Methodology for Assessing Tradeoffs between Operational and Environmental Performance in the National Airspace System

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***Abstract* - Given the growing interest in addressing aviation-related environmental challenges, environmental impacts need to be assessed along with operational performance for any large-scale proposed change to the air transportation system. Existing tools can evaluate operational and environmental performance separately, but do not adequately address tradeoffs between different goals. This work presents an integration approach for bridging the gap between system-wide operational performance tools and environmental models. The proposed methods are tested by bringing together the *systemwide*Modeler developed at the MITRE Corporation and the Aviation Environmental Design Tool being developed by the United States Federal Aviation Administration. An illustrative analysis demonstrates the methods presented.**

Keywords – air traffic control, environmental impact, aircraft noise modeling, emissions modeling, aviation fuel burn, fast-time simulation

I. INTRODUCTION

Meeting anticipated future growth in aviation demand will require integrated efforts to tackle many challenges, including those related to safety, security, infrastructure, capacity, and the environment. Environmental concerns in particular pose significant constraints to aviation growth [1]. There are several efforts in place such as the U.S. Next Generation Air Transportation System (NextGen) and the European Single European Sky ATM Research (SESAR) initiative that seek to find technological, operational, and policy solutions to allow for sustainable aviation growth [2-3].

Assessment of tradeoffs among environmental impacts and operational efficiency gains in the U.S. has thus far mostly been limited to aircraft noise and emissions impacts in the terminal area to ensure compliance with the regulatory requirements of the National Environmental Policy Act (NEPA) and the Clean Air Act or to assess fuel savings for operators [4]. In contrast, National Airspace System (NAS)-wide transformational initiatives such as NextGen will cover large geographical areas and therefore require new system-wide modeling and analysis capabilities to assess operational and environmental tradeoffs. The need for system-wide environmental analysis capabilities has also been recognized by the Federal Aviation Administration's (FAA) Research, Engineering and Development (RE&D) Advisory Committee (REDAC). Some of the recommendations of the REDAC for the FY2012 R & D Portfolio were to incorporate environmental issues in the research and strategic planning stages and develop linkages between NAS simulation tools and environmental models [5-6].

While there are specific modeling and simulation capabilities for evaluating system-wide operational and environmental performance separately, there have been limited efforts to address the tradeoffs between these different performance goals. There is a growing interest in bringing these disparate modeling domains together as illustrated by several recent studies. For instance, Sridhar et al. use simulated traffic data to assesses both CO_2, and non-CO_2 (including contrails) aircraft emissions and propose optimized re-route options to the air traffic system model that seek to mitigate climate change impacts of aviation [7]. Thompson et al. assess the system-wide environmental impacts of several NextGen scenarios in terms of noise, emissions, and fuel burn impacts [8]. However, most recent studies have used simplified methods for assessing environmental impacts recognizing the need for future work on incorporating high-fidelity environmental models which include detailed performance and emissions modeling by phase of flight [7-8]. The National Aeronautics and Space Administration (NASA) has also conducted studies on assessing system-wide environmental benefits of introducing advanced concepts and vehicles into NextGen based on the high-fidelity agent-based simulation tool Airspace Concept Evaluation System (ACES) and FAA's Aviation Environmental Design Tool [9-11]. ACES can provide some characterization of delay maneuvers on a flight by flight basis, but provides low resolution trajectories in the terminal area. A kinematic trajectory generator was used in the NASA work to improve on the terminal area trajectory definition from ACES [12-13].

The main objectives of this work are to identify key research challenges associated with developing linkages between NAS-wide simulation tools and environmental tools and illustrate the methodology developed here to address these challenges through a sample analysis. While the integration approach proposed here brings together *systemwide*Modeler, developed at the MITRE Corporation, and the Aviation Environmental Design Tool (AEDT), being developed by the United States Federal Aviation Administration Office of Environment and Energy, the methods developed can be applied to other models [11,14]. The paper is organized as follows – Section II presents relevant background information on *systemwide*Modeler and AEDT while Section III identifies major research challenges. Section IV discusses the methodology adopted in this work for developing linkages between *systemwide*Modeler and AEDT. Section V describes results from a sample analysis and Section VI summarizes key findings and highlights areas of future research.

