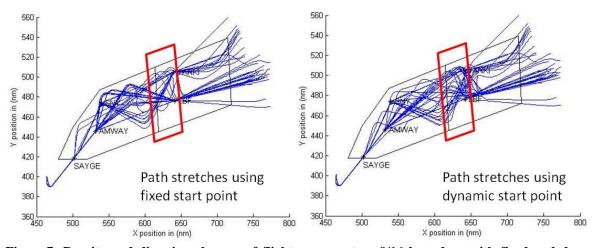

Figure 7. Density and direction changes of flights near sectors 9/16 boundary with fixed and dynamic start points

B. Perceived Workload and Controller Feedback

Controllers' subjective workload levels were measured and assessed for the effects of the EDA Configurations. The workload ratings were collected on the post-questionnaire form after each run. The Modified Bedford workload scale was used for the rating. The scale consists of ten levels of workload, where 1 is the lowest workload and 10 is the highest. The maximum and the average workload ratings were collected in each run.

The collected ratings were subjected to a mixed-model Generalized Linear Model. The model included five main effects, Configuration (Fixed and Dynamic), Sector (9, 16, and 15), Run Group (the First, Second, and Third six runs), Participant (Controllers 1, 2, and 3), and Scenario (Scenario 1, 2, and 3). The main interest of this study was the configuration effects; thus, the following two-way interaction effects were also included in the model: Configuration × Sector, Configuration × Run-Group, Configuration × Participant, Configuration × Scenario. In this model, Participant and the Scenario effects were treated as the random effects, because their levels were considered to be sampled from larger population against which the hypothesis test was conducted[13]. Configuration, Sector, and Run-Group effects were treated as the fixed effects. Thus, the analysis was a mixed-model analysis. Since the model included more than one random effect, the *quasi-F-ratio* (denoted as F^*) instead of the regular *F*-ratio (denoted as F) was used for computing the *p*-values for the fixed effects. The analysis results of the maximum and the average workload ratings were similar; thus, only the results of the average workload ratings are presented here. The result showed Configuration, Sector, Participant, and Condition × Run-Group effects to be statistically significant ($F^*_{3.28, 3.38} = 8.81$, $p = 0.042$; $F^*_{2.12, 6.90} = 7.67$, $p = 0.017$; $F_{2, 4} = 22.2$, $p = 0.007$; $F^*_{9.24, 7.88} = 4.22$, $p = 0.028$; respectively). Sector and Participant effects were expected, because Sectors 9 and 16 were usually busier than Sector 15, and people often have personal biases in selecting the workload ratings. The main interest of the study was the Configuration effect. To visualize the Configuration main effects, Figure 8 plots the means and standard errors of

the post-run average workload ratings for each condition. Figure 8 shows that the dynamic turn-out configuration resulted in slightly higher average workload ratings than the fixed turn-out configuration. The absolute difference between the means was small (0.31), however. It is always difficult to interpret a case where the difference is small but statistically significant. The important question is if the Configuration effect is operationally significant or not.
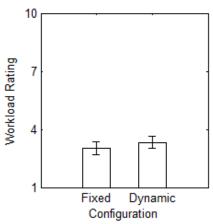

Figure 8: Means and standard errors of post-run average workload ratings by EDA Design Configuration

To examine that, Figure 9 depicts the Condition × Run Group interaction effect, another effect found statistically significant, by plotting the means of the workload ratings by each run group by each configuration. The plot shows that the average workload ratings steeply increased when the dynamic turn-out configuration was used rather than the fixed turn-out configuration especially during the first six runs (the solid line) compared to the later runs. This implies that there was learning in handling the dynamic turn-out configuration during the earlier runs.

Considering 1) the overall workload difference between the fixed and dynamic turn-out configurations was so small that it may be negligible, and 2) the controllers were able to learn to adapt to the dynamic turn-out configuration after a couple of runs, the study concludes that the configuration effect in the workload ratings is probably not operationally significant as long as controller training is provided to counter the slight workload increase.
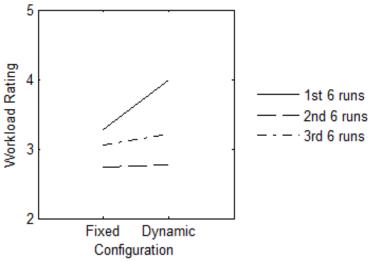

Figure 9: Means of post-run average workload ratings by Configuration × Run-Group.

The controllers' preference between the fixed vs. dynamic turn-out configurations was asked on the post-experiment questionnaire form. A continuous preference scale, where the left end of the line represents *Preferred Fixed*, the right end represents *Preferred Dynamic*, and the center was *Neutral*, was presented, and the controllers marked the point on the line that reflected their preference levels. Two controllers marked neutral, and one controller

marked near the dynamic end. This result is consistent with the workload analysis results that indicated there was no remarkable controller workload advantage/disadvantage in either EDA configuration as long as adequate initial training is provided for the Dynamic start-point configuration. The controllers' comments also showed that the dynamic turn-out configuration shortens the phraseology, but may cause a sense of urgency to accomplish the maneuver sooner. The controllers also expressed a concern as to whether pilots would be always able to comply with the dynamic turn-out point instruction for a path stretch due to time or workload constraints.

