Evolution of an Air Traffic Simulation Testbed into an Operational Tool

Kapil Sheth[1], Karl D. Bilimoria[2], and Banavar Sridhar[3]
NASA Ames Research Center, Moffett Field, CA 94035

Mike Sterenchuk[4], Tim Niznik[5], Tom O'Neill[6]
American Airlines, Fort Worth, TX 76155

Alexis Clymer[7], Sebastian Gutierrez-Nolasco[8], Kaj Edholm[9]
Crown Consulting, Inc., Moffett Field, CA 94035

Fu-Tai Shih[10]
SGT, Inc., Moffett Field, CA 94035

Abstract

This paper describes the 20-year evolution of the Future ATM (Air Traffic Management) Concepts Evaluation Tool (FACET) from a National Airspace System (NAS) based simulation testbed into an operational tool. FACET was initially developed as a testbed for assessing futuristic ATM concepts, e.g., automated conflict detection and resolution. NAS Constraint Evaluation and Notification Tool (NASCENT) is an application that later evolved within FACET for alerting airspace users to inefficiencies in flight operations and advising time- and fuel-saving reroute opportunities. It is currently in use at American Airlines Integrated Operations Center in Fort Worth, TX. This paper presents a historical perspective with descriptions of the concepts assessed, research conducted, and the operational capability developed, along with the NASA support and achievements.

Background

In the late 1990s, there was a desire for assessing an alternative parameter for the number of aircraft as a measure of controller workload and traffic flow management. The Center-TRACON Automation System (CTAS) developed at NASA Ames Research Center was a single Air Route Traffic Control Center (ARTCC or Center) based air traffic control simulation system. Due to a lack of data from adjacent Centers, accurate prediction of dynamic density (a proposed surrogate for number of aircraft in a local region of airspace) was not possible in the border sectors of the Center. That led to the development of FACET, which used traffic data from the Federal Aviation Administration's (FAA's) Enhanced Traffic Management System (ETMS, now called the Traffic Flow Management System or TFMS). The ETMS provided data for all 20 Centers, albeit with a slower update rate of one minute, as compared to the faster twelve-second single-Center data update. With that in mind, the first design for FACET (then called Air Traffic and Airspace Decision Support System, ATADSS), was done on December 3, 1997.

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[1] Aerospace Research Engineer, Flight Trajectory Dynamics & Controls Branch, MS 210-10, AIAA Associate Fellow. *kapil.sheth@nasa.gov.*
[2] Aerospace Research Engineer, Flight Trajectory Dynamics & Controls Branch, MS 210-10, AIAA Fellow.
[3] Ames Associate, MS 210-10, AIAA Fellow.
[4] Senior ATC Coordinator, Flight Dispatch, MS 635.
[5] Director, Operations Research and Decision Support, MS 5423.
[6] Senior ATC Coordinator, Flight Dispatch, MS 635.
[7] Senior Software Engineer and Task Manager, MS 210-8.
[8] Senior Software Engineer, MS 210-8.
[9] Senior Software Engineer, MS 210-8.
[10] Senior Software Engineer, MS 210-8.

Over the years, many concepts have been tested with FACET [1] due to its ability to simulate and play back with live-data connection capability to handle air traffic, wind, weather, and airspace constraints data. Figure 1 shows the graphical user interface with air traffic, Center/Sector boundaries, convective weather, and some of the active Special Use Airspaces. The flights arriving at Chicago O'Hare International Airport (ORD, colored in cyan), Newark Liberty International Airport (EWR, in pink), and Hartsfield-Jackson Atlanta International Airport (ATL, in yellow) are shown with a tail of 20-minute histories. FACET also provides predictions of aircraft locations and what-if analysis capability for assessment of various traffic management initiatives. A large number of publications (some listed in the Concepts Section below) are available in the literature for the concepts assessed using FACET. The second concept to be implemented in FACET, after the calculation and prediction of dynamic density, was automated aircraft-based conflict detection and resolution. Some of the other concepts evaluated later, and further described in the Concepts section below, are the airways in the sky or the airspace tubes concept, ATM as a network of nodes, and incorporation of user preferences for easing demand/capacity imbalances. There is an environment emissions model available within FACET to study the impact of domestic and global aviation on the atmosphere. A FACET version was also developed to simulate global traffic.
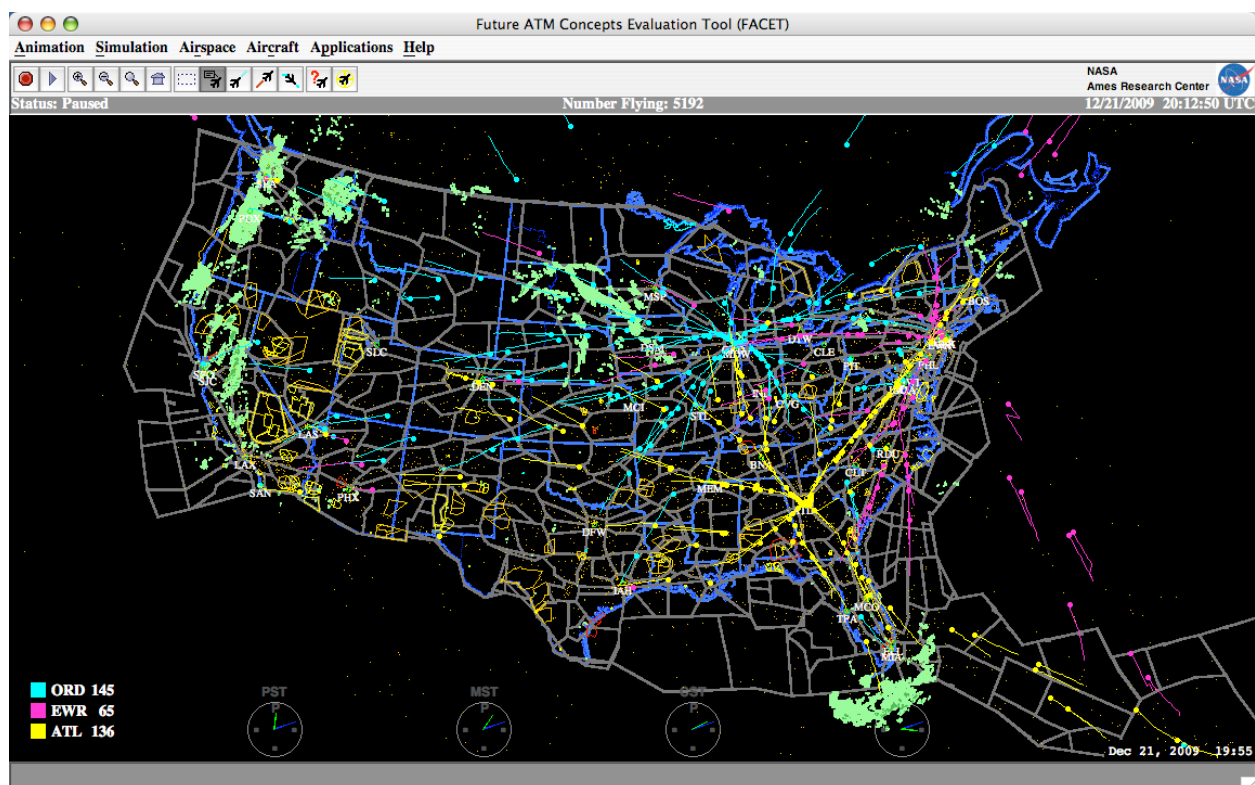