II. MODEL DESCRIPTION

Fast-time air traffic system simulation tools model the airspace system of interest at a low resolution with a focus on capturing key interactions among components such as airports, airspace sectors, and projected air traffic demand while estimating metrics of system performance such as delay. Delay is often expressed simply as time absorbed at a particular point in the airspace system, without an accompanying realistic aircraft maneuver such as a slow-down, a vector, vertical profile change, or a holding pattern. Environmental models, on the other hand, require detailed flight paths that explicitly express these delay absorption maneuvers. Developing linkages between the air traffic simulation and environmental domains involves identifying the key modeling gaps between these two domains. This section presents an overview of the models used in this work – *systemwide*Modeler and AEDT.

A. MITRE's systemwideModeler

NAS-wide operations tools generally include components such as flight schedules generators that also account for future growth, airport and airspace capacity models, flight trajectory models, etc. however, details associated with these components vary for each model or simulation. MITRE's *systemwide*Modeler is a fast-time discrete-event simulation used to evaluate NAS performance for a full day of air traffic operations. *systemwide*Modeler has been exercised for assessing NextGen operational improvements using performance metrics such as delay, system throughput, and controller workload [14].

In a typical *systemwide*Modeler simulation, 50,000-100,000 flights, representing one day of activity in the NAS, are simulated subject to capacity constraints for various NAS components modeled. The constraints issued to flights can result in flights being delayed, canceled, assigned to a different airframe, or rerouted. For this study, the constraints of interest are those that result in flights taking delay at 4-D trajectory points in en route airspace. The flight's lateral and vertical profiles are not modified in any way to reflect the absorption of the identified delay. The constraints placed by resources in *systemwide*Modeler only require that the flight not cross the identified trajectory point until some designated time.

B. FAA's Aviation Environmental Design Tool (AEDT)

Noise and emissions from aircraft operations have typically been assessed separately using analysis tools that can range from screening tools based on simplified assumptions to computationally-intensive high-fidelity tools used for NEPA analysis. While there are other international noise and emissions modeling capabilities such as those developed by the UK Department of Transportation and EUROCONTROL, this discussion focuses on the FAA Aviation Environmental Design Tool.

The FAA's Office of Environment and Energy is leading the development of the Aviation Environmental Design Tool, which is intended to be the next environmental regulatory compliance model that provides both noise and emissions modeling capabilities [15]. AEDT has a modular structure with various computational modules focused on performance, noise, and emissions calculations. AEDT models four-dimensional aircraft trajectories on a flight by flight basis while accounting for weather and terrain impacts and can be used for environmental studies ranging in scope from a single operation to a global analysis. User inputs to AEDT include information on aircraft lateral and vertical paths (in the form of radar tracks or simulation outputs), equipment type, number of operations, study airports, etc. AEDT study outputs include aircraft performance, a wide range of average and single-event noise metrics that can be used to generate noise contours or exposure at particular locations of interest, fuel burn, and emissions. Several pollutants including carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), particulate matter (PM), and sulfur oxides (SO_x) are modeled by AEDT [16].

III. KEY RESEARCH CHALLENGES

Operational and environmental analysis tools can have very different flight trajectory modeling requirements owing to varying analysis objectives. Air traffic system tools focus on capturing key system behavior at the NAS-wide scale in terms of system throughput, response to congestion and weather, delay propagation and distribution across several NAS resources, assessment of new ATM concepts, etc. Environmental models on the other hand are focused on assessing emissions, fuel burn, and noise for a given flight path and require flight-specific information on vertical and lateral flight path, equipment type, number of operations, etc. There are two cases in particular where there is significant gap between trajectory representation in operational and environmental models – terminal area modeling and delay maneuvers.

