EN ROUTE DESCENT ADVISOR CONCEPT FOR ARRIVAL METERING

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Abstract

The En-route Descent Advisor (EDA) is a set of decision support tool (DST) capabilities for managing complex en route traffic subject to metering restrictions. The goal is to enable controller procedures to evolve from today's emphasis on sector management towards procedures more oriented towards trajectory management. EDA will help controllers transition traffic from a "Free Flight" (minimally restricted) en route environment into an efficiently organized arrival flow into terminal airspace. EDA assists controllers with high-density arrival metering by providing fuel-efficient metering-conformance advisories that are integrated with conflict detection and resolution (CD&R) capabilities. Results of engineering analyses indicate that EDA advisories, based on accurate trajectory-prediction techniques, have the potential to reduce the rate of conflict-probe false alarms and missed alerts by 20% and improve the efficiency of transition airspace operations resulting in an annual nation-wide benefit of $ 291 million.

Introduction

Airspace users would like the National Airspace System (NAS) to be managed more dynamically than it is today with fewer air traffic control (ATC) restrictions.[1] Continued growth in traffic congestion will require increased use of dynamic flow restrictions (i.e., metering) to efficiently manage congestion and delays. This in turn will increase delays and deviations from the user's preferred trajectory within the en route airspace transitioning to congested terminal areas. The controller's ability to efficiently manage such situations today is limited by the tactical nature of current techniques for metering conformance (described in the next section) and the lack of supporting automation.

As part of the Free Flight Phase One (FFP1) program, the Federal Aviation Administration (FAA) is implementing the first generation of decision support tools (DSTs) for modernizing the National Airspace System (NAS). FFP1 products include two en route DST capabilities, the Traffic Management Advisor (TMA), and the User Request Evaluation Tool (URET).[2,3] TMA is a Center-TRACON Automation System (CTAS)[4] tool that enables en route traffic managers to meter arrival traffic through the distribution of metering delay times to en route sector controllers. URET is an initial implementation of conflict-probe (CP) capabilities to assist controllers with the prediction and resolution of conflicts. Conflict predictions are based on the computer analysis of radar-track and flight-plan data; controller resolutions are supported by trial-planning (what-if) tools.*

To achieve greater en route flight efficiency and user flexibility, additional DST capabilities are needed to help controllers strategically plan their metering actions with greater consideration for the downstream impact. Even with FFP1 capabilities for CP (URET) and arrival metering (TMA), controllers have no automation to help develop a conflict-free metering-conformance plan. In addition, the trend towards user flexibility and collaboration (between users and ATC) will be curtailed by the limitations of today's procedures for managing traffic between (and within) sectors.

While flight operations are managed from a trajectory point of view (user emphasis on flight limitations, preferred path, and schedule), air traffic operations are managed from an airspace point of view.[5] This paradox is a primary obstacle that must be overcome to fully realize the potential benefit of Distributed Air-Ground Traffic Management (DAG-TM) concepts.[†6] Although today's procedures may be supported by automation to yield some benefit, a fundamental change is needed to significantly increase controller productivity and the accommodation of user preferences (flexibility).

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* The generic reference to conflict probe is used here to focus on the core capabilities as opposed to the actual implementation of those capabilities in a specific software architecture. Additional FAA-sponsored research is underway to develop the Problem Analysis Resolution and Ranking (PARR) capability to enhance URET with automated resolution advisories.
† DAG-TM is a proposed instantiation of the Free Flight concept that attempts to increase throughput while striking a balance between user preferences and the equitable use of airspace resources.

The En route Descent Advisor (EDA) concept proposes DST technology to enable new procedures within en route airspace that support the transition of arrivals into high-density terminal airspace. EDA fills a void by providing controllers with automatic advisories for metering conformance that are integrated with capabilities for conflict detection and resolution (CD&R). This integrated advisory approach will enable controllers to efficiently meter flights upstream of congested airspace while ensuring separation. This paper describes the challenges of "transition" airspace, presents the core EDA capabilities, illustrates the EDA concept with an arrival-traffic scenario, and presents the potential benefits enabled by EDA capabilities.

Transition Airspace Challenges

Transition airspace is defined as en route airspace that transitions arrivals into the terminal area. In addition to the complex mix of aircraft types in all three phases of flight (climb, cruise, and descent), transition airspace typically involves complex traffic patterns (merging and crossing), and the natural compression of arrival traffic (descending/decelerating out of cruise). Perhaps the most complicating aspects of transition airspace are the delays and trajectory deviations associated with congestion in high-density areas. Metering restrictions are often imposed in response to dynamic overloads of airspace/airport capacity. This is important to the users because these restrictions are a significant cause of trajectory deviations, and the frequency of their occurrence is growing as airspace and airports become more congested. To improve the efficiency of transition-airspace operations, three critical challenges must be addressed: controller intent, metering conformance, and inter-sector coordination.

Controller Intent

Accurate knowledge of flight intent (route, speed, and altitude profile) is commonly considered the most critical component of trajectory prediction, the cornerstone of DST automation. Except for cases involving pilot-initiated deviations, intent modeling requires knowledge of the controller's planned actions. Transition airspace is particularly challenging due to the high frequency of flight profile changes, especially during metering/spacing operations.

Even with FFP1 tools, the lack of metering-conformance intent presents a problem. For CP, this lack of intent information introduces trajectory-prediction errors that may lead to missed alerts and/or false alarms. A metering-conformance action may actually avoid a conflict, that would otherwise have been predicted, and/or create an emergent problem that was not originally considered a factor. Figure 1 illustrates a scenario involving three flights. The eastbound arrival is transitioning to a congested terminal area and will be subject to arrival-metering delays. The other two flights represent crossing traffic that is coincidentally at the same altitude. In this situation, CP would predict a conflict between the Arrival and Overflight-A based on the latest track data and flight-plan information stored in the ATC Host computer. However, metering delays will result in a different trajectory for the Arrival than predicted by CP automation. In addition, missed alerts with other traffic may occur because controllers do not typically amend the Host flight plans* to reflect these tactical actions.[7,8] This performance degradation may significantly reduce the operational usefulness and acceptability of CP alerts during metering operations, a critical time when such decision support automation assistance may be needed.

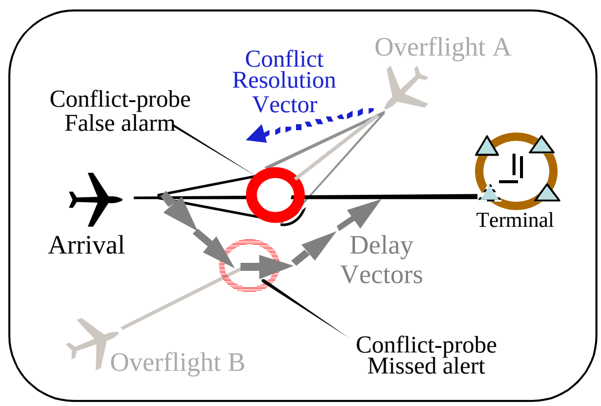

Figure 1. Conflict probe sensitivity to metering intent.

Metering Conformance

Although current methods for metering conformance vary with controller experience and technique, metering actions tend to be relatively tactical in nature with iterative corrections used to achieve conformance. Vectors are common since the tactical approach leaves little time or opportunity for speed reductions to be effective. Although TMA provides en route controllers with arrival-metering lists including arrival sequence, meter-fix times, and delay feedback, it does not provide the controller with clearance advisories to meet the meter-fix times. While the CP trial-planning function can be used to plan conflict resolutions, the function

* Current-day Host flight-plan ("6-7-10") amendments were designed to support flight plan processing and sector posting of flight strips (flight-plan data). Amendments are cumbersome for controllers to implement, due to the limitations of the controller interface, and have undesirable side effects on the generation and posting of flight strips.

does not consider metering conformance in its current operational implementation, and the manual nature of the trial-planning approach to problem resolution can be workload intensive if required on a frequent basis.