Figure 1: Display of FACET graphical user interface depicting air traffic, Center/Sector boundaries, convective weather, and Special Use Airspaces.

Capabilities of FACET

FACET is capable of modeling system-wide airspace operations, balancing fidelity and flexibility. The trajectory modeling in FACET is accomplished using table lookup of aircraft performance data. FACET supports three navigation laws available for propagation of aircraft positions. They are the great circle, rhumb line, and neighboring optimal wind routing. The geographical and FAA adaptation data (i.e., Center boundaries, Special Use Airspaces, Jet Routes and Victor Airways, navaids, etc. on a 56-day update cycle) are available, along with capacities of various airspace elements (e.g., Airport Acceptance Rates). Various weather products can be read in for display and algorithm development purposes (e.g., Rapid Update Cycle (RUC), Corridor Integrated Weather

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System (CIWS)). FACET also has elaborate filtering of aircraft/airspace data and graphical plotting of data. There is a MySQL database available for storing flight plans, sector count data, etc. The Application Programmer's Interface is robust, and many users have interfaced their applications with FACET. While FACET is able to simulate aircraft trajectories, it is also capable of connecting to a real-time input and playing back recorded air traffic, weather, and airspace constraint data.

All applications in FACET were developed to satisfy the requirements from NASA ATM researchers and other government/industry users. Some of the researcher-driven applications available within FACET are:

- Sector Modification (to assess dynamic redesign of sectors for reduced workload and traffic management),
- Flow Constrained Area (FCA) monitor and avoidance (algorithms for efficient routing of flights around constraints),
- Traffic Density Profile (to study density of traffic in rectangular or hexagonal grids),
- Weather Translation (to understand the reduction in airspace capacity due to the presence of weather),
- NAS Constraints (to model and evaluate the impact of original/alternate Traffic Management Initiatives (TMIs)).

Based on requests from airspace users (airlines, FAA, Air Force, etc.), several other applications were implemented in FACET. These are:

- MIT (Miles-in-Trail) Monitor (to enable FAA traffic managers to estimate the MIT implemented),
- Airspace Restriction Planner (to propose restrictions based on current conditions),
- Reusable Launch Vehicles (RLVs) Analysis (to study the impact of launch and return operations for RLVs, Space Shuttle, and other space vehicles on air traffic),
- Single-Aircraft Analysis Module (for post-operations analysis, to understand the path taken by a flight and the reasons for trajectory change(s) along the way),
- Fly-By Animation (to visualize the paths aircraft flew around weather in the last two hours, and where they plan to be in the next two hours).

Concepts Evaluated in the FACET Simulation Testbed

This section provides short abstracts of the papers where some of the concepts developed using FACET were described. These concepts are Airspace Complexity (referred to as Dynamic Density, DD) [2], Conflict Detection and Resolution (CD&R) [3], Flexible Airspace Utilization (Tube Structures) [4], ATM Network Characteristics (Network Resilience) [5], and Incorporation of User Preferences (Credits Concept) [6]. Some of the other concepts that were studied with FACET, but not described here, are Aggregate Flow Model (Linear Dynamic System Model, LDSM) [7], Integrated TFM Decision (Miles-in-Trail, rerouting, etc.) [8], Miles-in-Trail Passback Restrictions [9], and Contrails and Noise Modeling [10], among others.

Airspace Complexity (DD), (1998)

Predicted growth in air traffic and the desire for more user preferred routes in the National Airspace System (NAS) impose additional demand on air traffic control and traffic flow management systems. This demand can be met by alternate airspace configurations, modified traffic patterns, and staff reassignment. There was a need to understand the effect of changing airspace configurations and traffic patterns on the workload of air traffic controllers. This complex relationship is referred to as "Airspace Complexity" [2]. Research conducted at NASA on Dynamic Density (DD) indicated that it is a good measure of airspace complexity. Dynamic density was represented as a function of the number of aircraft and their changing trajectory geometries in a given airspace. In order to use dynamic density as a planning tool, it was necessary to project its behavior over the planning horizon. The objective of the work was to study how well dynamic density could be predicted into the future using the trajectory generation feature of the CTAS. Trajectories were generated to compute actual and predicted dynamic density using traffic data from Dallas/Fort Worth airspace. Using FACET, with the additional data from neighboring Centers, results showed that dynamic density could be predicted up to 20 minutes in advance (which was not possible earlier) and that errors in predictions could be further reduced by about 10-20% by accounting for departure traffic. Figure 2 shows the computation of DD using a linear combination of nine factors utilizing NAS-based traffic data in FACET. This research intended to contribute towards understanding and reducing air traffic controller workload, and in turn improve the safety of air traffic operations. Controller workload is complex to measure, and to date, DD has not replaced number of aircraft as the representative monitor/alert parameter for controller workload.
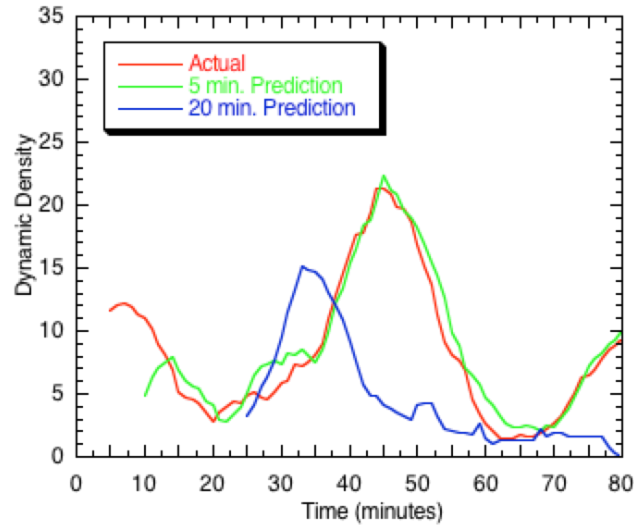
Figure 2: Representation of NASA's dynamic density metric [2] as a function of prediction time.