Flight trajectory modeling for air traffic system analysis tools is typically of mixed fidelity across the NAS. Many simulation tools such as *systemwide*Modeler capture en route flight trajectory characteristics with sufficient detail based on filed flight plans. However, terminal area representation of the flight trajectory typically is of a lower resolution and does not incorporate details of arrival and departure procedures close to the runway. Simulation tools are focused on capturing effects of system-wide changes and consequently adopt simplifying assumptions using low-resolution flight paths in the terminal area. Figure 1 provides a notional display of the differences in terminal area path definition in *systemwide*Modeler. The colored paths are radar tracks of departures and arrivals into the airport. The black lines represent low resolution trajectories from *systemwide*Modeler. The lower resolution terminal area path representation is not sufficient for estimating noise, emissions, and fuel burn impacts in the terminal area, which necessitates modification of *systemwide*Modeler trajectories prior to conducting an environmental analysis. Additionally, simulations model a few selected days of operations in the NAS and produce average daily performance metrics based on the days modeled. However, terminal area environmental modeling requires data that are representative of all operations at the given airport and not just those for the selected simulation days.

There have been recent efforts to improve terminal area path representation in NAS-wide operational analysis tools using published departure and arrival procedures or by developing backbone tracks based on radar data [8, 12, 17]. However, augmenting en route flight trajectories with published procedures in the terminal area may not accurately represent operational activity for environmental analysis purposes as radar tracks often deviate from published procedures due to ATC measures such as vectors, holds, shortcuts or direct-to clearances, etc. Backbone tracks with dispersion around the central track can serve well for enhancing terminal area representation depending on the sampling process for selecting radar track data, but can also be resource intensive. The methodology proposed in this work for enhancing terminal area trajectories from *systemwide*Modeler consists of creating a Terminal Radar Approach Control (TRACON) Path Library (TPL) for the Core 30 airports [18]. Improving terminal area trajectory resolution for non-Core 30 airports will be addressed in future work.

The second area where trajectory representation from most operational models is insufficient for environmental modeling purposes is the characterization of delay. Delay is often expressed in units of time along with the location along a flight trajectory where the delay is expected owing to constraints imposed by NAS resources. Changes to the flight trajectory necessary for accommodating the delay imposed by congestion (related to traffic, weather, or other constraints) such as speed changes, vectors, or holds are not provided by most fast-time NAS-wide operational tools. Environmental models require detailed information on every point along the flight trajectory (latitude, longitude, altitude) for evaluating noise, emissions, and fuel burn. Consequently, *systemwide*Modeler trajectories with delay information need modifications that include delay maneuvers before they can be supplied to AEDT.

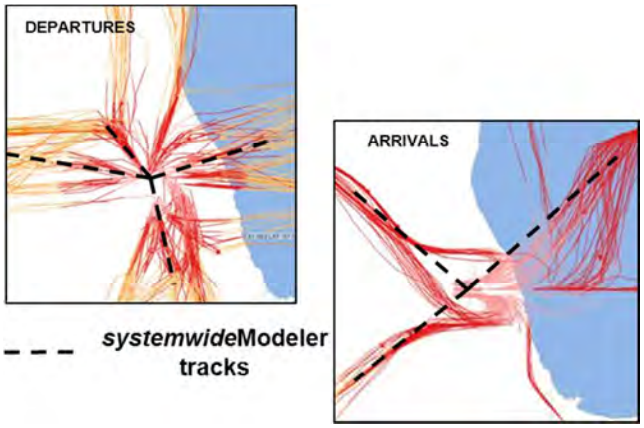

Figure 1: Notional terminal area path representation in *systemwide*Modeler

IV. METHODOLOGY

A. *Terminal Area Trajectory Representation*

For the purposes of this work, the representation of air traffic in the airport terminal area relies on the creation and then sampling of a TRACON Path Library (TPL). The TPL is a collection of flight paths that traverse the terminal area, either as departures or arrivals. The TPL stores information on the latitude, longitude, and altitude of each track point for all terminal area flight paths considered. The TPL can either consist of radar track data representing present day NAS operations from the FAA National Offload Program (NOP) data repository or may be populated with proposed RNAV/RNP procedures [19]. This paper presents the process developed for the creation of a TRACON Path Library (TPL) populated with arrival radar paths for the Core 30 airports. Arrival radar track data was collected and analyzed for seven of the Core 30 airports – ATL, BOS, BWI, CLT, DCA, DEN, and DFW. On-going research involves adapting this TPL creation process for generating a TPL with departure radar tracks.

