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NOISE ESTIMATION FRAMEWORK FOR ADVANCED AIR MOBILITY

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ABSTRACT

Community acceptance and adoption has been identified as a critical and challenging component as we prepare our communities for Advanced Air Mobility (AAM) operations. Although AAM vehicles may be significantly quieter than traditional rotorcraft, the proposed scale of operations and proximity to the built environment makes noise generated from AAM operations a concerning element. Therefore, it is essential to incorporate noise estimation in the planning stage. The presented analysis demonstrates a noise estimation framework for AAM operations. The framework utilizes simulation models and the current state of knowledge combined with laboratory data to inform the modeled sound sources. This framework is part of the Advanced Air Mobility – Community Integration Planning Tool. The noise estimation framework takes trajectories of proposed AAM operations and simulates them with the Advanced Acoustic Model to compute their noise exposure.
Combined with demographics, the results can assess the potential for noise impact of the proposed operations. The framework is developed to provide quick and credible noise results with the ability to vary temporal and spatial granularity while accommodating different types of vehicles. The paper involves proposed multiple AAM cargo operations in the Midwest region of the United States.

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1. INTRODUCTION

Under a Small Business Innovation Research (SBIR) contract with the National Aeronautics and Space Administration's (NASA), a team (as represented by the authors' organizations, led by Crown Consulting Inc.) is in Phase 2 of the development of an Advanced Air Mobility – Community Integration Planning (AAM-CIP) tool. The tool is a platform for data fusion, analysis, and display of results for AAM stakeholders; support of integration of AAM with existing transportation systems; and an AAM system design toolset that can be used to configure route networks that conform to airspace allocation, rules, and restrictions. The goal of the AAM-CIP tool is to enable robust exploration of the potential for AAM design space, evaluation of market tradeoffs, and characterization of key challenges. The noise estimation framework described in this paper is one of the tools found within the AAM-CIP toolset.
This paper describes the noise estimation framework of the AAM-CIP tool. Section 2 provides background on the project. Section 3 describes the data and methodology used with the tool. Section 4 discusses the noise results from the tool. Section 5 addresses conclusions and recommendations. Section 6 contains the authors' acknowledgements, and Section 7 contains the cited references.

2. BACKGROUND

The novel vehicle concepts envisioned for AAM have the potential to revolutionize air transportation and create new aviation markets. Minimizing the noise generated by these vehicle systems and community noise exposure is critical for the acceptance of these new vehicles operating in both urban and rural environments. The operating conditions, configurations, and flight modes of multirotor and electric Vertical Takeoff and Landing (eVTOL) aircraft are vastly different from helicopters, which are dominated by blade vortex interaction and high-speed impulsive noise [1]. AAM aircraft are characterized by lower tip speeds and multiple rotors associated with distributed electric propulsion. These aircraft generally have lower maximum sound levels but have much different directivity and multiple operating modes. To ensure community acceptance of these aircraft, a detailed understanding of the noise characteristics and more accurate prediction are needed even at the conceptual design stage to ensure that noise is being considered throughout the design process.

NASA's Urban Air Mobility (UAM) Noise Working Group laid out a comprehensive roadmap to address AAM vehicle noise [2]. A National Academies study on advancing aerial mobility identified AAM noise as a critical hurdle to overcome for societal acceptance of AAM operations, including vehicle noise, human perception of the noise signatures, and public acceptance [3]. A 2018 UAM market study represented a preliminary analysis that utilized helicopter noise data and decreased the sound levels by fixed intervals to assess the effect of cumulative noise levels [4]. However, the fidelity of these analyses needs to include more realistic acoustic data that accurately captures the directivity and spectral acoustic energy distribution across the numerous operating states of distributed propulsion aircraft. Until recently (and only in a limited fashion), the competitive nature of the AAM market has caused manufacturers to not disclose such data. With NASA's mobile acoustics laboratory, NASA and Joby have recorded and produced usable data for noise modeling purposes [5]. Most recently, the European Union Aviation Safety Agency published a proposal on assessment and limitation of air taxi noise [6]. The U.S. Federal Aviation Administration has also recently awarded USD $19 million in grant funding to develop and research noise modeling and noise reduction efforts for AAM aircraft [7]. To help broaden the knowledge base, and as described in Section 3, this study utilizes NASA-generated acoustic hemispheres for notional AAM vehicles for comparison to existing flight test-based helicopter noise signatures.