Conflict Detection and Resolution (CD&R), (2001)

The feasibility of airborne separation assurance for free flight was investigated using FACET. Two schemes for performance of CD&R were evaluated in a simulated air traffic environment [3]. These methods were based on a geometric optimization approach and on a modified potential-field approach. Both CD&R methods were implemented in FACET. The evaluation was based on a realistic free flight traffic scenario constructed with initial conditions from actual air traffic data. Approximately 1,000 aircraft were represented in a 6-hour air traffic scenario. Safety, efficiency, and stability metrics were evaluated. It was observed from results that all conflicts
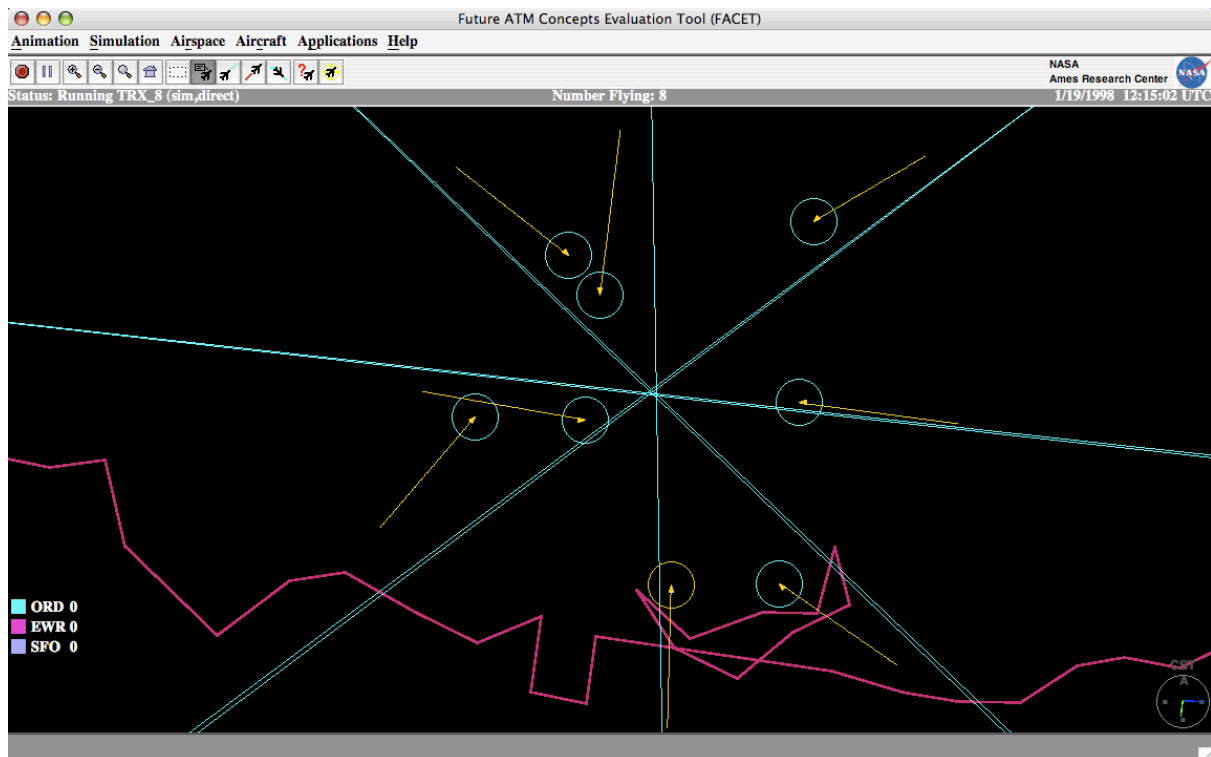

Figure 3: The geometric optimization method resolution for eight aircraft on a collision course.

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were resolved, the impact on efficiency due to deviation maneuvers was small, and the impact on system stability associated with domino-effect conflicts was low to moderate (based on the method used). Figure 3 shows a sample resolution maneuver through lateral deviation for eight aircraft arriving within 5 nmi of each other (blue lines) causing 28 unique conflicts. Using the geometric optimization method, as can be seen in the figure, all conflicts were resolved. The circles represent 5 nmi diameter rings around the aircraft.

Flexible Airspace Utilization (Tubes), (2007)