In order to ensure that the arrival flight paths in the library sufficiently describe operational characteristics for a given airport (fleet, configurations, fixes, etc.), this work defines an arrival flow as a collection of flight paths grouped by arrival fix, runway, and aircraft type. Given that the term “arrival fix” is not rigorouslydefined in the NAS and can vary by airport, *systemwide*Modeler uses an ad hoc cluster analysis technique to find coalescences of flight trajectories at about 50-60 NMI from arrival airport [20]. The arrival fix as identified by *systemwide*Modeler is used as the starting point of the arrival path with the corresponding runway end as the last point of the path. Taxi information is currently not included in the definition of terminal area paths. TPL paths are also classified according to aircraft type where the International Civil Aviation Organization (ICAO) equipment designation taken from radar data is mapped to the Integrated Noise Model (INM) equipment types using aircraft type mapping provided by AEDT.

Environmental studies conducted at the airport-level for NEPA or FAR Part 150 studies typically use one year of radar data to appropriately capture prevailing conditions at the airport. Given the NAS-wide scope of this work collecting and analyzing one year of radar data at each airport is not feasible. Consequently, the TPL is required to contain adequate observations to capture path variability for an airport given changing traffic, weather, temporal, and seasonal considerations. The coefficient of variation (CV) of path distance is used here as a statistical measure of path variability that captures the spread in path distance relative to a nominal mean path distance. This statistic is defined as the sample standard deviation divided by the sample mean of path distance.

The criterion for determining the appropriate sample size needed to capture TRACON path variability is the lack of significant change in the CV value as more observations are added. A stable value of CV for a given flow implies a sample size that is sufficient to capture path variability for a given flow. It is important to note the distinction between sample days and observations. An observation refers to a single flight in a given flow where multiple observations of the same flow can be encountered on a given sample day. Sample days are randomly selected over the course of one year. The process for determining the sample size requirements of the arrival TPL is as follows.

First, CVs are computed for all flows for a given airport and the change in the CV value per flow as new observations are added is tracked. Note that in accordance with the Central Limit Theorem a minimum sample size of 30 flights is used for the computation and plotting of a CV value to allow for a normal approximation for the distribution of the sample mean with an expected value equal to the population mean [21]. While flows with fewer than 30 observations that occur relatively infrequently relative to flows that represent routine operations are not included in the CV analysis, they are included in the TPL and may not have stable CV values. This work assumes that rare, low-count flows exist, and a low sample size for such rare flows will limit representation of variance, but their contribution to overall inaccuracy in environmental modeling may be likewise small. Additional work validating noise results based on using TPL radar paths will be needed to test the assumption regarding rare, low count flows made here.

Figure 2 shows this progression of CV values for arrivals into ATL (Atlanta Hartsfield International Airport) for a random subset of 100 flows as the sample size increases. In Figure 2 the number of days sampled increases along the x-axis; days are randomly ordered and sample size is cumulative. The graphics show that CV values, per flow, stabilize from left to right as sample size increases. At a sample size of 100 days for a large majority of the flows the maximum absolute change in CV value between the last sampled day and the previous 20 days (per flow) is 0.005 or less indicating a stable CV value. Similar results were also seen for other six airports analyzed here implying that a TPL sample size on the order of 100 days is sufficient to achieve CV stability for flows with greater than 30 observations.