C. Impact of Uncertainty on Number of Tactical Maneuvers

Another difference seen between the Fixed and Dynamic configurations was the number of tactical maneuvers controllers had to issue to avoid LOS situations or TOD uncertainty issues. Figure 10 shows the number of tactical maneuvers undertaken due to potential LOS situations and TOD uncertainty.
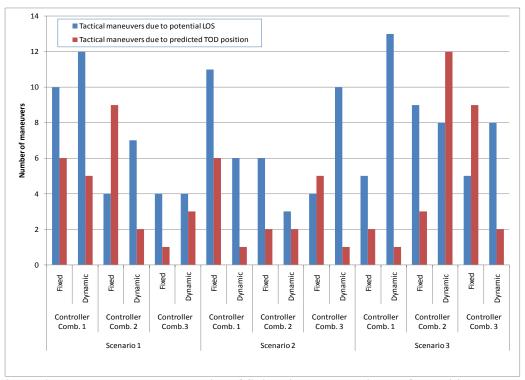

Figure 10: Tactical Maneuvers due to potential LOS situations and predicted TOD position

Data are grouped by controller combination and scenario to allow for direct comparison. From Figure 10, it can be seen that for 5 out of the 9 pairs, the number of tactical maneuvers was less for the Fixed configuration than for the Dynamic configuration. The increase in tactical advisories in the Dynamic configuration could be attributed in part to the turn-out initiation uncertainty which is more prevalent in the Dynamic configuration than the Fixed configuration. This uncertainty results in aircraft not flying on the de-conflicted path that EDA's CD&A logic had determined with its look-ahead time as mentioned in section VI.A resulting in a possible increase in LOS situations which, to solve, require controllers to issue tactical commands.

The number of tactical maneuvers due to TOD prediction error decreased from the Fixed configuration to the Dynamic configuration for six of the nine pairs, increased for two pairs and is equal for one pair. This result could be due to the increased variability in the lateral paths of aircraft in the Dynamic configuration compared to that in the Fixed configuration (see Figure 7), thus increasing the spread of possible TOD locations in the Dynamic versus Fixed configuration. The number and paths of overflights was fixed for all scenarios, so with a wider spread of TOD locations in the Dynamic configuration, the number of possible LOS situations between arrivals descending on top of overflights is reduced. This, in turn, would reduce the number of tactical maneuvers undertaken due to TOD prediction error.

While the increased spread of TOD locations of arrival aircraft may have decreased the number of tactical maneuvers in the Dynamic configuration, the random selection of aircraft weights introduced in each run as described in section V. sub-section C, also introduced TOD uncertainty along the actual aircraft track. Not only does

the difference in weights in the simulated aircraft and the EDA trajectory prediction (EDA TP) have an impact on the TOD, the difference between the winds in the aircraft or pseudo-pilot system and the EDA trajectory predictions also impacts the TOD location. The combined impact can be seen in Table 2.

Table 2.   Effect of wind and weight difference on TOD

	Winds match in aircraft and EDA traj. predictions	Resultant tailwind in aircraft (EDA TP has stronger headwind than aircraft headwind)	Resultant headwind in aircraft (EDA TP has weaker headwind than aircraft headwind)
Aircraft weight = EDA TP weight	N/A	Aircraft descent is earlier than EDA TP	Aircraft descent is later than EDA TP
Aircraft weight is > EDA TP weight	Aircraft descent is earlier than EDA TP	Aircraft Descent is earlier than EDA TP	Depends on relative magnitudes
Aircraft weight is < EDA TP weight	Aircraft descent is later than EDA TP	Depends on relative magnitudes	Aircraft Descent is much later than EDA TP

The difference in TODs can cause situations in which LOS can occur. For example an overflight may be flying at a lower cruise altitude than the arrival aircraft, and if the arrival aircraft has a heavier weight than EDA has modeled, then the aircraft will begin its descent sooner than the prediction. The TOD errors are shown in Figure 11 and indicate that, with the chosen random weights, more than half of the aircraft descend earlier than the predicted TOD. This could be due to two of the scenarios (12 data runs) having a resultant tailwind in the pseudo-pilot system, causing aircraft to descend earlier than the EDA predicted TOD (see Table 2). A marker on the EDA provisional route was provided to represent the range of possible error around the predicted TOD. However, controllers stated that they did not rely heavily on the TOD range error marker in judging potential LOS. As previously mentioned, in instances where controllers judged that a LOS might occur, they would issue speed, heading or altitude changes as needed in order to maintain separation.