The concept of tube structures for aircraft have been considered as a means to provide flexible, conflict-free trajectories for future ATM application. An analysis of five airspace tube structures, or corridors in the sky, was conducted [4] using FACET. Three designs were previously defined and two new designs were generated for this research. Five metrics to characterize the performance of these tubes were described. The metrics addressed the spatio-temporal utilization of airspace, frequency and angles at which aircraft cross tubes, along with separation of aircraft with and without tubes. All of the designs were incorporated into the FACET simulation platform for evaluation. The results indicated that these designs of tubes have low utilization, and improvements are needed for viability and additional benefits. Other structural parameters for consideration in future designs were presented along with visualization of a simple three-dimensional tube network. Figure 4 displays one futuristic version of airspace tubes for 6 airports at 5 different altitude levels. For the research, 22 airports with 55 links were studied for evaluation purpose.
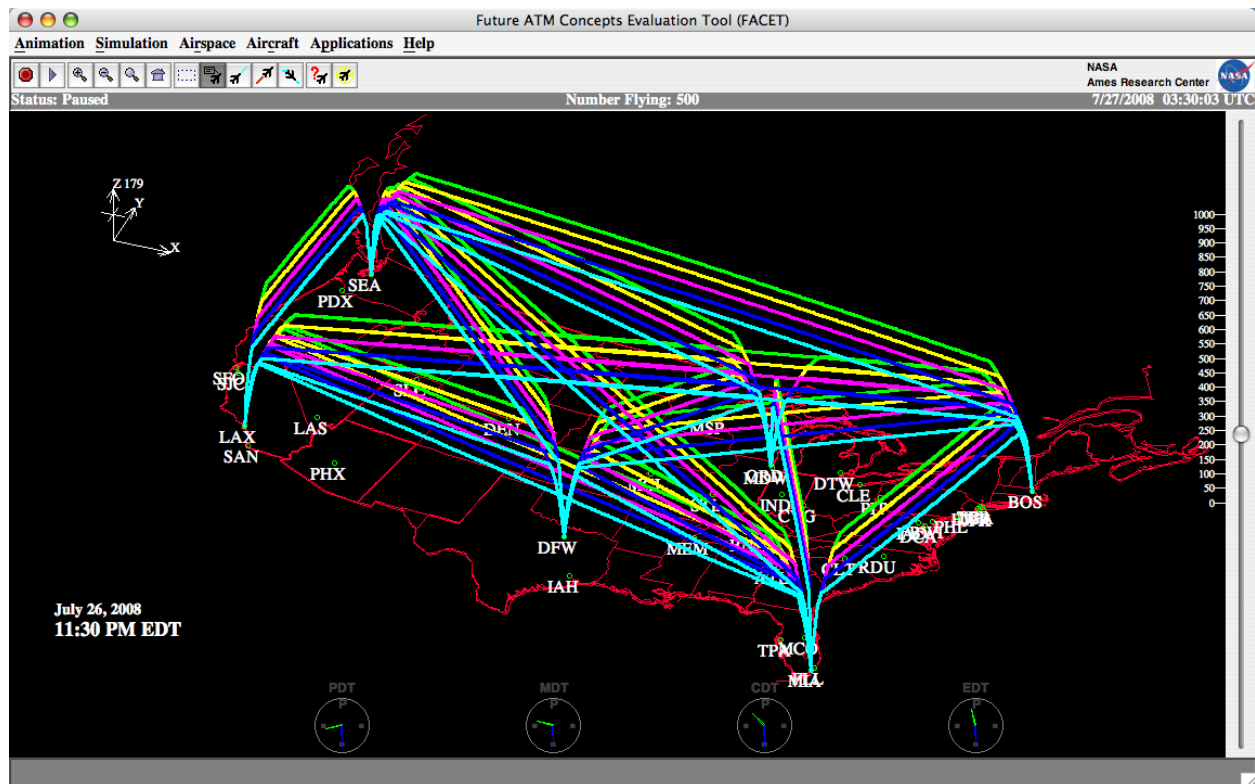

Figure 4: A description of futuristic airspace tube networks for six airports and five altitude levels.

ATM Network Characteristics (Scale-Free Networks), (2009)

There are big changes anticipated for air traffic in both developed and developing countries. The demand for air traffic in the United States is expected to grow to multiple times the current levels of traffic in the next few decades. This research modeled demand for air traffic as a network with several thousand nodes. Methods have been developed to study the network characteristics of large complex systems in many natural and engineering fields. Several networks exhibit the "scale-free" property that as the network grows in size, a small number of components have a disproportionate influence on the successful operation of the network. By establishing various airspace

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fixes/airports as nodes, and connections for flights between nodes, the research described the network properties of the U.S. air traffic system and used future scenarios of air traffic growth to understand the performance of future air traffic networks [5]. The air traffic network exhibits an exponentially truncated scale-free behavior. It was shown that a three-times growth in the overall traffic may result in a ten-times impact on the density of traffic in certain parts of the United States. Thus, in addition to bottlenecks at major airports, the risk of en route traffic saturation requires route restructuring and the introduction of new operational concepts, such as automation to increase en route capacity. Figure 5 shows the complementary cumulative distribution function (ccdf) as a function of the number of nodes on a log-log scale. It is observed that once the number of nodes approaches about 500, the linearity breaks down and the impact of a perturbation is felt significantly on the air traffic network. Similar behavior is observed for triple traffic scenarios of the future. This research was an example of FACET usage for researchers in developing concept and technology to address potential future infrastructural issues.
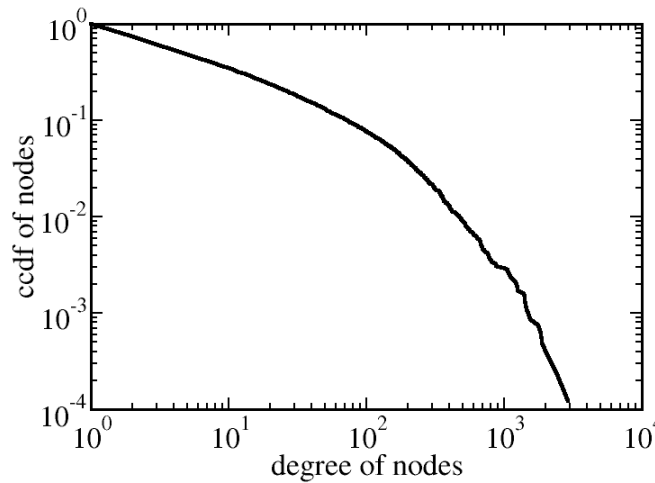

Figure 5: The scale-free behavior of the power-law for air traffic network with number of nodes.

Incorporation of User Preferences (Credits Concept), (2010)