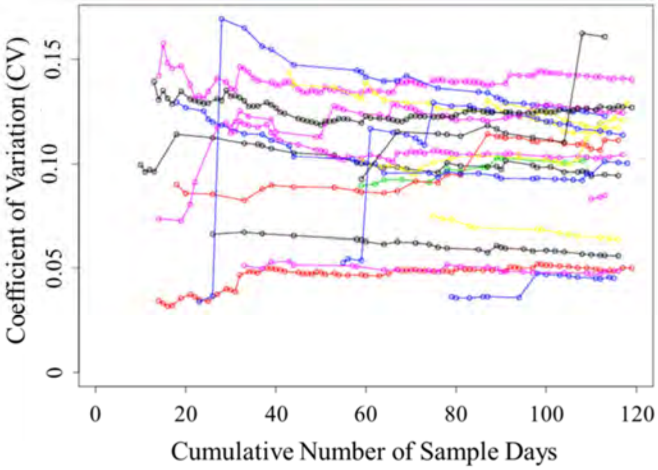

Figure 2: Coefficient of variation for a random subset of 100 flows, ATL arrivals

Next a validation exercise was carried out for three of the airports studied – ATL, BOS, and BWI. This validation exercise compares path variability as captured by radar tracks from100 randomly sampled days with that captured by one year of radar track data. The TPL with a sample size of 100 days is a subset of the one year of data used. First, the CV of each flow as computed based on the TPL with 100 sample days was compared with the corresponding CV value determined based on one year of radar data. The distribution of the difference in CV was found to be roughly symmetric around zero, with some greater probability mass on the positive side indicating that the path variability as assessed by the TPL with 100 sampled days was comparable to using one year of arrival radar track data.

As a second validation step, a statistical test of equality of variances comparing the TPL with 100 sample days and the one-year radar track data set was also conducted using the Levene test [22]. The null hypothesis for this test was that the variances for each flow are equal for the two data sets, i.e. having one year of radar track data does not add new information in terms of path variability. The resultant p-value was compared to an alpha level of 0.05 to test for statistical significance of difference in variances with p-values less than 0.05 signaling a rejection of the null hypothesis, i.e., variances are different. For most flows (92%), the p-values exceed 0.05, i.e., a failure to reject the null that the variances are equal. The Levene test was also performed for BOS and BWI and results for both airports showed at least p-values for 99% of flows analyzed exceeding 0.05. This analysis did not adjust alpha values to account for multiple tests, since the tests were independent.

As a last step, a geographical visualization of radar tracks for the TPL with 100 days of data as compared with one year of data was undertaken. ATL arrival flight tracks are plotted in Figure 3, for flows with sample size >=30, for 365 days (green) and for 100 days (blue). It should be noted that all blue-colored tracks overlay and obscure green-colored tracks, since the 100-day sample is a proper subset of the 365-day sample. The figure shows a significant mass of blue covering the main geographic area of aircraft movement and ATC vectoring. Some minor differences can be observed between the two data sets with outlier green tracks that do not follow the major traffic patterns at ATL; additional testing will be required to assess the impact of not including these tracks in the TPL. This graphic depiction is a further confirmation that 100 days of sampling can be deemed sufficient for the purposes of this work. Future work will involve comparing fleet mix for 100 randomly sampled days with one year of data to ensure that environmentally significant aircraft types are adequately represented in the TPL.

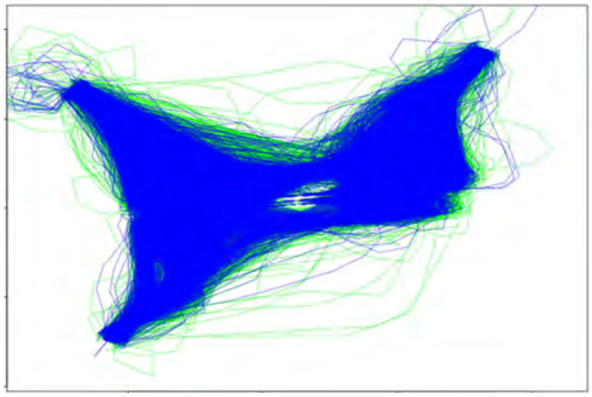

Figure 3: Flight tracks for ATL arrivals: 100-day sample (blue color) and 365-day sample (green color)

Finally, once such a TRACON path library is created, *systemwide*Modeler en route flight plan-based paths are connected with radar tracks from the TPL such that a smooth lateral and vertical transition between the en route and terminal domains is enforced. Selection of a TRACON path is done via random sampling.

