Analytical Approach for Quantifying Noise from Advanced Operational Procedures

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This paper presents a method for improving the fidelity, accuracy, and utility of noise analysis techniques for the development and environmental review of advanced operational procedures. Advanced procedures have the potential to reduce aircraft noise using several methods including lateral track management (noise-preferred routes and track dispersion or concentration), vertical profile management, or speed and configuration management. Traditional noise analysis techniques such as the Aviation Environmental Design Tool model noise using a Noise Power Distance method, which does not fully capture aerodynamic and velocity effects. An alternative physics-based modeling approach has been developed to capture higher-fidelity noise impacts. This framework has been used to evaluate several candidate operational procedures for community noise impact.

I. INTRODUCTION
Next-generation flight procedures are a key component of air traffic management modernization efforts in the United States [1] and Europe [2]. Specifically, performance-based navigation (PBN) is intended to play a key role in streamlining navigation standards and procedures to improve capacity, efficiency, and safety in the future ATM system. PBN enables greater flexibility in terms of lateral and vertical routing, speed control, and procedural design flexibility. The noise impacts of PBN and other advanced operational procedures have been investigated in several specific contexts (for example, [3]–[6]), but work remains to model and mitigate noise implications arising from new procedures.

The increased use Area Navigation (RNAV) and Required Navigation Performance (RNP) procedures has resulted in a concentration of lateral tracks near airports due to the increased precision of these procedures. While this increased precision has allowed operational benefits such as reduced path length, better terrain avoidance, and lower approach minimums, it has also resulted in noise concentration and community opposition as aircraft fly consistent and repetitive tracks over the same over communities.

There is potential to use the advanced capabilities of PBN to lessen community noise impact from aviation. This study develops a physics-based modeling approach for community noise estimation which is used to examine several methods for reducing approach and departure noise, including: noise-preferential lateral paths to increase overflight of areas with noise-compatible land use, modified thrust and speed schedules, steep climbs and descents, reduction in level flight at low altitude, tuned flap and landing gear use, and strategic flight track dispersion.

II. METHODOLOGY
A. Noise Analysis Tools

Currently, the Aviation Environmental Design Tool (AEDT) is the primary analysis package used in the US to evaluate community noise impacts near airports. AEDT uses Noise-Power-Distance (NPD) lookup tables to calculate noise from data generated through flight test and/or analysis. A functional relationship between engine throttle setting and source-to-observer slant distance yields noise estimates for specific locations on the surface. The noise frequency spectrum is obtained empirically from representative aircraft families at set power levels and aircraft configurations. This analysis method results in a simple and computationally tractable noise estimation capability for engine noise sources. Aerodynamic noise contributions, however, are not fully incorporated into the model. For instance, total noise, including both engine and aerodynamic (airframe) noise, is derived empirically for a reference speed of 160 knots. Any speed difference from this reference value results in potential inaccuracies in airframe noise estimates [7].

To address the limitations of NPD-based noise modeling, higher-fidelity models can be used to capture various noise sources, shielding, and propagation. Such models can be used to directly calculate source noise throughout a flight event or to calculate higher-fidelity NPD data sets that capture configuration and speed effects. The Aircraft Noise Prediction Program (ANOPP) is one model that can be used for this purpose. ANOPP was originally developed by NASA in the 1970s to provide predictive capabilities in individual aircraft studies and parametric multivariable environmental evaluations. The program was developed with a modular framework and open documentation to allow for interface
Component-level aircraft and engine parameters are required inputs for noise analysis using ANOPP. For the noise analysis framework currently under development, the Transport Aircraft System OPTimization (TASOPT) is used to supply these performance parameters. TASOPT jointly optimizes the airframe, engine, and full flight trajectory of a “tube and wing” transport aircraft using physics-based computations to predict aircraft weight, aerodynamics and performance without the need for traditional empirical regression methods [9]. TASOPT is used in the analysis presented here to design aircraft matching the performance of existing aircraft types to provide the detailed component performance parameters required for ANOPP noise analysis.