The tactical nature of current metering-conformance techniques makes it difficult for DSTs to model and predict controller intent. In addition, the manual aspect requires a significant amount of work on the controller's part over and above their nominal duties. Current procedures only require metering conformance to within approximately 1-2 min per flight.[2] Even if trial planning was applied to the metering-conformance problem, this level of uncertainty is problematic with respect to conflicts in that one minute of time error may exceed the 5 nm requirement for en route separation resulting in the need for additional actions to maintain separation between sequential flights.

Inter-sector Coordination

Controller procedures have evolved over several decades of radar control to be highly adaptable and robust to "off-nominal" events such as missed clearance, pilot deviation, lost communication, and missed coordination between sectors. The result is an unprecedented level of safety in terms of aircraft separation. However, given the limitations of 1970's-era technology and infrastructure, it was necessary for these procedures to be oriented towards sector airspace. This "sector orientation" is a natural outcome of the need to clearly delegate ATC responsibilities/liabilities, expedite traffic through sectors, and mitigate the risk of inter-sector confusion.

Sector-orientation

Today's sector-oriented operations are characterized by the planning and control of flights within a sector with an emphasis on the expeditious hand-off to the next sector. Controllers may not allow a flight within their sector to enter the next sector unless the downstream (receiving) controller accepts the hand off. Conditions for hand-off acceptance typically include several factors such as the absence of any immediate conflicts.

Each sector is managed by a controller team consisting of at least a radar "R" position, and if workload necessitates, a radar associate "RA" position. Additional controller "associates" may assist the team during peak workload situations. In general, radar controllers monitor their sector, communicate with flights, issue clearances, and take action to maintain separation and conform to restrictions (e.g., airspace structure and required metering/spacing). In addition to data management and flight strip marking, RA positions assist the radar controller with the monitoring of the traffic situation and pilot "read back" of clearances to mitigate the risk of blunders. Acting as a "second pair of eyes/ears" becomes the priority role for the RA position under high workload conditions.

Tactical separation is the sector team's top priority. Radar controllers tactically detect and resolve conflicts with a typical look-ahead horizon of 5-10 min. To complement this, FFP1 automation provides the RA[*] position with URET CP capabilities to help monitor traffic, detect problems (conflicts with other flights or airspace restrictions), trial plan resolutions, and coordinate resolutions with other sectors. CP provides the RA position with an upstream look-ahead horizon of10-20 min that can potentially reduce the traffic problems encountered by the radar controller.

The advantage of classic sector-oriented procedures is the clear allocation of responsibility to individual controller positions with minimal dependence on automation. Although exercised rarely, each sector has the authority to delay or restrict their acceptance of new hand offs from upstream sectors. This process allows each individual sector to limit the scope of the incoming traffic problem. However, a convenient and expeditious solution from one sector's point of view may not be the best overall solution for a group of sectors. Sector-oriented procedures have limited potential to distribute workload and facilitate coordinated actions across sectors. Sector-oriented procedures do not encourage upstream controllers to issue clearances that resolve predictable problems that impact downstream sectors. As a result, subsequent sectors must often correct their portion of a flight's trajectory, a practice that often frustrates the user community and contributes to downstream workload.

Trajectory Orientation

Although FFP1 capabilities introduce benefits under today's sector-oriented paradigm, an even greater potential benefit could be unlocked by a shift towards a "trajectory-oriented" paradigm facilitated by new automation. Trajectory orientation is an ATC counterpart to the natural orientation of the airspace user. Aircraft operators consider not only the flight's current state and immediate tactical challenges (e.g., weather and traffic), but also their strategic plan to

[*] During single-position sector operations, the R-side has direct access to URET capabilities.

return to their route and nominally complete their mission (e.g. required time of arrival).

Trajectory-oriented operations are characterized by the upstream planning and coordination of flight-path changes that nominally conform to downstream metering restrictions and separation minima. Not all predicted problems need to (or should) be solved upstream, only those that are highly probable within a reasonable horizon (e.g., 10-20 min).[9] The goal is to resolve predictable problems earlier, while finding an efficient balance between acting too soon (false alarm) or too late (missed alert).

Compared to sector-oriented operations, the trajectory-oriented approach has the potential to push problem detection/resolution upstream and re-distributes workload from the downstream sectors (where problems are located) to upstream sectors (that control the flights just upstream of the problem). This approach has the potential to increase both flight efficiency and the robustness of individual sectors to disturbances (and uncertainties) in the traffic flow. Finally, Trajectory orientation is essential for the realization of the Free Flight concept, particularly the DAG-TM elements such as trajectory negotiation and free maneuvering. Collaborative trajectory planning will require pilots and controllers to have a consistent, shared model of intent.

Trajectory orientation necessitates a fundamental shift in thinking towards multi-sector teamwork. There are several potential operational concepts for controller roles, responsibilities, and procedures that may enable a transition to trajectory-oriented operations.[*] A description of these potential concepts is provided in Ref. 10. For the purposes of this paper however, the focus will be on the "Upstream (sector) Team" concept whereby the radar and radar associate positions leverage DST capabilities to facilitate trajectory-oriented actions. Providing such capabilities to the controller team is a fundamental goal of EDA.

Core EDA Capabilities

To facilitate trajectory-oriented operations, decision support automation is needed to assist controllers with the inter-sector planning, coordination, and execution of any necessary flight plan changes. Manual trial planning techniques are not adequate for arrival-metering situations.[11] The EDA solution proposes a higher level of active-advisory automation based on accurate 4D trajectory-prediction capability.

Field tests have validated an EDA arrival-time accuracy of 15 sec[12] based on a single clearance advisory issued prior to top of descent. Even greater operational accuracy is readily achievable using mid-descent updates (routinely needed today without automation), and state-of-the-art capabilities in surveillance, wind prediction,[13] and data link. Trajectory prediction accuracy is key to gaining controller confidence in DST alerts/advisories, extending the effective time horizon for problem detection, and reducing the need for corrective clearances to achieve a desired traffic state. In addition, good precision between airborne Flight Management Systems (FMS) and ATC-DST trajectory predictions will maximize the potential for DAG-TM concepts by ensuring the interoperability of air and ground automation.[14,15] Further details on EDA trajectory-prediction methods and prediction-accuracy validation results may be found in Ref. 12, 16, and 17.

In addition to accurate 4D trajectory-prediction capability, two core EDA capabilities have emerged from the lessons learned in previous controller-in-the-loop simulations in the early 1990's. Although controllers positively received the EDA metering-conformance advisories, they emphasized the need for a greater level of conflict-resolution automation (to reduce the workload associated with manual "trial plan" methods), and the need for automation support to facilitate coordinated actions across multiple sectors. The following two sections describe the formulation of the EDA capabilities to address these controller concerns. These capabilities include active clearance advisories that integrate metering conformance with conflict detection and resolution (CD&R), and the management of "active" and "provisional" (flight) plans.

Integration of Metering Conformance and CD&R

A unique feature of EDA is the capability to generate active clearance advisories for conflict-free metering conformance (i.e., suggested instructions for speed, altitude, and route changes). Algorithms for accurate metering conformance, conflict detection, and conflict resolution have been developed and integrated within research-prototype software.[12,18] This section presents an overview of the conceptual approach and motivation to the EDA algorithms for arrival-metering advisories.

Improvements in metering-conformance accuracy (e.g., reductions in error from 1-2 min[2] to 15 sec[12]) have the potential to unlock benefits both downstream and

[*] It may be interesting and beneficial to extend the lessons of flight deck crew resource management (CRM) to the ATC counterpart of controller roles, responsibilities, and procedures.

upstream of the meter fix. Downstream of the meter fix, within terminal airspace, errors of 1-2 min rival the size of the desired approach spacing and may also exceed the controllable range of delay for "short side" arrival routes (leading to excessive gaps between slots). A reduction in meter-fix error may improve the efficiency and throughput of terminal-arrival operations.