B. En route Delay Maneuvers

Delay maneuvers commonly used by air traffic control include speed changes, vectors, and holding patterns. Any combination of these maneuvers may be used to slow down a flight in order to absorb delay depending on the prevalent traffic conditions, airspace sector characteristics, aircraft type, weather, etc. This work focuses on a simplified approach for absorbing delay in a realistic manner with the main objective of capturing associated environmental metrics. As such, trajectory modifications are intended to capture associated changes in flight distance as well as aircraft performance which influence noise, fuel burn, and emissions resulting from aircraft activity. Trajectory modifications will not reflect controller workload implications and should not be used for other such purposes. Given the lack of a speed control capability in the current beta versions of AEDT, this work focused on developing an algorithm for incorporating flight vectors as the primary mechanism for delay absorption. Flight trajectories from *systemwide*Modeler are modified by including delay vectors at locations along the trajectory where *systemwide*Modeler models delay resulting from resource constraints or congestion. On-going work is focused on developing an algorithm for introducing holding patterns to absorb excessive delays predicted by *systemwide*Modeler.

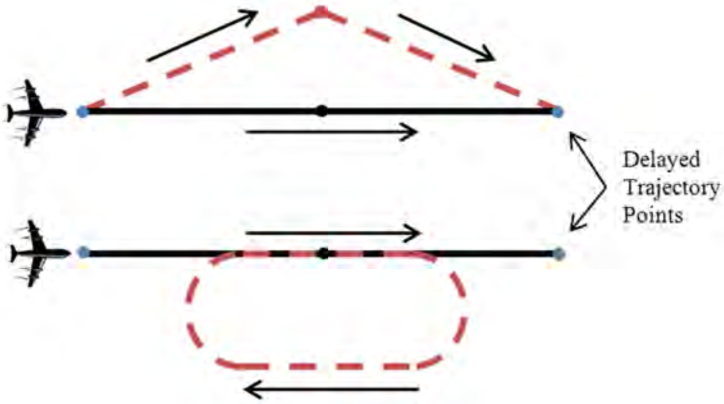

Figure 4: Delay absorption maneuvers – vectors and holds

The delay absorption algorithm presented here assumes that delay is absorbed by vectoring for small delays or by holding for larger delays. Figure 4 shows a schematic of a sample vector and a holding pattern. The methodology for incorporating holding patterns is work in progress. Vectoring is represented by turning away from the planned trajectory at some newly inserted divergence point, flying to a newly inserted delay absorption point, and turning back to rejoin the original trajectory. Holding is represented by turning away from the planned trajectory at some divergence point, flying in a race track pattern as is commonly found in practice, repeating the pattern as necessary, and returning to the original trajectory at the divergence point.

Delay vectors and holds are only introduced in the en route climb, cruise, and descent segments of the trajectory. Terminal area delay is assumed to be captured by variability in the radar paths from the TRACON Path Library. The delay absorption algorithm involves introducing additional points in the *systemwide*Modeler trajectory as needed to account for predicted delay subject to simplifying assumptions regarding turn angles, flight speed, length of delay, etc. Constraints imposed by *systemwide*Modeler resources delay passage of a particular trajectory point by a flight at sector entry points or trajectory points where different arrival flows merge. Delay absorption maneuvers are inserted into the trajectory at specific locations where *systemwide*Modeler imposes constrains such that the delay is absorbed prior to the passage of the delayed trajectory point. Aligning the insertion of vectors or holds with locations along the trajectory where *systemwide*Modeler predicts delay allows the fuel burn and emissions impacts to better reflect the phase of flight that the delay was encountered at. The altitude at which the delay maneuver is inserted has a significant bearing on the resulting fuel burn impacts and is driven by the location at which *systemwide*Modeler predicts delay.