The noise computed in ANOPP is dependent on the aircraft’s flight profile, including position, speed, flap and gear configuration, and engine state (a function of thrust, Mach number, and altitude). In order to obtain the flight profile data for ANOPP, a flight profile generator was created to compute thrust from existing radar track data or for user-specified segment requirements. TASOPT does not provide drag estimates as a function of configuration, so drag polar information must be supplied to the profile generator from external sources. One source of drag polars for existing aircraft is Eurocontrol’s Base of Aircraft Data (BADA 4) [10], a database of aircraft performance parameters obtained from aircraft manufacturers. BADA 4 also serves as a source of data for idle thrust level as well as an additional source of weight information. A tool to translate the performance outputs from TASOPT and BADA4 into inputs for ANOPP has been created as part of this research. The analysis architecture for the integrated TASOPT and ANOPP tool is summarized in Figure 1.

Although the TASOPT-ANOPP tool is capable of higher fidelity noise modeling than AEDT, the computation time for noise analysis in ANOPP is longer than for AEDT. Therefore, AEDT is used for analysis of procedures in which changes in airframe noise are not likely to have a substantial impact on overall results. In these cases, AEDT replaces ANOPP within the framework shown in Figure 1, using custom flight profile definitions generated from TASOPT and BADA4 performance data rather than the internal AEDT aircraft performance models to provide increased modeling flexibility.
For existing radar data, the profile generator uses track, altitude, ground speed, and configuration information to compute the required thrust to match a median profile for each segment of the trajectory. The median profile is selected based on the minimum root-mean-squared (RMS) distance for a set of radar profiles to the mean altitude of those profiles. The mean altitude and distance-to-mean are calculated at 0.1 nautical spaced interpolated points along the profile ground tracks. Takeoff and climb portions of the profile are determined based on the ICAO A and B definitions for the velocity profile [11]. Takeoff thrust is then determined by calculating profiles using different takeoff thrust levels and selecting the profile for which the end-of-takeoff segment point is closest to that of the median profile. Climb thrust is determined by calculating profiles using the selected takeoff thrust and different climb thrust levels and selecting the profile for which the end-of-climb segment point is closest to that of the median profile. If flap and gear configuration information is not available, flap configuration changes are governed by aircraft-specific weight and speed ranges derived from public or airline-provided data sources.

An example radar-matched flight profile, with the full set of profiles and mean and median profiles from which it was calculated, is shown in Figure 3. This set of profiles includes Boeing 737-800 flights to all runways from 20 days in 2015-2016 at Boston Logan International Airport (KBOS). The flights in the highest 10% of altitudes at a point 5 nautical miles from the start-of-takeoff roll are shown in green, the flights in the middle 80% at that point are shown in blue, and the flights in the lowest 10% at that point are shown in red. The mean profile is shown in white, the median profile (the closest actual flown profile in terms of RMS distance to the mean) is shown in black, and the radar-matched profile calculated using the tool is shown in magenta.

C. Population Exposure Calculation

In order to calculate noise impacts, both noise results and demographic variables (population and environmental justice) are compiled on a consistent 0.1nm square grid. Noise grids and population data are indexed and overlaid such that impact variables can be calculated efficiently and quickly. This enables calculation of population exposure and other impact or equity metrics for procedure changes on specific runways, as well as optimization of advanced procedures to minimize location-specific population impact. Figure 4 shows an example of a re-gridded population map for the Boston area, allowing for computationally efficient noise impact evaluation in that area.

III. Model Validation

Results from the noise model were compared to existing Federal Aviation Administration (FAA) noise certification data. The FAA certifies noise from civil aircraft for three flight procedures, each with an associated measurement location. The details of the flight procedures and the observer locations are given in 14 CFR Part 36. Noise levels are certified in terms of effective perceived noise levels (EPNL) and are recorded at the observer locations summarized in Table 1 and Figure 5 [12]. They include a flyover profile with the observer directly under the departure flight path, an approach profile with the observer directly under the approach path, and a lateral profile with the observer offset from the runway at the loudest point of the departure.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Speed (KIAS)</th>
<th>Configuration</th>
<th>Thrust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flyover</td>
<td>V2+10kt to V2+20kt</td>
<td>2nd Setting from clean</td>
<td>Max T/O to 300m altitude, then reduced to maintain 4% climb gradient</td>
</tr>
<tr>
<td>Approach</td>
<td>Vref+10kt</td>
<td>Full flaps + landing gear</td>
<td>As required to maintain 3° glideslope</td>
</tr>
<tr>
<td>Lateral</td>
<td>V2+10kt to V2+20kt</td>
<td>2nd Setting from clean</td>
<td>Max T/O</td>
</tr>
</tbody>
</table>