The procedure and outcome of a human-in-the-loop simulation experiment were assessed for a novel market-based concept to incorporate user preferences in air traffic management. The purpose of the research was to study the feasibility of incorporating user flight preferences in air traffic demand and capacity management [6]. Five airline dispatchers specified flight priorities for multiple routes. These priorities were used for airspace constraint management by creating a new credit- or priority-ranked flight departure schedule. One air traffic manager prescribed and managed the airspace constraints. The dispatchers were trained on the system with different traffic scenarios. A realistic data set that included convective weather was used for assessing the concept. Based on the experiment results, it was learned that the credits concept allowed users to prioritize their flights and to distribute delays as per their preference. It was also observed that the delays could be reduced and equitably distributed among users with respect to a first-come first-served (FCFS) schedule, without violating airspace constraints. The study elicited several factors for prioritizing flights from the users' perspective, which could be used in future fast-time simulations. Such a mechanism could be used in the future where users could specify their priorities, without revealing their specific objectives, to help air traffic flow management to address demand/capacity imbalances while avoiding airspace constraints. Figure 6 shows various panels. The top-left and top-right panels show the system and a specific user's delays with the prescribed priorities. The bottom-left panel shows the utilization of credit- or priority-points as a function of time, and the bottom-right panel represents an overall performance index for that user.
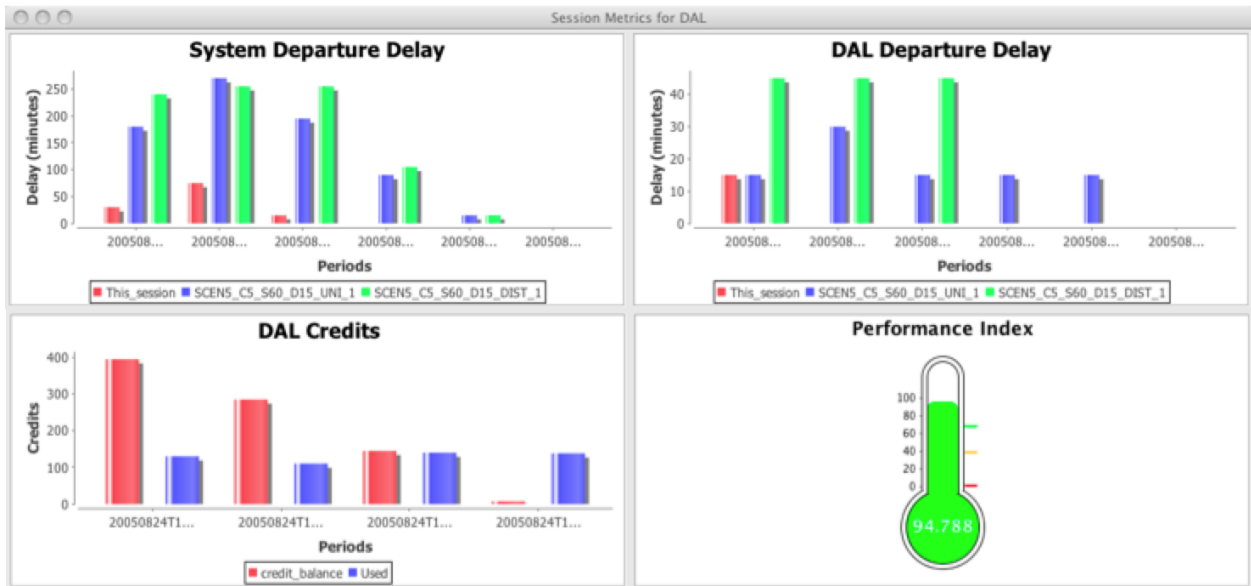
Figure 6: Sample overview of metrics from an experiment run as a function of time for various delay and performance parameters.

Evolution of FACET to an Operational Tool

The NAS Constraint Evaluation and Notification Tool, or NASCENT, grew out of several progressive enhancements to FACET. As mentioned earlier, a paper was published in 2002 on the integration of traffic flow management decisions [8]. In that paper, an algorithm for local rerouting around congested sectors, Flow Constrained Areas (FCAs), and weather polygons was presented. The implementation of this algorithm in FACET provided a generic polygon-avoidance capability. Also, since a robust and predictable analysis infrastructure was available within FACET, the NAS-based Direct-To functionality, from the CTAS-based single-Center implementation, was added around 2005. The Direct-To function assessed if the currently active aircraft flight plan had a large deviation in it that was inefficient, and identified a direct route that could save the aircraft in-flight time and fuel. That function did not check if the proposed direct route to a downstream fix on the flight plan crossed forecasted weather.

The Dynamic Weather Routes (DWR) concept implemented in CTAS was an extension of the Direct-To functionality. It checked if the direct route to a downstream fix intersected weather and, if so, added one or two auxiliary waypoints to avoid it. If it still saved the flight a user-specified amount (e.g., five minutes) of time, an advisory was presented to the flight operator. While this concept was being assessed, it became apparent that the flight operators and traffic managers needed to understand the impact of such advisories on the sector congestion. FACET, with its predictive capability, was a good choice for integrating with the CTAS-based DWR tool to provide the sector congestion analysis along the current route and along the proposed route [11]. FACET also provided information about any FAA-issued required reroutes information. This integrated system was tested at American Airlines (AAL) in Ft. Worth, TX from July 2012 to September 2014 [12, 13]. Figure 7 shows the user display of the DWR system at AAL during that period. It shows the traffic map (top-left) with the embedded DWR flight list. The sector congestion windows (top-right for current flight plan, and right-middle for proposed route) and the flight route information (bottom) are shown.
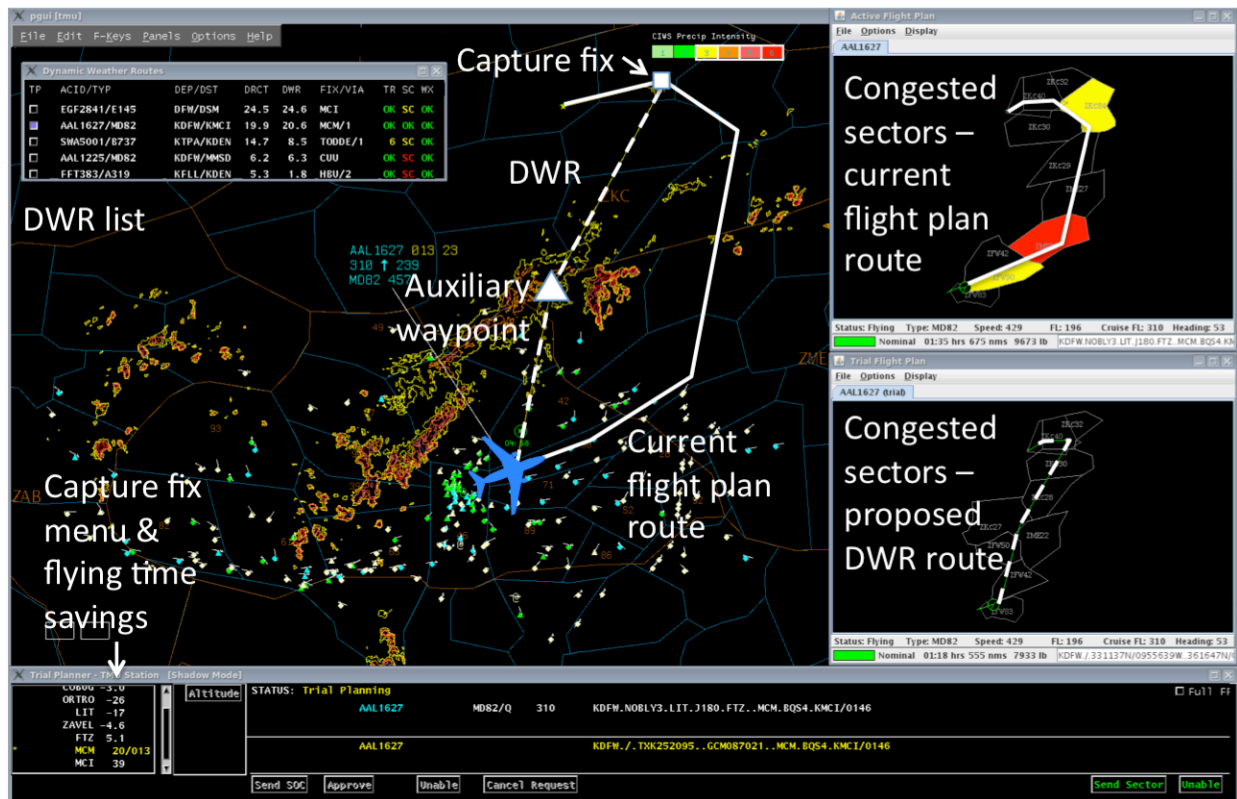
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Figure 7: Description of the user interface for a single-Center DWR system at American Airlines.