The selection of vectoring or holding as the delay absorption maneuver is determined by the amount of delay that needs to be absorbed subject to simplifying assumptions about flight performance. Vectoring as a means for accommodating delay is given preference over holding which reflects standard ATC practices since holding involves increased workload for air traffic controllers and pilots. The preferred turn angle or a lateral heading change from the divergence point in a vector is currently conservatively assumed to be 35 degrees relative to the original trajectory based on flyability considerations for various aircraft types and performance results from AEDT. Constraints on the lateral turn angle in the NAS are dependent upon several considerations including altitude, speed, aircraft type, boundaries with other control sectors, conflicting traffic, etc. This algorithm includes the preferred turn angle as a variable which can be updated in future refinements of this approach. A flight is assumed to turn at three degrees per second as per FAA guidance in a holding pattern [23].

V. SAMPLE ANALYSIS

A sample noise and emissions analysis was conducted as a demonstration of the methodologies developed to establish connectivity between *systemwide*Modeler and AEDT. It is important to note that the main objectives of this sample analysis were to conduct initial tests of the methods developed and identify major shortcomings. The focus here was not on the accuracy of the noise and emissions results but on testing whether the appropriate inputs had been passed to AEDT for an environmental assessment. Further testing will be continued as future work to ensure that the methods developed are robust and scalable to NAS-wide studies. The next few sections provide an overview of the study inputs and discuss key results.

A. AEDT Study Inputs

This sample analysis used seven LAX to BOS flights from a *systemwide*Modeler scenario as track and operations inputs to AEDT. En route delays were imposed on the LAX to BOS flights as a result of demand exceeding capacity for terminal and en route resources in *systemwide*Modeler. Information on latitude, longitude, altitude, time at every trajectory point for each of the seven LAX to BOS flights along with associated aircraft type was extracted from the *systemwide*Modeler test scenario as inputs to AEDT. *systemwide*Modeler trajectory outputs were combined with radar tracks from the TRACON Path Library based on the approach described in Section IV. The arrival TRACON Path Library tracks were used for sampling paths arriving into BOS. Representative departure radar tracks were selected for LAX that matched the *systemwide*Modeler outputs for this study. Finally the path stretch algorithm was applied to those flights that were modeled to experience delay by *systemwide*Modeler to accommodate delays in the form of vectors.

B. AEDT Outputs

This section presents key results from the AEDT runs for the sample analysis that demonstrate the methodologies discussed in Section III. Figure 5 presents an AEDT display of the seven LAX to BOS flights modeled in this study. The blue en route tracks are outputs from *systemwide*Modeler that are combined with red tracks in the terminal area using inputs from the TRACON Path Library. AEDT provides performance results for these flights based on input information on trajectories and aircraft type. Both noise and emissions results were generated for this sample study using AEDT.

Figure 5: AEDT performance display for the LAX-BOS sample analysis (blue paths - *systemwide*Modeler outputs and red tracks - TRACON Path Library)

Figures 6 and 7 provided details on LAX and BOS terminal performance along with noise contours associated with the seven operations. The noise contours were generated for the dB DNL noise metric by scaling up each trajectory to account for 100 operations. As such noise contours presented are for 700 departure and arrival operations respectively distributed evenly across the seven paths presented. The outer-most contour corresponds to 55 dB DNL whereas the inner-most contour is at 70 dB DNL. Noise results are seen to reflect the tracks and operations modeled appropriately.