Table 1. Description of FAA noise certification flight profiles
In order to validate the noise analysis framework, six aircraft types were modeled using TASOPT. Each of these types was modeled on flight trajectories representing the noise certification profiles. The trajectories were modeled in ANOPP as well as AEDT 2b. Effective Perceived Noise Level (EPNL) results at each certification measurement location were generated and compared to published certification levels [13]. These results are shown in Figure 6. An agreement within -2.24 to 3.71 dB between the ANOPP noise results and the FAA data was found for each of these six aircraft and the three observer locations, with many of the measurements agreeing within 1 dB of the recorded value. The magnitude of these differences is similar to those obtained with AEDT modeling, indicating that the TASOPT/ANOPP modeling framework is accurate within current industry standards for operations in the vicinity of airports.

In addition to validation against certification levels, noise results were compared to empirical noise monitor measurements at Boston Logan Airport for a representative set of narrowbody arrivals. The purpose of this comparison was to evaluate model accuracy at observer locations farther from the airport than the certification points. For noise monitors located 20 nautical miles (flight distance) from the arrival runway, modeled noise corresponded to median measured values within 7 dB in all cases. Discussions with noise experts indicate that measured noise data can have a scatter of up to 15 dB [14] due to variation in atmospheric conditions and short-duration changes to aircraft thrust. Therefore, the TASOPT/ANOPP modeling framework is capable of predicting noise within expected measurement scatter at locations far from airports. Observers at these distances are outside the traditional 65 dB Day-Night Level (DNL) significant noise contour, but are still exposed to aircraft noise and associated annoyance factors.

IV. LOW NOISE PROCEDURE CONCEPTS

A variety of procedure concepts have been identified with the potential to reduce community noise and are discussed below.

A. Modified Climb Profiles

A typical climb profile consists of an initial high-thrust climb segment to a thrust cutback height between 800 and 1,500 feet above ground level, followed by a thrust reduction and acceleration segment to a target climb speed. This climb speed is generally 250 knots below 10,000 feet. Variations on this procedure, including recommendations for flap retraction schedules, are defined by the FAA Noise Abatement Departure Procure (NADP) 1 and 2 [15] and ICAO departure procedures A and B [11].

Noise levels observed on the surface are driven by engine thrust level, altitude, and speed over an observer location. Climb profiles may be modified in several ways to change these variables and the resulting noise characteristics of departing aircraft. First, the climb profile can be made steeper by maintaining maximum thrust throughout the initial climb phase as shown in Figure 7. The objective of this modification is to increase flight altitude at a given distance from the runway relative to the baseline procedure.

In order to avoid the additional engine source noise and engine wear that results from maximum-thrust departures and climbs, the departure profiles can also be modified by...
adjusting acceleration targets. One option is to stipulate that
aircraft must accelerate to a slower speed than in standard
operations. A notional profile showing a modified acceleration
height is shown in Figure 8. Climbing at a slower speed results
in a steeper climb and therefore higher altitude at a given
distance from the runway for a fixed thrust level and
configuration. An additional objective of a modified speed
departure is a reduction in airframe noise.

B. Modified Descent Profiles

Typically, approach procedures employ a descent angle, or
glide slope, of 3 degrees. This helps ensure a safe landing
through a consistent, stabilized approach. It is possible for
most modern aircraft to fly a steeper glide slope, allowing the
aircraft to maintain a higher altitude in order to reduce noise
impacts as it approaches the airport. There are also potential
safety concerns with steeper approaches. Excessively steep
approaches could increase the risk of runway excursion, which
was the second leading cause of fatal commercial jet aircraft
accidents between 2006 and 2015 [16]. More work is needed
to evaluate the impact of steeper approaches on stability
criteria for various aircraft types and glideslope angles. Two
notional methods for implementing steeper approach profiles
are shown in Figure 9.