Upstream of the meter fix, improved metering accuracy has the potential to reduce the frequency and degree of en route conflicts. A key discriminator of the EDA concept is the sequential approach that considers metering-conformance solutions first, followed by CD&R iteration, rather than the other way around. Metering restrictions impose spacing requirements on sequential flights that at least meet (and typically exceed) the criteria for minimum radar separation. This can be particularly advantageous in transition airspace where the natural merging and compression of arrival traffic leads to a significantly greater frequency of potential conflicts. With sufficient accuracy, metering-conformance actions tend to "de-conflict" traffic within a metered flow. EDA leverages this characteristic to reduce the number of potential conflicts within a metered arrival stream, using simple metering-conformance algorithms, before having to resort to more complex algorithmic techniques for resolution.

Figure 2 illustrates the concept. Consider a single flight that is subject to a metering restriction and simultaneously predicted to be in conflict with another flight. Controllers have at their disposal the ability to modify the flight's route, altitude, and speed profile to resolve both problems (metering delays and conflicts). The large oval region notionally depicts the envelope of possible 4D trajectories for the flight. The slightly smaller hexagonal region (γ) represents the subset of possible trajectories that are conflict free. The even smaller triangle (β) represents the subset of trajectories that are in conformance with the metering constraint. Finally, the small polygon (α) represents the target envelope of trajectories that simultaneously conform to all constraints. The relative size of each envelope indicates the "degree" of that constraint. Most conflicts require only small deviations for resolution (leaving most of the envelope open). Comparatively speaking, the metering constraint represents a two-point boundary value problem that is considerably more constraining.

The goal of conflict-free planning is to find a solution within the intersection envelope. Although the natural predisposition of controllers is to address separation first (e.g., region γ), the potential advantage of first considering metering conformance (e.g., region β) is that it significantly reduces the search space for finding a total solution (region α). For this reason, a "metering-conformance-first" algorithm was implemented within the EDA research prototype as the basis for conflict resolution of arrival traffic.[19] In addition to the beneficial side effect of reducing potential conflicts between metered flights, the this algorithm provides EDA with a powerful approach for gaining controller acceptance of active advisories.[*] An example scenario will be presented in a later section to illustrate the application of this EDA algorithm.

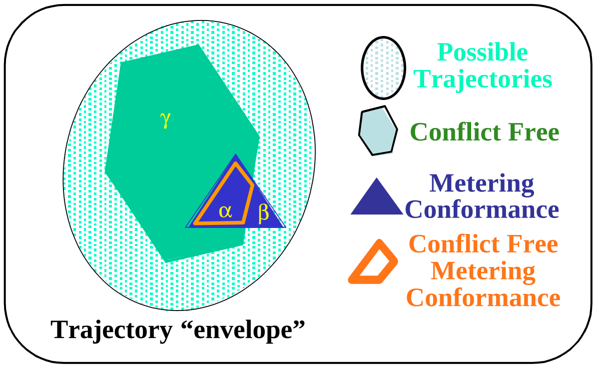

Figure 2. Envelope of possible trajectories.

Active/Provisional Planning Concept

Active advisory tools, such as EDA, must model appropriate controller options and preferences in order to generate problem-resolution advisories that are acceptable to controllers. This presents a challenge in terms of supporting a controller's situational awareness while striking the right balance between automation alerts (e.g., predicted conflicts and delays) based on the current traffic state, and alerts based on potential changes under consideration by one or more controllers. The basis of such alerts must be absolutely clear to controllers (i.e., whether the alert is based on current traffic state, or potential changes). Anything less may result in a lack of situational awareness leading to unnecessary control actions or problems that go undetected too long.[†] Furthermore, the management of flight-plan intent is an essential element needed to support the multi-sector coordination of trajectory changes. This is particularly important for transition airspace, compared to simpler en route airspace, where

[*] Controller-in-the-loop simulations of the EDA research prototype in the early 1990's led to the qualitative observation that it was far more challenging to develop controller-acceptable advisories for conflict resolution than for metering conformance.

[†] This critical awareness issue shares similarities with the flight deck related to pilot-FMS interaction. Even rare cases of mode confusion may outweigh the benefits of automation under nominal conditions, let alone be operationally unacceptable for reasons of safety.

flight path changes are the rule, rather than the exception. The EDA approach to address these challenges is described next in terms of the concept of "active" and "provisional" planning.

Genesis of Active/Provisional Planning

The EDA concept for active and provisional planning was initially formulated in 1990 as an ATC counterpart to a flight management system (FMS) concept.[19,22] In the FMS domain, the "active plan" represents the mission profile as a series of profile segments and/or waypoints defined by route, altitude, speed, and/or time constraints. The active plan drives the FMS trajectory predictions that are used to derive the flight guidance for lateral, vertical, and time-based navigation. The FMS also provides the pilot with "provisional-planning" capability. This capability enables the pilot to assess the implications of an alternative 4D trajectory while the aircraft remains on the active plan. Provisional planning allows the pilot to assess plan changes before they are made "active" for flight guidance.

The EDA concept extends this FMS planning approach to a more complex ATC application. This complexity stems from the controller's simultaneous responsibility for many flights and the complex interactions between flights (particularly within transition airspace). The ATC application necessitates a distinction between two categories of "plans," namely aircraft plans, for the modeling the intent of individual flights; and controller plans, for enhancing controller awareness of any dependencies between potential sector actions and facilitating the coordinated resolution of plans that may potentially conflict across sectors.

Aircraft Plans (Flight-Plan Intent)

The success of an active advisory tool depends in large part on the adequate modeling of flight-plan intent. Intent may be gleaned from the current ATC Host computer flight plan, radar-track update, airspace-adaptation data, and heuristic algorithms[20] used to infer controller intent when clearances/instructions are not reflected in official Host flight-plan amendments.* EDA stores such intent information in a unique "aircraft plan" for each flight. Aircraft plans form the basis of trajectory predictions for guiding the computational integration of the aircraft equations of motion. Problem-detection functions utilize the resulting 4D trajectories to predict downstream problems such as predicted conflicts or the lack of metering conformance.

For the purposes of EDA, each flight is represented by an "active aircraft plan" that is designed to reflect the current ATC intent for that flight. Active aircraft plans are made available to all sectors to support a common situational awareness across sectors. Authorization to modify an active aircraft plan is granted only to the sector that currently controls the flight.

A "provisional aircraft plan" represents an alternative plan for a flight that a controller would like to consider as a modification to the active aircraft plan for that flight. Provisional aircraft plans differ from active aircraft plans in that any controller may initiate one for a flight in any sector. Controllers can generate a provisional aircraft plan manually (i.e., trial plan), or incorporate modifications based on automated advisories, such as those generated by EDA or the Problem Analysis Resolution and Ranking (PARR) tool.[23] This allows individual sectors to assess a traffic situation (nominally based on the active aircraft plans) and formulate their own preferences for change.

Figure 3 illustrates a simple example based on two flights (A and B), in separate sectors (1 and 2), that will merge and transition through sector 4 to arrive at the meter fix. Although both flights would be subject to metering delays, this case will focus on the actions of Sector-1 relative to flight A (the next section will address the situation involving simultaneous actions across sectors for both arrivals). The solid lines depict the trajectories that are based on the active aircraft plans prior to metering conformance. The conflict probe predicts a loss of separation at the merge point, based on a probe of the "un-delayed" trajectories (based on the current active aircraft plans). However, both flights must also be delayed for metering conformance. In this case, the Sector-1 controller uses the automation to suggest a provisional aircraft plan for flight A. The automation feedback indicates the plan, a delay vector to the north, is predicted to be conflict free (i.e., no alert). If satisfied, the controller may promote the provisional aircraft plan to active status and issue the corresponding instructions to the flight.