Figure 6: Sample LAX departures and noise results

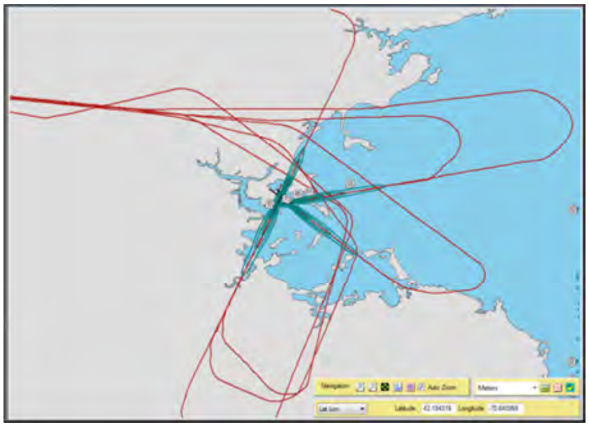

Figure 7: Sample BOS arrivals and noise results

For two of the LAX to BOS tracks, *systemwide*Modeler predicted delays based on NAS resource constraints. The path stretch algorithm described in Section IV was used to introduce vectors into the composite track consisting of *systemwide*Modeler and TRACON Path Library inputs. Figure 8 shows the sample tracks modeled with and without the delay vectors. The total flight distance covered by the delay vector corresponds to the delay that *systemwide*Modeler predicts and the speed assumptions in the path stretch algorithm. The speed and descent profile assumed by AEDT to model the performance of these tracks may introduce deviations between the delay predicted by *systemwide*Modeler and the time required to fly the corresponding track as modeled by AEDT. For the flights shown in Figure 8, the time needed to fly the tracks as modeled by AEDT performance was within 25% of delay predicted by *systemwide*Modeler. Future work will focus on aligning the speed assumptions in order to improve consistency in delay modeling between *systemwide*Modeler and AEDT performance.

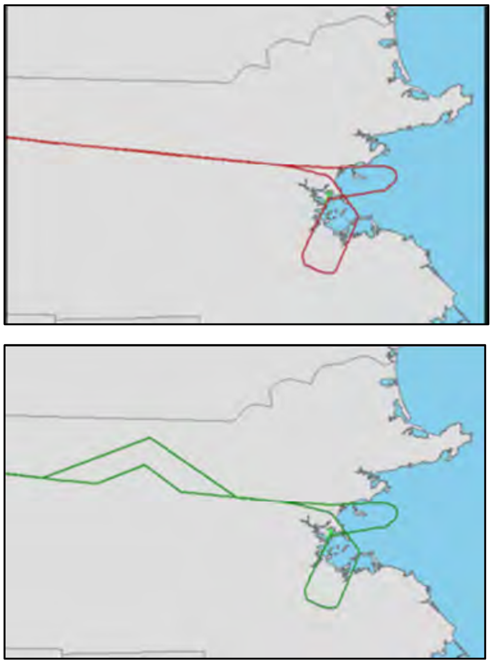

Figure 8: BOS arrivals modeled with and without delay vectors

VI. CONCLUSION

This paper was focused on identifying key research challenges associated with establishing connectivity between airspace system tools and environmental models. MITRE's *systemwide*Modeler and FAA's Aviation Environmental Design Tool were the exemplars used for this research. Disparities in flight trajectory definition in terms of level of fidelity and representativeness of operations required in the terminal area and in the characterization of en route delay were seen to be the major challenges associated with bridging the gap between simulation tools and environmental models. A TRACON Path Library with arrival radar tracks was developed to improve terminal area path representation from *systemwide*Modeler. An approach for introducing delay vectors into *systemwide*Modeler paths was also developed to represent delay as flight path changes which are necessary inputs for AEDT. Finally a sample study was conducted to illustrate the methods developed in this work.

On-going work primarily involves further testing and refining the methods presented here and investigating the scalability of the approach to NAS-wide studies. More specifically, a departure TRACON Path Library is being developed for improving terminal area representation of *systemwide*Modeler trajectories building upon the methodology developed for the arrival TPL. Additionally, the approach for introducing delay vectors will be further tested in order to better align performance assumptions between *systemwide*Modeler and AEDT. A methodology for introducing holds for absorbing excessive delays is also under development. Finally, expanding the analysis scope to regional and NAS-wide studies is a major objective for future work in order to enable a direct comparison of operational and environmental benefits for NAS-wide NextGen improvements.

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