During the testing, it was apparent that, due to additional AAL hubs at Chicago O'Hare (ORD), Los Angeles (LAX), Miami (MIA), etc., it was necessary to provide these advisories for all 20 Centers simultaneously, and not just for Fort Worth Center (where the main AAL hub, Dallas/Fort Worth (DFW), is located). With that goal in mind, the DWR algorithm was implemented from scratch in FACET. Additional capabilities available within FACET due to the NAS-based environment are advisories that avoid constraints other than convective weather (Special Use Airspace, Temporary Flight Restriction, etc.) using the generic polygon-avoidance functionality developed in 2002 [8]. This consolidated functionality in FACET is called NAS Constraint Evaluation and Notification Tool or NASCENT [14, 15]. Due to the availability of FAA-issued Ground Delay Programs (GDPs) and Ground Stops (GSs) information within the System-Wide Information Management (SWIM) traffic flow management data, NASCENT is able to identify flights for which time- and fuel-saving advisories are available, and also determine if those flights are affected by current FAA traffic management initiatives (e.g., required route restrictions, GDPs, or GSs). It also identifies flights affected by Airspace Flow Programs (AFPs), and Collaborative Trajectories Options Program (CTOP), among some of the TMIs used by the FAA. Figure 8 shows the user display of the NASCENT application at AAL from September 2016 to the present. It shows the traffic map (top-left), the sector congestion windows (right-top for current flight plan, and right-middle for proposed avoidance route), NASCENT flight list (bottom-left), flight details (bottom-right) and a small required-reroute window, if a flight is affected by an FAA reroute advisory (overlapping the bottom-right window). In the top-left window, the Memphis Center (ZME) limit polygon is shown in cyan. A limit polygon was created for each of the 20 Centers in the NAS, using historical traffic data. It represents how far aircraft are cleared downstream by that Center's controllers. This limit polygon provides a means to improve controller acceptability of the NASCENT-generated advisories.

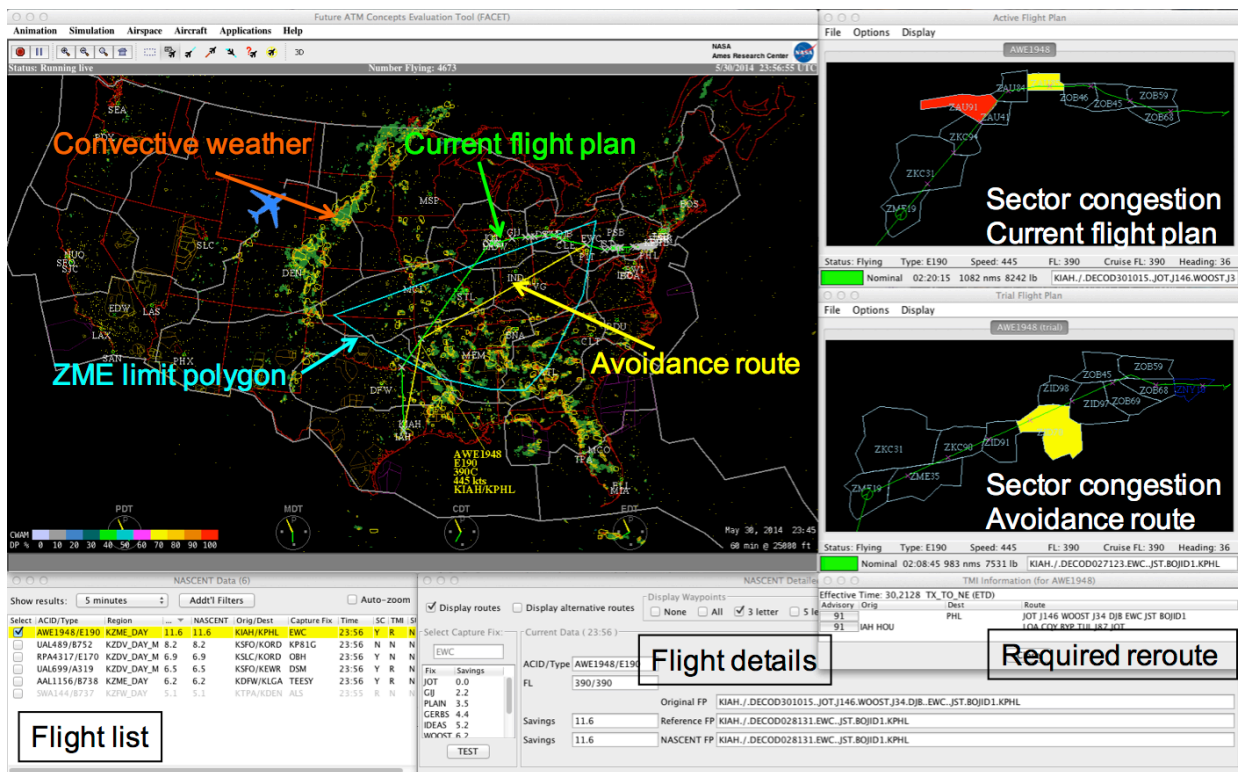American Institute of Aeronautics and Astronautics

Figure 8: Description of the user interface for the nationwide NASCENT system at American Airlines.