A far more critical situation exists with respect to multi-sector interactions when the provisional aircraft plans of one sector interact or conflict with the provisional aircraft plans of another. Such a situation is described next to illustrate the concept of "controller plans."

* A supplementary process for streamlined controller inputs was developed for the EDA research prototype in 1990 to support controller-in-the-loop simulations. The technique applied point-and-click/keyboard short cuts, integrated with the primary traffic display, to fill flight plan gaps that are not currently modeled by the FAA Host computer and don't lend themselves to heuristic rules (Ref. 21).

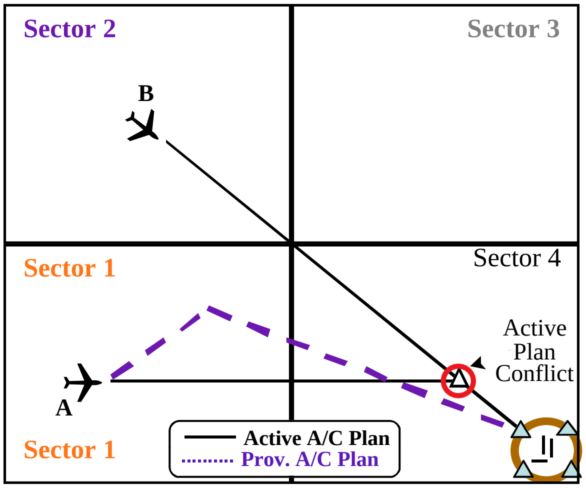

Figure 3. Active and provisional aircraft plans.

Controller Plans

Controller plans define the set of all aircraft plans that are of interest to a sector. Controller plans form the basis for automated alerts (e.g., predicted conflicts and delays) in that they distinguish between the current "active" traffic state (shared by all sectors), and an alternate traffic plan that may be considered by an individual sector. This distinction is critical because controllers (and advisory algorithms) must consider the potential interaction between the aircraft plans of multiple flights as well as the implications of potential changes to those plans. This is particularly relevant when more than one controller would like to change the active aircraft plan of the same flight. Controller plans provide the foundation necessary to automatically organize and manage the potentially overwhelming combinations of active and provisional aircraft plans.

The "active controller plan," defined as the set of all active aircraft plans, is shared by all sectors to ensure consistent feedback on "active" alerts for predicted conflicts and metering conformance. "Provisional controller plans," on the other hand, are uniquely defined for each sector, allowing controllers to assess their own alternate traffic plan separate from the current active controller plan. A provisional controller plan is defined as the combined set of all provisional aircraft plans (under consideration by a specific sector) and the active aircraft plans for all other traffic. The provisional controller plan drives the "provisional" alerts for each sector (i.e., probes of the alternate traffic plan).

Whereas current operational implementation of trial planning only supports the analysis (probing) of trial-plan changes for one flight at a time (per sector), the provisional-controller-planning approach supports the simultaneously analysis of provisional aircraft plan trajectories for multiple flights. This allows each sector/controller to evaluate the impact of plan changes for one flight on the plan changes for other flights (as well as the active aircraft plans for the remaining flights). If many flights are being metered, this allows each sector to consider the interaction of the potential metering-conformance actions between metered arrivals, and between metered arrivals and other traffic.

This provisional-controller-planning approach is intended to facilitate, when needed, multi-sector collaboration of provisional aircraft plans. If two sectors/controllers are considering separate provisional aircraft plans for the same flight, either controller may "swap in" the provisional aircraft plan of the other to enable their automation to analyze the potential interactions of the aircraft plans reflected in their provisional controller plan.* This will enable controllers to leverage their automation to assess traffic impact and collaborate on traffic solutions before committing to a specific course of action.

The key to managing the potentially overwhelming combination of active and provisional aircraft plan interactions is the following. The aircraft plan content of each sector's provisional controller plan must be uniquely defined for each controller/sector through automation settings (defining which advisories should be automatically included) and/or explicit controller inputs. Such inputs would be used to edit provisional aircraft plans already under consideration, invoke advisory functions, and/or swap in a different provisional aircraft plan (perhaps from another sector or pilot). In addition, the role of the DST automation is to automatically detect "secondary" problems and provide the controller with adequate cues to maintain situational awareness. Secondary problems are defined as provisional aircraft plan interactions that do not warrant alerts, but deserve a warning. In comparison, "primary problems" are defined here as the problems predicted by the automation and alerted to the controller (e.g., conflicts and metering-conformance delays).

For example, figure 4 illustrates a more complex version of the situation presented earlier in figure 3. In this case, the Sector-2 controller actions will be considered relative to their impact on the other sectors. Picking up from figure 3, the Sector-1 controller is still considering a metering-conformance maneuver to the north for flight A. At the same time, the Sector-2

* This approach, combined with FMS integration via data link, lends itself to air-ground trajectory collaboration (Ref. 19).

controller must plan the delay action for flight B. One option that could be proposed by the automation, or trial planned by the controller, is to vector flight B to the east through Sector 3. However, such a plan would automatically trigger an alert to a potential conflict with the active aircraft plan for flight C. Alternatively, the Sector-2 controller may consider an alternate plan involving a delay vector to the south, through Sector 2. Although this plan is clear of the active aircraft plans for all other traffic, it would in fact conflict with Sector-1's provisional aircraft plan for flight A if either sector activated their plan. Although this sort of secondary interaction would occur rarely in simple en route airspace, it can occur much more frequently in transition airspace where a larger portion of the traffic must be delayed for congestion.

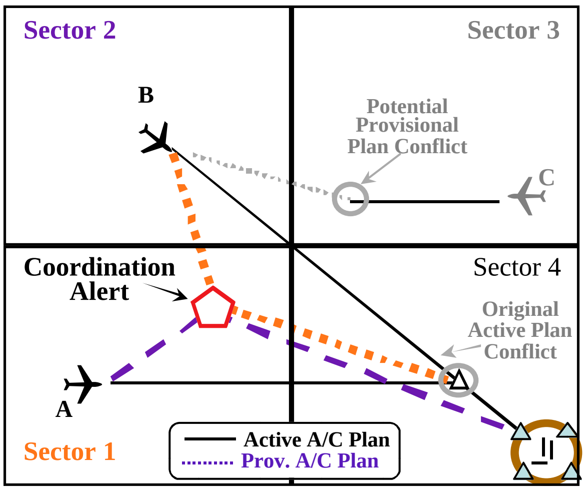

Figure 4 Provisional plan coordination alert.

The solution proposed here is for the DST to automatically compare the provisional controller plans across sectors and identify such secondary interactions. Once identified, the concept calls for the DST to generate a "coordination alert" to warn each controller that their respective provisional aircraft plans have a potentially negative interaction.* Once identified, and alerted, the controllers and/or automation have the opportunity to develop a coordinated plan.

This conceptual approach to active/provisional controller planning offers a framework for managing potential flight-plan changes that enables DST automation to identify sector interdependencies. Accurate knowledge of these interdependencies is needed to maintain inter-sector situational awareness, reduce the potential for conflicting actions between sectors, and minimize the effort necessary to coordinate multi-sector actions. In particular, this planning approach provides a mechanism by which individual controllers may consider active clearance advisories, evaluate modifications, and coordinate actions, all while maintaining a model of intent that is consistent across neighboring sectors. Although it is anticipated that workload levels will challenge the feasibility of this concept, further research is planned to develop, evaluate, and refine the algorithms and automation needed to address such challenges.

Example Scenario

Figures 5-7 present an example scenario to illustrate the value of integrating metering-conformance advisories with CD&R. The figures were developed from screen dumps of a real-time simulation problem run on the EDA research prototype. No reference to active/provisional planning is made, as the implementation of that capability has not yet been completed. Several graphic details have been simplified or removed to facilitate presentation.