C. Noise-Preferred Lateral Paths

Using performance-based navigation technology, approach
and departure procedures can be defined with increased
precision. RNAV allows increased precision on straight
procedure segments, while RNP approaches allow precise
curved ground tracks. RNAV and RNP approaches have been
implemented primarily for terrain avoidance and fuel
efficiency [17]. The same technology may have applications
for noise-preferred procedure design, using precise guidance
to avoid noise-sensitive areas and place procedures over
regions of compatible land use. The population noise exposure
impacts of lateral path tailoring can be evaluated using the
TASOPT/ANOPP framework combined with underlying
population and land use data. A notional noise-preferred RNP
approach procedure to Boston Logan Airport Runway 4R is
shown in Figure 10 that maximizes flight time over water. The
geometry of the procedure (final turn radius and final
approach segment length) are identical to those used in an
RNP Special approach flown regularly by JetBlue Airways
flights to New York JFK Runway 13L, providing an existence
case for the operational feasibility of this lateral track.

D. Additional Concepts for Advanced Procedures

Several procedural concepts are currently under
consideration that require further refinement and impact
assessment, including application of novel modeling
techniques and consideration of multiple non-standard noise
metrics.

1) Ambient Noise Masking

The same technology that enables noise-preferential lateral
path procedures may enable location-specific noise masking.
The concept is to use of areas with high background noise
levels to mask the sound of aircraft overflights. Under this
concept of ambient noise masking, lateral tracks are designed
to fly over highways or other areas in which overflights might not be noticeable given the background noise levels.

Noise analysis is currently underway on notional arrival and departure procedures that overfly major interstate highways. An example procedure definition for an RNP approach to Runway 4R at Boston Logan Airport is shown in Figure 11. The procedure includes radius-to-fix curved segments to follow sections of Interstate 93, a major arterial roadway serving Boston’s downtown core. Representative underlying noise levels from roadways and airports are shown by the color gradient [18] — detailed road noise analysis is currently underway. In order for a substantial benefit to arise from noise-masking procedures, ambient noise levels and tonal characteristics from surface traffic must be sufficient to cause aircraft noise to be relatively less perceptible. Surface noise modeling is currently underway to determine the geometry and characteristics of roadway noise contours.

![Figure 11. Notional RNP procedure definition for noise-masking approach following major freeways to Runway 4R at KBOS overlaid on BTS total road and air noise contours](image)

2) Flight Track Dispersion

One consequence of PBN procedure implementation is a significant reduction in the variability of aircraft trajectories relative to legacy radar-based procedures. This decrease in lateral variability—also called flight track dispersion—could have significant noise impacts. Noise complaints have increased at many airports since the implementation of PBN. For example, at San Francisco International Airport PBN flight tracks were implemented in 2014. After this implementation, noise complaints increased by an order of magnitude, from 14,726 in 2014 to 152,336 in 2015. Similarly, in Washington D.C. complaints increased from 1,286 in 2014 (before PBN implementation) to 8,670 in 2015 (after implementation) [19]. Pushback from communities near Charlotte, North Carolina after the implementation of PBN motivated the rollback of certain RNAV departure procedures at Charlotte Douglas International Airport (KCLT) [20]. Community concerns about flight track concentration due to PBN pose a fundamental challenge for procedure design.

One potential approach to address the challenge of noise is to introduce dispersion into the lateral flight paths followed by aircraft flying a particular approach or departure procedure. This could be accomplished in a variety of ways, including the use of an Open SID architecture for RNAV and RNP departures. The Open SID enables aircraft to fly an initial RNAV or RNP flight leg after departure. After this initial segment, aircraft transition to following vectors or direct-to waypoint clearances given by air traffic control (ATC). This enables some natural dispersion in that ATC will not vector two aircraft identically or issue direct-to clearances at the same ground track location for all aircraft.

Analysis is currently underway to understand the impact of Open SID procedures and other track dispersion mechanisms on community noise exposure in terms of single-event and integrated metrics.

V. RESULTS

The analytical approach described above was used to quantify noise for several procedures including modified climbs, modified descents, and noise-optimal lateral trajectories. Several advanced operational procedures are still under investigation. Due to lack of consistent background noise data and the need for novel noise metric development, potential benefits from ambient noise masking have not yet been evaluated. Viable methods to model flight track dispersion and population impacts also remain under development.