American Airlines has been evaluating the NASCENT system at the ATC Coordinator's desk since August 2016. The ATC Coordinators have provided feedback on the acceptability of the advisories generated by NASCENT. Based on the advisories, various statistics have been generated. These include parameters like the number of advisories for various origin and destination airports and city-pairs. The statistics for time- and fuel-savings are also generated. Figure 9 shows the number of advisories for the top 50 city-pairs for AAL flights over a 9-month period. Once the ATC Coordinators accept a particular advisory, they provide the advisory route to the dispatcher handling the flight. The dispatcher would, in turn, send an Aircraft Communications Addressing and Reporting System (ACARS) message to the pilot, if they concurred with the advisory. The pilot, if she/he concurred, then would request a route clearance from the air traffic controller responsible for the flight. AAL has provided some of the ACARS data and an analysis of various latencies is being conducted currently.
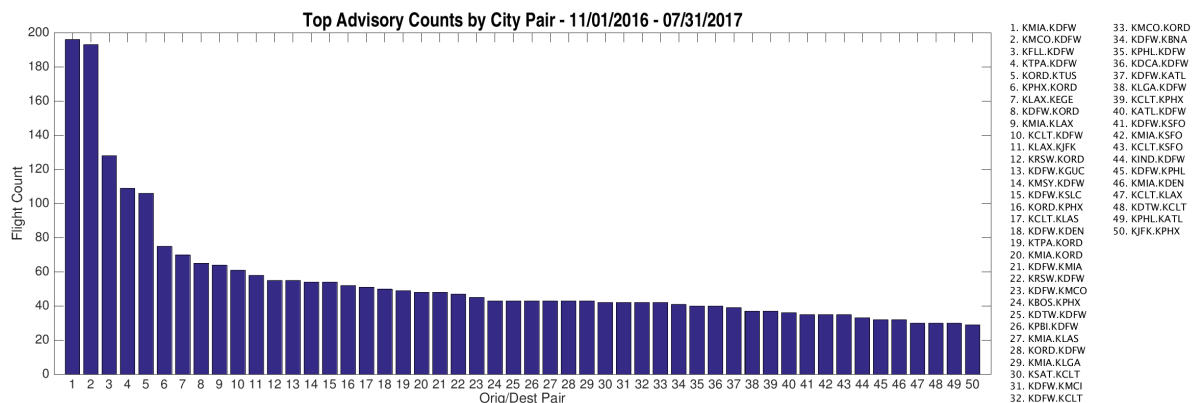

Figure 9: Number of efficient route advisories for top-50 city-pairs for 9-months of American Airlines flights.

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These latencies are the differences in times for when the advisory first appeared, when the advisory was accepted by the ATC Coordinator, when an ACARS message was sent by the dispatcher, and when a flight plan amendment was observed in the SWIM data feed. Those results will be presented in a future publication.

Projects and Resources

For any endeavor to sustain momentum over a two-decade period is difficult, both in industry and in government. Three main factors are perceived as drivers for the continued development of FACET software. First, a dedicated team pursued the growth of the system. Second, continued communication within NASA and with external entities regarding the specific capabilities developed within the tool. And third, continued support from NASA due to desired Traffic Flow Management (TFM) applications and strategic scale TFM problems.

Several projects supported FACET development including the Advanced Airspace Transportation Technologies (AATT), the Concepts and Technology Development (CTD), and the Airspace Technology Demonstration (ATD). Currently, the Applied Traffic Flow Management (ATFM) sub-project of ATD, called ATD-3, is supporting FACET technology for the Multi-Flight Common Route (MFCR) and Multi-Agent Air/Ground Integrated Coordination (MAAGIC) development. MFCR is the extension of single-flight rerouting technology (earlier referred to as Dynamic Weather Routes or DWR) to multiple flights from a traffic manager's perspective [16, 17]. The MAAGIC concept relies on integration of ground-based rerouting technology (DWR/MFCR) with cockpit-based NASA technology called Traffic Aware Strategic Aircrew Requests (TASAR). This work will ensure the sustained use and development of FACET capabilities.

In the beginning, FACET was in development with just two software developers. Over the years, as the demand for its use increased, it was supported by up to 13 developers. Currently, eight developers support the development, testing and analysis of FACET software under ATD-3 sub-project. It is estimated that the average cost of FACET development has been about 2-3 million US Dollars per year.

Achievements and Commercialization

Over the years, FACET software has received much recognition for its contribution to ATM research. These include numerous NASA awards, other government and public organizations, and industry awards. FACET software was the recipient of the following awards:
Turning Goals Into Reality (NASA, 2001),
Demo God Trophy (Demo Conference, 2002),
Distinguished Level Excellence in Technology (Raytheon Corporation, 2002),
Honor Award (NASA Ames Research Center, 2005),
Software of the Year Award (NASA, 2006),
Aerospace Engineering Software Award (AIAA, 2009),
Excellence in Aviation Research (FAA, 2010),
Aviation Safety Symposium (Airline Dispatcher's Federation, 2010 and 2012),
Government Invention of the Year (NASA, 2011).

In addition, FACET software has received two patents (# 7702427 and # 8290696) and two other patents for the weather rerouting technology (# 9171473 for DWR and # 9558670 for NASCENT). The animations created using FACET software have been featured on television networks (CNN, ABC and CBS) and USA Today website. Animations created using FACET software have been running at the Smithsonian Institution's National Air and Space Museum for over ten years. They first were put on display in 2007 with the "America By Air" exhibit. They are still providing an insight into the traffic over the continental United States to the general public. The White House National Science and Technology Council (NSTC) utilized a FACET image for their 2007 National Aeronautics Research and Development Plan. Many university professors (MIT, UC Berkeley, Stanford, etc.) have utilized FACET animations for various classroom and conference presentations, as well as testimony at the U.S. Congress. One Kennedy Space Center employee was able to complete a Master's thesis on spaceflight impact on the NAS due to FACET software.