The scenario is based on the old Denver Center airspace (prior to the 1996 airspace re-design) and focuses on the northeast portion of a small arrival rush to the Denver airport. Figures 5-7 illustrate a plan view encompassing three major high-altitude arrival sectors. The terminal area (TRACON) and airport are located in the lower left corner. The Standard Terminal Arrival Routes (STARs) are displayed as three bold lines that merge at PONNY and SMITY intersections, and enter the TRACON at the KEANN meter fix. Radar-track and data tags are used to depict each flight's position, flight level, and groundspeed. The timeline on the left side graphically depicts the metering information from TMA. The left column depicts the TMA Scheduled Times of Arrival (STA) at the meter fix while the right column depicts the Estimated Time of Arrival (ETA). The difference represents the delay to be absorbed for metering conformance. Predicted conflicts are indicated by a conflict-probe (CP) list of the flights involved (and time to first loss of separation) and conflict markers depicting the corresponding locations of each conflict.

* The concept also calls for a complementary DST function to identify "dependency alerts" to warn controllers when the conflict-free nature of a provisional aircraft plan depends on the activation of a provisional aircraft plan for one or more other flights.

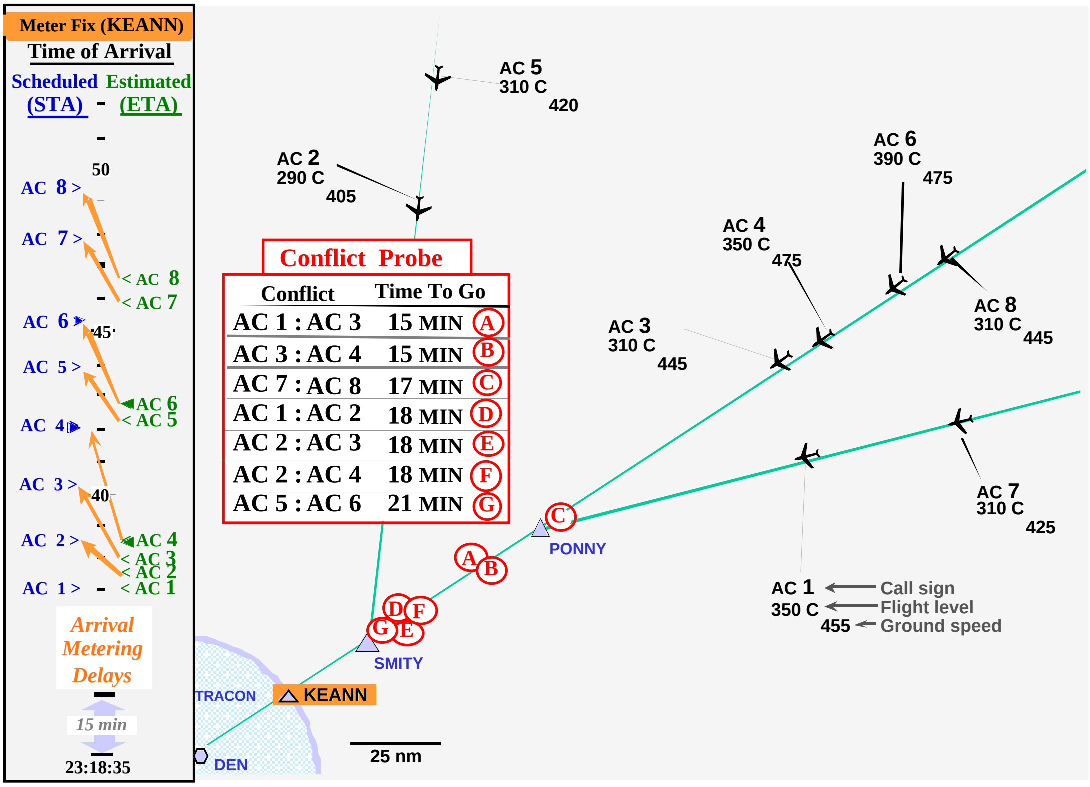

Figure 5. Conflict probe without metering conformance.

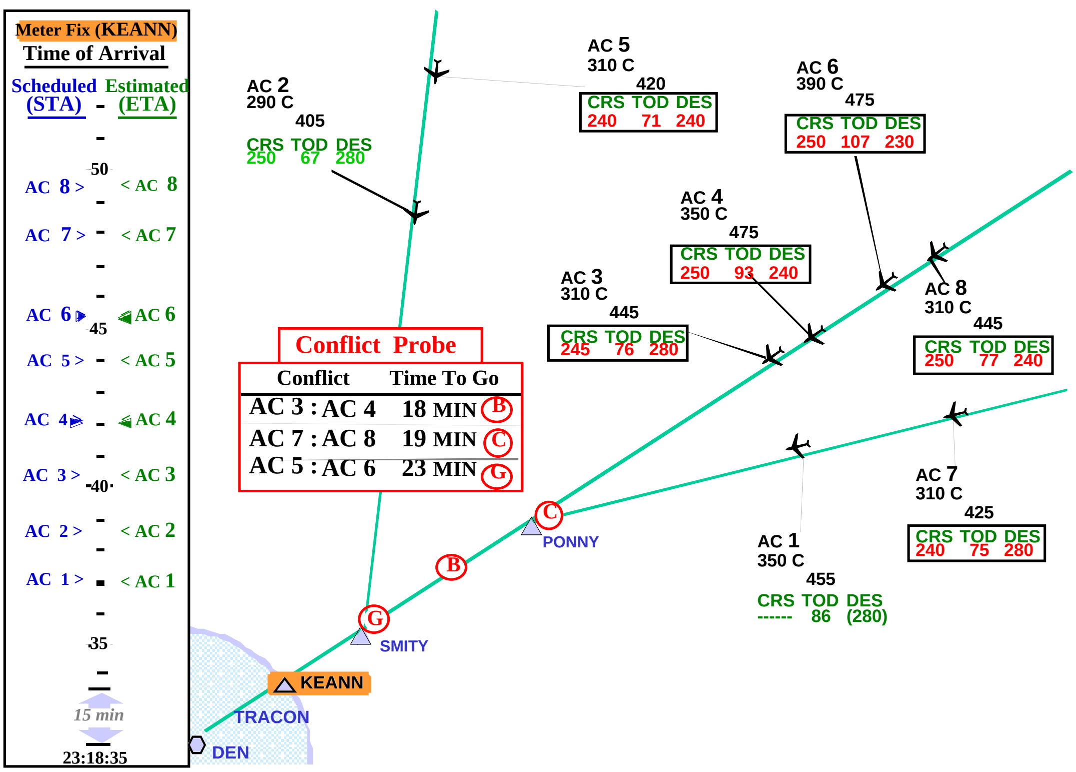

Figure 6. Conflict probe of metering-conformance plans.