Although controllers did not indicate any significant impacts on EDA usability for the traffic conditions simulated in this experiment, it is assumed that for eventual operational use, there will need to be some sort of mechanism to mitigate the potential impact of TOD prediction errors on controller ability to maintain safe separation of traffic. One idea under consideration is a visual indication on the DSR to represent an area of airspace that needs to be protected around descending aircraft. Another idea that has been discussed is a "handshake" between the pilot and controller via voice communication or datalink message at or before the point at which the aircraft actually begins to descend.
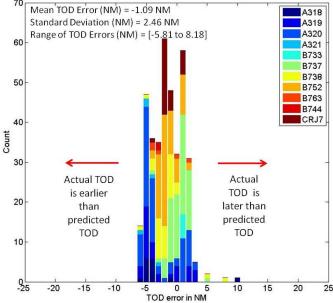

Figure 11.   Difference between actual and predicted TOD (TOD error)

In this simulation, two traffic scenarios utilized a wind configuration in which the winds in the pseudo-pilot system had a lower magnitude headwind than the winds input to EDA for trajectory predictions. The third scenario

represented the converse situation, with a stronger magnitude headwind in pseudo-pilot (PP) system than that used in EDA for its trajectory predictions. The impact of these differences in winds can be seen in Table 3.

Table 3.   Impact of wind difference on arrival time at meter fix

	Ground speed differences	Impact on arrival time at meter fix
EDA predicts stronger headwind than that encountered by aircraft	EDA TP predicts lower ground speed than actual PP ground speed	Actual time of arrival is earlier than predicted time of arrival – delay needed
EDA predicts weaker headwind than that encountered by aircraft	EDA TP predicts higher ground speed than actual PP ground speed	Actual time of arrival is later than predicted time of arrival – speed up needed

Figure 12 is a histogram of the measured difference between the STA and the actual time of arrival (ATA) at the meter fix across all the runs. The plot shows that most aircraft arrived early at the meter fix. This is attributable to the fact that more runs (two scenarios) include higher winds in EDA than in the pseudo-pilot system, resulting in a positive mode. Near the meter fix, controllers focused primarily on maintaining sufficient spacing between successive aircraft, and did not attempt to reduce meter fix crossing-time-error to zero because speed or path changes would have minimal effect very close to the meter fix.
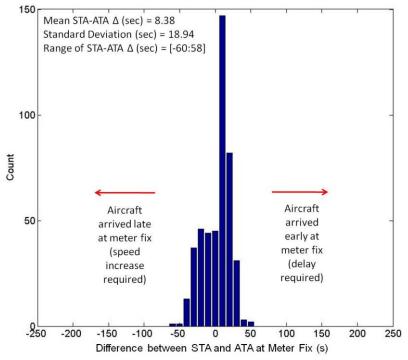

Figure 12.   Difference between STA and ATA at meter fix

VII.   Conclusion

The results of the data analysis, controller feedback, and observations indicate that the 3D PAM concept is feasible for the sources and magnitude of uncertainty modeled in this simulation. Although the EDA algorithm did include a nominal look-ahead time to account for the time required to deliver and execute the EDA advisory, the aircraft may still turn earlier or later than this time, resulting in a different trajectory being flown than that predicted by EDA. This difference in path, coupled with the difference between predicted winds and wind aloft, could cause a mismatch between the STA and ETA, resulting in a corrective advisory. More than half of the aircraft descended before their predicted TOD due to the wind and weight combinations used in the runs. However, controllers did not indicate that the TOD errors significantly impacted their ability to use EDA effectively as a decision support tool.

Comparing the Dynamic and Fixed EDA configurations, 87 aircraft received two or more EDA advisories in the Dynamic configuration, with 48 aircraft receiving two or more advisories in the Fixed configuration. The Dynamic configuration increased the amount of traffic on the sectors 9 and 16 boundary leading controllers to perceive a higher traffic complexity than the Fixed Configuration. Although the Dynamic configuration had slightly higher average workload ratings than the Fixed configuration, a learning curve was evident in the data analysis, leading to the conclusion that as long as controllers are provided adequate training, the Dynamic configuration should not pose any workload problems. However, controllers also mentioned other concerns regarding the use of Dynamic turn-outs and indicated in discussions that the consistency provided by the use of Fixed turnouts would make that the preferred EDA configuration.

The results of the HITL simulations and field trials conducted to date suggest that the 3D PAM concept and the underlying EDA automation are viable candidates for near-to-mid-term implementation as a NextGen capability that will enable TBO. Next steps include additional HITL simulations that will develop the concept and EDA prototype software to a level of maturity to enable a successful technology transfer to the FAA. Functions that are identified as necessary to successful EDA implementation will be identified as requirements to be included as part of the technology transfer package between NASA and the FAA. Operational considerations identified during the HITL simulations will be documented. For example, there has been discussion among controllers and EDA development personnel that for operational deployment, there will need to be a mechanism to mitigate the impact of TOD prediction errors. In addition to the HITL simulations, other types of data analyses (such as closed-loop simulations) will be performed to better quantify trajectory prediction error and its impact on the usability and feasibility of EDA as a decision support tool.

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