The FAA Collaborative Decision Making (CDM) group recommended that FACET software be implemented at all airlines and other flight operators in its 2001 general report. The recommendation was not carried out; however, FACET software did operate in a live data mode at two airlines, Northwest Airlines (Minneapolis, MN) and Southwest Airlines (Dallas, TX). Additionally, FACET software was commercialized for its predictive capability of sector congestion by FlightExplorer, Inc. (a flight tracking software company) in 2006. At that time, FlightExplorer had 80% of the U.S. airlines and all cargo operators as their customers.

Conclusion

It has been a long journey spanning two decades. Numerous concepts have been assessed using the Future ATM Concepts Evaluation Tool (FACET). The software has been tested with live functionality at three airlines and commercialized by a flight tracking software company for its live sector congestion information. The NAS Constraint Evaluation and Notification Tool (NASCENT) was developed for the weather avoidance capability available within FACET. It is being used in real-time operations at American Airlines' Integrated Operations Center in Fort Worth, TX. A motivated team (of researchers, software developers, and industry partners), robust research agenda, and NASA's continuous support over two decades were key elements in the success of this endeavor. FACET has demonstrated return on tax payers' investment in research funding, specifically, as an education tool for the general public, an assessment capability for aviation's impact on the environment in terms of emissions and noise, and by providing tangible benefits to the airlines and the economy.

FACET has been used for research purposes by many NASA programs, and is currently the concept implementation system for one of the components of the Airspace Technology Demonstration, ATD-3 sub-project. Based on the current plans, FACET will provide enhancements and improvements for arrival traffic, rerouting multiple flights simultaneously, and other concepts, while integrating with other FAA and commercial technologies. Capabilities will also be developed for providing use cases for newer implementations like data communication, and pre-departure and airborne rerouting.

Acknowledgment

References

[1]Bilimoria, K., Sridhar, B., Chatterji, G., Sheth, K. S., and Grabbe, S., "FACET: Future ATM Concepts Evaluation Tool," *Air Traffic Control Quarterly*, Vol. 9, No. 1, 2001, pp. 1-20.

[2]Sridhar, B., Sheth, K., and Grabbe, S., "Airspace Complexity and its Application in Air Traffic Management," *2nd USA/Europe Air Traffic Management R&D Seminar*, Orlando, FL, December 1998.

[3]Bilimoria, K., Sheth, K., Lee, H., and Grabbe, S., "Performance Evaluation of Airborne Separation Assurance for Free Flight," *AIAA Guidance, Navigation, and Control Conference,* Denver, CO, August, 2000.

[4]Sheth, K., Islam, T., and Kopardekar, P., "Analysis of Airspace Tube Structures," *27th Digital Avionics Systems Conference*, St. Paul, MN, October, 2008.

[5]Sridhar, B. and Sheth, K., "Network Characteristics of Air Traffic Flow," *Encyclopedia of Complexity and Systems Science*, Ch. Complex Dynamics of Air Traffic Control, pp. 234-242, April 2009.

[6]Sheth, K., Gutierrez-Nolasco, S., Courtney, J., and Smith, P., "Simulations of Credits Concept with User Input for Collaborative Air Traffic Management," *AIAA Guidance, Navigation, and Control Conference,* Toronto, Canada, August, 2010.

[7]Sridhar, B., Soni, T., Sheth, K., and Chatterji, G., "An Aggregate Flow Model for Air Traffic Management," *Journal of Guidance, Control, and Dynamics,* Vol.29: 992-997, 2006.

[8]Sridhar, B., Chatterji, G., Grabbe, S., and Sheth, K., "Integration of Traffic Flow Management Decisions," *AIAA Guidance, Navigation, and Control Conference,* Monterey, CA, August, 2002.

[9]Sheth, K., Gutierrez-Nolasco, S., and Petersen, J., "Analysis and Modeling of Miles-in-Trail Restrictions in the National Airspace System," *AIAA Aviation 2013,* Los Angeles, CA, August 2013.

[10]Sridhar, B., Chen, N., Ng, H., and Morando, A., "Modeling and Simulation of the Impact of Air Traffic Operations on the Environment," *Air Traffic Control Quarterly,* Vol.20: 285-310, 2012.

[11]Sheth, K., McNally, D., Petersen, J., Morando, A., and Shih, F., "Consideration of Strategic Airspace Constraints for Dynamic Weather Routes," *12th AIAA Aviation Technology Integration and Operations Conference*, Indianapolis, IN, September 2012.

[12]McNally, D., Sheth, K., Gong, C., Osborne, J., et al., "Operational Evaluation of Dynamic Weather Routes at American Airlines," *10th USA/Europe Air Traffic Management Research and Development Seminar*, Chicago, IL, June 2013.

[13]McNally, D., Sheth, K., Gong, C., Sterenchuk, M., et al., "Dynamic Weather Routes: Two Years of Operational Testing at American Airlines," *11th USA/Europe Air Traffic Management Research and Development Seminar*, Lisbon, Portugal, June 2015.

[14]Sheth, K., McNally, D., Morando, A., Clymer, A., Lock, J., Petersen, J., and Shih, F., "Benefit Analysis of Multi-Center Dynamic Weather Routes," *14th AIAA Aviation Technology Integration and Operations Conference*, Chicago, IL, June 2013.

[15]Sheth, K., McNally, D., Somersall, P., Morando, A., Clymer, A., and Shih, F., "Assessment of a National Airspace System Airborne Rerouting Tool," *11th USA/Europe Air Traffic Management Research and Development Seminar*, Lisbon, Portugal, June 2015.

[16]Sheth, K., McNally, D., Morando, A., Clymer, A., Lock, J., Petersen, J., and Shih, F., "Benefit Analysis of Multi-Center Dynamic Weather Routes," *14th AIAA Aviation Technology Integration and Operations Conference*, Chicago, IL, June 2013.

[17]Sheth, K., Clymer, A., Morando, A., and Shih, F., "Analysis of Multi-Flight Common Routes for Traffic Flow Management," *AIAA Aviation 2016*, Washington, D.C., June 2016.

[18]Bilimoria, K., Hayashi, M., and Sheth, K., "Subject Matter Expert Evaluation of Multi-Flight Common Route Advisories," *AIAA Aviation 2017*, Denver, CO, June 2017.