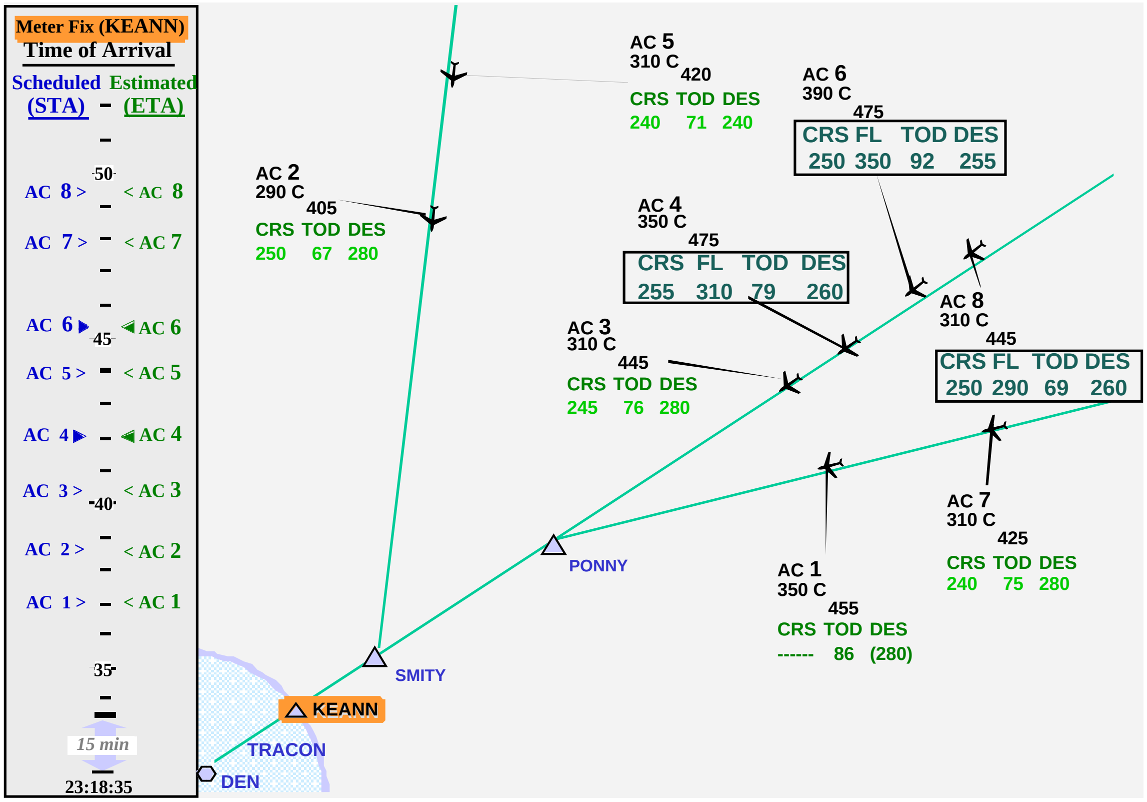

Figure 7. Conflict-free flow-rate conformance.

Figure 5 illustrates the baseline case (EDA metering advisories suppressed), reflecting FFP1 capabilities.* The arriving flights are just about to be delayed for metering. The timeline depicts "un-delayed" ETAs based on the current aircraft track, cleared routes, company "preferred" descent speeds (per the EDA database), winds aloft, and the aircraft performance models. The conflict-probe analysis predicts 7 conflicts (due primarily to the unresolved congestion at the meter fix depicted by the bunching of timeline ETAs).

Figure 6 represents the same traffic state except that the automatic EDA metering-conformance advisories are enabled (with EDA conflict resolution suppressed). This figure does not depict an end state in and of itself, but it does illustrate an intermediate step in the advisory-generation process that is useful for discussion. The figure illustrates the predicted result if the controller where to follow the advisories. Note that the timeline ETAs (based on the advisories) are now in conformance with the STAs. The EDA metering-conformance advisory for each arrival is presented in the 4th line of the data tag†. For example, the metering-conformance advisory for flight AC4 calls for a cruise speed reduction to 250 knots indicated airspeed (KIAS) followed by a descent 93 nm‡ from Denver at 240 KIAS. A detailed description of the full range of EDA metering-conformance modes and advisories (cruise speed, cruise altitude, top of descent, descent profile, and path-stretch vectoring) are provided in Ref. 12.

The true significance of this case is reflected in the conflict list which indicates, based on the EDA metering advisories) that only 3 conflict pairs remain compared to the seven pairs originally identified in figure 5. Boxes are used in the figure to indicate the advisories that are associated with the remaining conflicts. This reduction was due to the characteristic described earlier regarding the tendency of strategic metering-conformance actions to prevent arrival conflicts, particularly in congested situations. Since the TMA STAs are generated to be conflict free at the

* Primary differences between this EDA-based display and actual FFP1 capabilities include the use of timelines and CP display at the radar position, and the probing of conflicts between metered arrivals.

† Although not shown here, other EDA advisory information for top of descent and "path-stretch vectoring" are displayed directly on the map using color and graphical cues for position.

‡ The top of descent (TOD) calculation is used to support descent advisories for "classic" aircraft and conflict-probe modeling of TOD for FMS-equipped aircraft using vertical navigation automation

meter fix (as well as to meet the airport/runway acceptance rate), conformance actions reflect the meter-fix spacing. The resulting reduction in predicted conflicts reduces the scope/complexity of the problem to be solved by explicit conflict resolution algorithms.

Figure 7 illustrates the final goal of strategic trajectory planning for conflict-free metering conformance. For this case, the EDA automatic-resolution function[18] was activated. Although normally active, this function was de-activated for the previous two cases (figures 5 and 6) to illustrate the contribution of metering conformance to conflict probe. This function, based on an algorithm designed specifically for arrival metering, rapidly resolves any remaining conflicts by iterating on the EDA advisory "degrees of freedom." For example, the algorithm analyzes each conflicting arrival and evaluates simultaneous changes to cruise speed and altitude while reserving the descent speed degree-of-freedom for maintaining the TMA STA.

Figure 7 indicates that the three remaining conflicts of figure 6 were solved with modified advisories for three flights: AC4, AC6, and AC8. For example, instead of a cruise speed reduction to 250 KIAS followed by a descent at 240 KIAS (figure 6), the conflict-free EDA advisory for AC4 now calls for a cruise speed of 255 KIAS, an immediate descent to flight level 310, followed later by a 260 KIAS descent when the flight is within 79 nm of Denver. The EDA advisories for all flights are currently conflict free and in conformance with separation minima. Other EDA conflict-resolution techniques such as semi-automatic and manual (trial-plan) resolutions[21] could have been used to generate and/or modify these resolutions according to the controller's preferences. In either case, less conflict-resolution work is required by either algorithm/technique to home in on a solution because EDA started with the metering-conformance advisories.

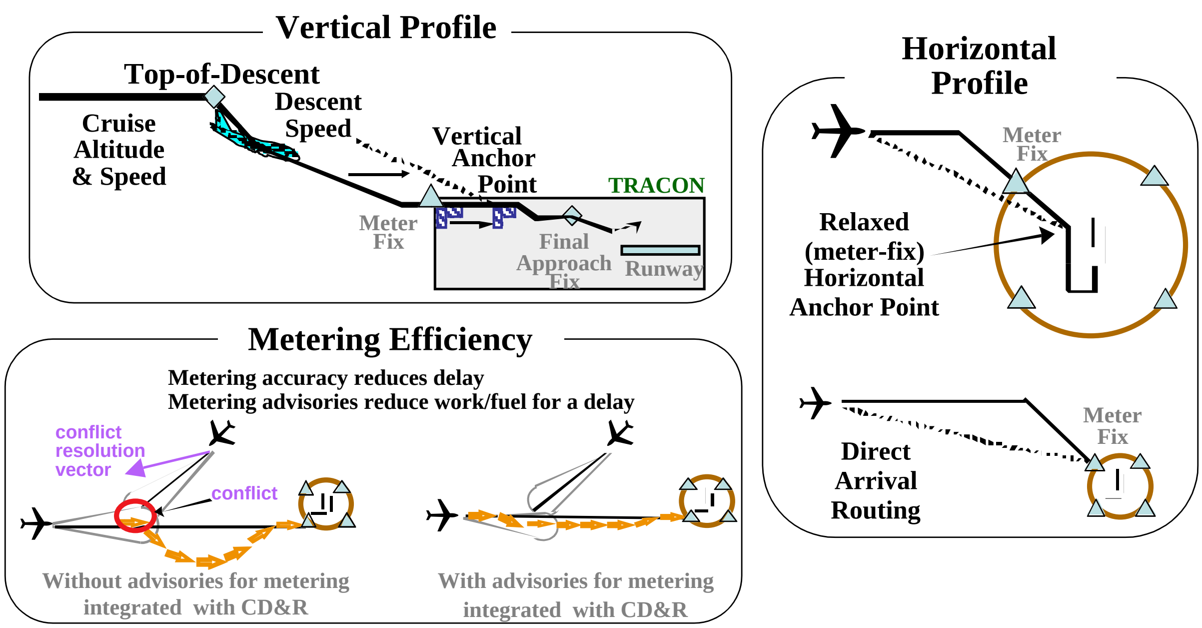

Figure 8. EDA Benefit Mechanisms.