A. Modified Climb Profiles

The noise impacts of the maximum thrust climb profile were modeled for a Boeing 737-800 flying on a straight-out lateral trajectory representative of an existing RNAV departure procedure from Boston Logan Airport. Since the aircraft operates at higher thrust levels, source noise from the engine increases relative to standard departure procedures. However, the steeper climb profile increases aircraft height throughout the profile, partially counteracting the impact of increased source noise. The modeled climb profile, including airspeed and thrust level, is shown in Figure 12. Peak noise level ($L_{A_{MAX}}$) contours calculated using ANOPP are shown in Figure 13 for both the maximum thrust climb profile case and a baseline unmodified profile case. Compared to the baseline, the maximum thrust case results in shortening of noise contours, corresponding to a reduction in surface noise from departures far from the airport. However, the maximum thrust case also results in an increase in noise contour width relative to the baseline near the airport which leads to slightly larger total contour area for the maximum thrust case. Communities located near the departure runway are exposed to higher maximum noise levels under this scenario, making it an attractive option for airports located in sparsely-populated regions.
Figure 12. Baseline and maximum thrust profiles for a Boeing 737-800

Figure 13. $L_{A,\text{MAX}}$ (dB) contours for a Boeing 737-800 flying a baseline climb profile and a maximum thrust climb profile showing increased lateral extent and reduced overall length of steep climb contour

Noise impacts were also modeled for a series of reduced climb speed cases, representing flight profiles that are a result in changing the final 250 knot acceleration height. Three aircraft types were examined: a Boeing 737-800 (B738), a Boeing 777-300 (B773), and an Embraer E-170 (E170). For each aircraft type, the baseline profile was flown until speeds of 180 knots, 200 knots, 220 knots, and 240 knots were reached, after which the aircraft held that reduced airspeed until 10,000 feet before finally accelerating to the baseline profile’s maximum speed of 250 knots. Thrust in each case was held constant to that of the baseline profile, while the altitude changed according to the aircraft performance characteristics using the assumption that the aircraft transitions from the takeoff configuration to the clean configuration according to the speed windows of each flap setting. A sample climb profile of a Boeing 737-800 with a 200 knot acceleration speed compared to the baseline profile is shown in Figure 14. The ANOPP-calculated $L_{A,\text{MAX}}$ contours on the ground for this profile compared to the baseline is shown in Figure 15 for the same straight-out lateral path as in Figure 13.

Figure 14. 250 knot (baseline) and 200 knot climb speed profiles for a Boeing 737-800

Figure 15. $L_{A,\text{MAX}}$ (dB) contours for a Boeing 737-800 flying a baseline climb profile and a 200 knot maximum speed profile showing unmodified lateral extent and reduced overall length of reduced-speed climb contour

The slower speed of these profiles leads to longer persistence of noise exposure over a given point on the ground. For a large enough increase in persistence, this could counteract the noise benefits of procedures like these when measured using integrated noise metrics like SEL and DNL. SEL contours, also calculated using ANOPP, are shown in Figure 16 for a Boeing 737-800 flying the same profile and trajectory as in Figure 15.
Figure 16. SEL (dB) contours for a Boeing 737-800 flying a baseline climb profile and a 200 knot maximum speed profile showing unmodified lateral extent and reduced overall length of reduced-speed climb contour

The combined results of this parametric reduced speed analysis for each of the three aircraft types and noise metrics is shown in Figure 17. Across each aircraft type, holding a climb speed below the 250 knot baseline case to 10,000 feet results in the reduction of the overall noise contour area compared to the baseline, indicating that the reduction in airframe noise due to the reduced speeds is significant. A fixed climb speed of 200 knots generally results in the lowest noise levels across both noise metrics. Much of this is due to the slowest velocity setting of 180 knots requiring many aircraft types to keep flaps extended, resulting in higher airframe noise.

B. Modified Descent Profiles

To illustrate the impacts of modified descent profiles, steep approaches and two-segment steep approaches were modeled. These operations were modeled with a Boeing 757-200 on a straight-in approach using the noise modeling architecture described previously. This aircraft type was selected due to its slow deceleration characteristics in the BADA 4 aircraft performance model – a steep-approach procedure that is flyable by a 757-200 should also be flyable by other jet aircraft types according to this model. The approach was modeled with the flight profile generator at a constant landing airspeed, full flaps, and landing gear extended beginning with a level flight segment at 5,000 feet until glideslope interception. The steep approach was modeled at a 3.77° glide path angle, representing the maximum descent angle currently allowed for Approach Category C aircraft on non-precision approaches [21]. The profile for the steep approach is shown in Figure 18 and the resulting noise contours are shown in Figure 19.

Figure 18. Flight profile definition for a Boeing 757-200 on a 3.77° steep approach compared to a baseline 3° glideslope

Figure 19. L_{MAX} (dB) contours for a Boeing 757-200 flying a 3.77° steep approach compared to a baseline 3° glideslope

Multiple two-segment steep approach procedures with various initial descent angles were also modeled for a Boeing 757-200. For these procedures, the aircraft maintained level
flight at 5,000 feet before intercepting an initial steep approach segment. The steep approach segment is configured to intercept a standard 3° glideslope at 1,000 feet above ground level. The thrust required to maintain this two-segment glideslope is determined by the aircraft's drag characteristics. After the transition altitude, the aircraft follows a 3° descent to the runway. The flight profiles are shown in Figure 20 and the resulting noise contours for two of the steeper approach segments are shown in Figure 21.

C. Noise-Preferential Lateral Paths

Procedures that use noise-preferential lateral paths take advantage of location-specific land use, population densities, and geographic features to minimize cumulative impact from noise. These procedures have strong noise reduction potential at airports near noise-insensitive areas (such as bodies of water and undeveloped land). In many cases, modified procedures to maximize overflight of these features require divergence from normal straight-in approach or straight-out departure paths, thus requiring PBN guidance. Notional procedures are currently under development as part of this research that leverage the bodies of water surrounding Boston Logan International Airport (KBOS) to minimize arrival noise. The $L_{\text{A,MAX}}$ contours for a Boeing 737-800 flying one such noise-preferential RNP approach to Runway 4R and a straight-in ILS approach to the same runway are shown in Figure 22. The flight profile was modeled using the TASOPT and BADA4 methodology described above, while the noise contours for these profiles were calculated using AEDT. Although the absolute size of the contours does not change substantially, the noise-preferential curved RNP approach avoids overflight of densely populated areas on the straight-in arrival corridor. The noise contours shift to the area over the water, substantially reducing the noise burden on the communities in the area.

The 2-segment steep approach profiles result in a reduction in $L_{\text{A,MAX}}$ around the region of the steep descent between about -14 nautical miles and -4 nautical miles from touchdown. While there exist substantial operational and technological barriers to actual implementation of steep approaches, this example demonstrates that 2-segment approach procedures do have some potential to reduce approach noise in communities away from the airport.
VI. CONCLUSION

The objective of this research is to develop a noise analysis framework to evaluate advanced operational procedures and to apply that framework to a broad array of candidate procedures with noise reduction potential. By integrating aircraft design and performance calculations from TASOPT with high-fidelity noise modeling in ANOPP, a broad set of procedures can be analyzed for effects not captured by standard noise-power-distance based methods. This paper summarized the process of developing the analysis architecture that provides improved fidelity, accuracy, and utility; validating the integrated TASOPT/ANOPP model using FAA certification data and empirical measurements; and modeling candidate advanced operational procedures using a combination of TASOPT and AEDT for potential noise impact reductions.

With growing community concern about aircraft noise, airport operators and regulators are evaluating potential mitigation strategies in terms of noise reduction. The TASOPT/ANOPP noise model introduced in this paper provides a toolset for evaluating procedures with speed and configuration dependence. As presented in this paper, initial modeled results indicate a strong speed effect on airframe noise characteristics, suggesting potential procedure concepts with noise-driven speed constraints. Noise reductions may also be obtained with vertical adjustment on approach, including steep approaches or multi-segment glideslope adjustments. Additional procedural concepts are currently under examination, including flight track dispersion concepts and noise masking with ambient conditions.

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