EDA Benefits

EDA has the potential to contribute significant benefits in terms of flight efficiency, airspace throughput, controller workload, and user flexibility. Many of these benefit mechanisms are directly enabled by the improvement in metering-conformance accuracy that has been validated in field trials.[12,16,17] The following sections will first describe the EDA benefit mechanisms followed by a summary of results from an engineering assessment of potential EDA benefits.

EDA Benefit Mechanisms

Figure 8 presents a graphical depiction of the primary benefit mechanisms in three categories: vertical profile, horizontal profile, and metering efficiency.

Vertical Profile Mechanisms

Two benefit mechanisms enable vertical-profile efficiencies through the improvement of metering-conformance accuracy. The first mechanism focuses on the profile leading up to the meter fix where metering-conformance capabilities allow the controller to plan and implement clearances that are more fuel efficient and less restrictive than today. The result is more fuel-efficient cruise/descent profiles, and greater vertical-profile flexibility for the user, during metering.

The second mechanism focuses on the relaxation of altitude and speed restrictions at the meter fix itself. In this case, EDA metering-conformance accuracy has the potential to reduce the need for, and extent of, static restrictions that reduce flight efficiency and user flexibility. Many of the meter-fix restrictions are needed today to segregate flows, add predictability, and prevent unacceptable peaks in the arrival flow. Altitude and speed restrictions also serve to reduce the variability in performance across different aircraft types within the same arrival stream. EDA metering accuracy may be leveraged to reduce these restrictions because terminal area controllers will be able to depend on well-spaced flows. This relaxation of arrival constraints (referred to here as a "relaxed vertical anchor point") allows each aircraft type to operate in a more efficient manner according to its performance characteristics.[*]

Horizontal Profile Mechanisms

Similar to the vertical profile mechanism, the horizontal profile mechanisms are divided into two cases: one that focuses on the flight path up to the meter fix, and another that focuses on the flight path past the meter fix. The first horizontal mechanism leverages the EDA metering accuracy to reduce the need for, and extent of, static lateral restrictions prior to entering the terminal airspace. By helping controllers to accurately space arrivals independent of path, EDA reduces the controller's need to merge flights early to establish "in-trail" spacing. This results in greater user flexibility and flight efficiency in that users may be left on their preferred routing longer (and more often) as they transition into the terminal area.

The second mechanism focuses on the relaxation of the lateral restriction at the meter fix itself, a horizontal counterpart to the vertical anchor point. EDA metering accuracy, coupled with good TMA metering schedules, will deliver each flight to the terminal feeder controller in just the right state for merging. It is anticipated that segregated arrival and departure corridors will remain an operational necessity for high-density terminal airspace. However, within the geographical confines of such arrival corridors EDA accuracy may allow a relaxation of path restrictions and increase the extent to which arrivals may routinely fly by (as opposed to directly over) a meter fix.[†] Together, the horizontal- and vertical-anchor points contribute towards the Free Flight concept[1] goal of removing static restrictions and delaying arrival merges as far as it is safely and operationally feasible to do so given the specific nature and characteristics of each terminal area.

Metering Efficiency Mechanisms

Four mechanisms are described within this category, two with respect to flow efficiency, and two with respect to problem resolution.

Flow Efficiency: In terms of flow efficiency, EDA has the potential to reduce the extent and impact of arrival-metering restrictions through improvement of metering-conformance accuracy. Two mechanisms are enabled in terms of airport throughput and delay efficiency.[24,25] First, a reduction in the variation of meter-fix crossing times will help reduce gaps in the terminal-area arrival flow and increase airport throughput (reduce delays). Second, the improved meter-fix accuracy will also enable the terminal airspace to be operated with less delay ("front loading") because arrivals will be delivered accurately. This mechanism results in a more fuel-efficient delay distribution between the terminal and en route airspace because delay actions normally taken in the terminal area are shifted upstream of the meter fix where flights operate more efficiently.

Problem Resolution: EDA enables two benefit mechanisms related to the resolution of metering-conformance and conflict problems. First, with respect to metering conformance, EDA advisories have the potential to improve the efficiency of metering actions in terms of both fuel efficiency and controller workload. EDA advisories are synthesized from detailed data (aircraft performance, winds aloft, radar track) that would otherwise be impossible to master without automation. EDA advisories have the potential to help controllers plan and execute metering actions quicker and more efficiently when compared to today's manual techniques. In addition, workload reductions may be enabled through a reduction in the number of clearances/instructions that need to be issued to achieve a level of conformance.

Second, EDA advisories also have the potential to reduce the workload associated with conflict detection

[*] Relaxed vertical-anchor point benefits will vary with airspace, runway configuration, and arrival flows.

[†] The flexibility for arrival routing is bounded by the airspace that is segregated for arrival operations (i.e., to avoid mixing of high-density arrival and departure flows). There are also limits to the depth that these anchor points can go within the terminal without handicapping the terminal controller's flexibility to modify the flow as needed.

and resolution through a reduction in the rate of false alarms and missed alerts associated with metered arrivals. Furthermore, as illustrated in the previous sections, the trajectory-oriented metering conformance actions enabled by EDA will reduce the likelihood of arrival conflicts. At the same time, the EDA arrival-conflict-resolution capabilities will help controllers prevent arrival conflicts before they would be consciously detected without the automation assistance.

EDA Benefits Summary

A series of engineering studies were conducted to estimate the annual nation-wide benefits associated with most of the mechanisms described above. The study analyzed data representing actual 1997 traffic levels and the transition airspace serving 37 high-demand airports.[26] Results are based on the analysis of archived traffic, actual airspace restrictions, performance-based trajectory modeling, and a fast-time simulation comparison of current and future (EDA) operations. Results are presented as a function of benefit mechanism for each of four benefit categories: flight efficiency, flexibility, workload, and throughput). Flight efficiency and throughput benefits were calculated based on a $0.10/lb cost for fuel and baseline rates for aircraft, crew, and maintenance time (defined in Ref. 26). Qualitative information is presented for those cases for which it is premature to quantify metrics at this time.

For those metrics that were quantifiably possible to estimate, results indicate a nationwide annual savings of $291 million for the airspace users. The largest portion results from the trajectory-efficiency mechanisms that save $85 million under existing terminal-arrival meter-fix restrictions and $88 million annually when the meter-fix restrictions are relaxed (67% from vertical anchor points and 33% from horizontal anchor points). The next largest benefit results from improved flow efficiency enabled by improved metering-conformance accuracy. Results indicate an airport-throughput savings of $42.9 million and en route-terminal delay distribution savings $47.7 million.

The next largest benefit results from improved problem resolutions. EDA advisories are estimated to save $25 million in terms of the efficiency of metering conformance, and $2 million in terms of fewer trajectory deviations for unnecessary conflict-resolution actions. Although the $2 million savings in flight operations costs is small, the same mechanism results in a significant reduction in the rate of CP false alarms and missed alerts. Compared to operations with and without EDA, study results indicated a 21% and 30% reduction in missed and false alerts, respectively, with a 5% reduction in overall conflict alerts.

Critical among the qualitative benefits is the potential impact of EDA on controller workload. Workload is potentially reduced by EDA problem-resolution advisories in that fewer clearances/actions will be operationally necessary. Additional benefit may be derived from the improved distribution of workload, across sectors, enabled by the strategic “trajectory-oriented” nature of the EDA metering advisories. Although difficult to quantify at this time, such workload savings may translate into significant operational benefits such as improved sector capacity. Additional benefit may be derived from the integration of EDA with data link. EDA access to data link messages will improve intent modeling while data link access to EDA will reduce the effort needed to compose up link messages. Simulation results indicate that EDA advisories identified the controller-preferred type of clearance (route, altitude, speed changes) two-thirds of the time, with the clearance details (e.g. speed values, chosen altitude etc.) acceptable without modification three-fourths of the time (Ref. 27).

Concluding Remarks

The goal of EDA is to improve the operational efficiency of en route transition airspace, particularly under arrival-metering conditions, by facilitating trajectory-oriented ATC operations. A primary enabler for trajectory orientation is the strategic (20 min) planning of ATC actions (trajectory changes) to address downstream problems such as metering. To accomplish this, EDA provides controllers with decision support automation to help plan, coordinate, and execute plans across sectors. Although the current automation-assisted technique of trial planning is not adequate for arrival metering, a higher level of automation involving active clearance advisories may enable a solution. A core capability of EDA is to provide controllers with advisory capabilities that integrate metering conformance with conflict detection and resolution. Results of engineering analyses indicate that EDA advisories, based on accurate trajectory-prediction techniques, have the potential to not only improve the performance of conflict probe (as illustrated in the scenario), but also significantly improve the throughput and efficiency of transition airspace operations resulting in an annual nation-wide savings of $ 291 million.

Going forward, software development activities are underway to restore the basic active advisory capability within NASA's current CTAS baseline along with a modern implementation of the active/provisional planning process. This system will initially support engineering and human factors design assessments in 2002 leading to the completion of a "concept development" research prototype. The purpose of that prototype will be to support real-time controller-in-the-loop simulations in 2003 and simulation evaluation of Distributed Air-Ground Traffic Management concepts in 2004.

References

1 Final Report of the RTCA Task Force 3, "Free Flight Implementation," RTCA Inc., Washington D.C., October 26, 1995. www.RTCA.org

2 Swenson, H., et al, "Design & 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.

3 Brudnicki, D., and McFarland, A., "User Request Evaluation Tool (URET) Conflict Probe Performance and Benefits Assessment," 1st USA/Europe Air Traffic Management R&D Seminar, Saclay, France, June 1997, MP97W112.

4 Erzberger, H., Davis, T., and Green, S., "Design of Center-TRACON Automation System," AGARD Guidance and Control Symposium on Machine Intelligence in Air Traffic Management, Berlin, Germany, May, 1993. pp. 11-1-11-12.

5 Green, S. M. and Jackson, J.W., "Complexity in Air Traffic Management," *Automation, Control and Complexity*, edited by Samad T. and Weyrauch, New York: John Wiley & Sons, 2000.

6 Green, S., Bilimoria, K., and Ballin, M. G., "Distributed Air-Ground Traffic Management for En route Flight Operations," AIAA 2000-4064, Guidance, Navigation, and Control Conference, Denver CO, August 2000.

7 Arthur, W. C., Lindsay, K. S., September 1999, User Request Evaluation Tool (URET) Initial Two-Way Host Interface Functional Accuracy, MTR99W0000090, The MITRE Corporation, McLean, VA.

8 Lindsay, K. S., January 2000, Results of a URET Operational Utility Experiment, WN 00W0000081, The MITRE Corporation, McLean, VA.

9 Erzberger, H., Paielli, R.A., Isaacson, D.R., and Eshow, M., "Conflict Detection and Resolution In the Presence of Prediction Error," 1st USA / Europe Air Traffic Management R&D Seminar, Saclay, France, June 1997.

10 Leiden, K. and Green, S., "Trajectory Orientation: A Technology-Enabled Concept Requiring a Shift in Controller Roles and Responsibilities," Paper 081, 3rd USA/Europe Air Traffic Management R&D Seminar, Naples, Italy, June 2000. <http://atm-seminar-2000.eurocontrol.fr>

11 McNally, B. D., Erzberger, H., Bach, R., and Chan, W., "Controller Tools for Transition Airspace," AIAA-99-4298, AIAA Guidance, Navigation, and Control Conference, Portland OR, August 1999.

12 Green, S., Vivona, R., Grace, M., and Fang, T., "Field Evaluation of Descent Advisor Trajectory Prediction Accuracy for En route Clearance Advisories," AIAA-98-4479, AIAA Guidance, Navigation, and Control Conference, Boston MA, August 1998.

13 Cole, R., et al., "Wind Prediction Accuracy for Air Traffic Management Decision Support Tools," Paper 110, 3rd USA / EUROCONTROL Air Traffic Management R&D Seminar, Naples Italy, Jun. 2000.

14 Green, S. M., T. Goka, and D. H. Williams, "Enabling User Preferences Through Data Exchange," AIAA-97-3862 Guidance, Navigation and Control Conference, New Orleans, LA, August 1997.

15 RTCA Special Committee 194, "Concepts for Services Integrating Flight Operations and Air Traffic Management Using Addressed Data Link," DO-269, RTCA Inc., Washington D.C., 2001. www.RTCA.org

16 Williams, D. H., and Green, S. M., "*Flight Evaluation of the Center / TRACON Automation System Trajectory Prediction Process*," NASA/TP-1998-208439, July 1998.

17 Green, S., Grace, M., and Williams, D., "Flight Test Results: CTAS and FMS Cruise/Descent Trajectory Prediction Accuracy," Paper 84, 3rd USA / Europe Air Traffic Management R&D Seminar, Naples, Italy, June 2000.

18 Slattery, R. and Green, S.M., "Conflict-Free Trajectory Planning for Air Traffic Control Automation," NASA TM-108790, January 1994.

19 Green, S.M., Williams, D.H., and den Braven, W.: "Development and Evaluation of a Profile Negotiation Process for Integrating Aircraft and Air Traffic Control Automation," NASA TM-4360, April 1993.

20 Celio, J. C., et al., "Free Flight Phase 1 Conflict Probe Operational Description," MITRE Corp., McLean, VA, March 2000. www.mitrecaasd.org/library/tech_docs/index.html

21 Green, S., "EDA Concept Definition," Milestone 5.10, Advanced Air Transportation Technologies Project Office M/S 262-4, NASA Ames Research Center, Moffett Field, CA 94035, September 1999. <www.asc.nasa.gov/aatt>

22 Williams, D., and Green, S., "Airborne Four-Dimensional Flight Management in a Time-Based Air Traffic Control Environment," NASA TM-4249, March 1991.

23 Kirk, D. , Heagy, W., and Yoblanski, M., "Problem Resolution Support for Free Flight Operations," IEEE Transactions on Intelligent Transportation Systems, Vol. 2, No. 2, June 2001.

24 Erzberger, H., "Design Principles and Algorithms for Automated Air Traffic Management," AGARD Lecture Series No. 200 on Knowledge-based Functions in Aerospace Systems, Madrid, Paris, San Francisco, Nov. 1995.

25 Hunter, G., Weidner, T., Couluris, G., Sorensen, J., Bortins, R., " CTAS Error Sensitivity, Fuel Efficiency, and Throughput Benefits Analysis," TR96150-02, Seagull Technology, Los Gatos, CA, July 1996.

26 Coppenbarger, R., Green, S., and Weidner, T., "Comprehensive Benefits Assessment for the En route Descent Advisor," NASA AATT Milestone 5.8.1 Report, Advanced Air Transportation Technologies Project Office M/S 262-4, NASA Ames Research Center, Moffett Field, CA 94035, Sept. 1999. <www.asc.nasa.gov/aatt>

27 Den Braven, W., "Design and Evaluation of an Advanced Air-Ground Data-Link System for Air Traffic Control," NASA TM-103899, January 1992.