3. DATA AND METHODOLOGY

The Advanced Acoustic Model, Version 3.2 (herein given the abbreviation of "AAM3" to differentiate it from AAM), is a suite of time simulation-based software tools allowing users to model vehicle sound levels at receiver positions from any traditional or evolving transportation noise source [8]. AAM3's noise sources are defined by sets of sound hemispheres, each hemisphere being centered on a noise source of the aircraft, or as a single compact source at the vehicle's center [9]. Traditionally, most sets of sound hemispheres are one-third octave band (broadband) levels.

AAM3 has a single track/operation mode (SOM) and a multi-track/operation mode (MOM). SOM is intended for in-depth research of a single event. MOM is primarily for the use in the NOISEMAP suite to compute cumulative noise metrics. SOM has more capabilities and functionality than MOM, e.g., only SOM allows the effects of wind and temperature gradients and only SOM outputs Sound Exposure Level (SEL) and audibility metrics. Both of AAM3's modes allow for the computation of the effect of topography (ground elevation and shielding) and variable ground impedance on the resultant noise exposure. AAM3's sound propagation algorithms are those from NASA's Aircraft Noise Prediction Program (ANOPP) [10].

AAM3 is uniquely suited to accurately estimate the noise exposure from AAM vehicle operations. In addition to the noise directivity capability via its hemispherical database setup, AAM3 can model the aircraft's attitude angles, i.e., roll, angle of attack and yaw, nacelle angle (for tiltrotors) during each trajectory, and implementation of up to 10 localized sound spheres which can be used to model multirotor aircraft. The nacelle tilt angle is the angle between the pitch axis and the rotor axis, which is 90 degrees for helicopter mode and 0 degrees for airplane propeller mode.

With their ANOPP2 [10], NASA developed prediction-based approaches for generation of Noise-Power-Distance data with application to UAM/AAM vehicles [11]. The reference (conceptual) vehicles for this process were called the quadrotor and "lift plus cruise" (L+C) vehicles. The authors reformatted the data for AAM3 at more than 40 flight conditions and shared the baseline acoustic data which became fundamental in the development of the noise estimation framework. Data is provided between the 10 Hz and 10 kHz one-third octave bands.

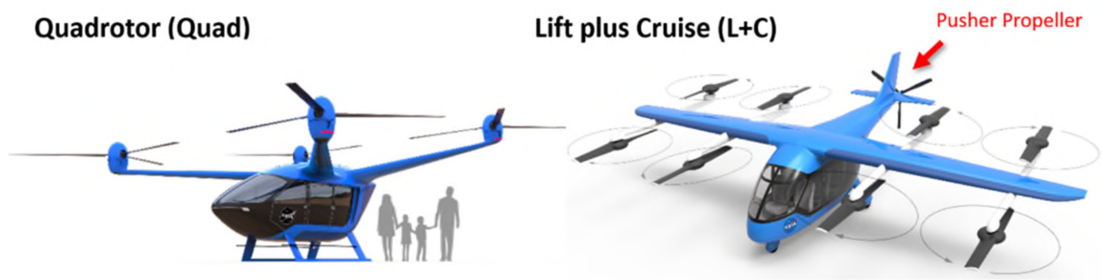
Specifications for the quadrotor and L+C vehicles are summarized in Figure 1. The quadrotor features four 3-bladed rotors rotating at a constant 1,200 RPM, with fixed (non-tilting) nacelles. The L+C vehicle utilizes eight non-tilting 2-bladed lifting rotors operating at 2,100 RPM and one 3-bladed pusher propeller operating at 7,500 RPM. The L+C vehicle is intended to operate as a fixed-wing aircraft in forward flight and operate the lift rotors only during the VTOL phases of flight. As forward speed increases, a greater portion of the lift is generated by the wings until it is entirely in wing-borne flight. The conceptual sound spheres have limitations such as the lack of motor noise, rotor-airframe interaction effects, and more; however, the dominant propulsion noise related to the rotors is captured for 40+ aircraft operational states and this analysis captures the dominant noise mechanisms that drive A-weighted sound exposure. Additionally, this level of fidelity is sufficient for developing the AAM CIP tool that can be utilized by stakeholders to understand the noise effects of AAM operations. The study presents the development of the framework and future studies can incorporate data of any fidelity available in the sound sphere format.

For context, this study compares its results to that of a Bell CH-146 Griffon helicopter. The Griffon is a Royal Canadian Air Force utility tactical transport 4-bladed helicopter with a cruising speed of 119 kts, a maximum gross weight of 11,900 pounds (5,400 kg) and a rotor span of 45 ft (14 m) [12-13].

Figure 2 shows Overall Sound Pressure Level (OASPL) hemispheres at approximately 100 knots forward flight speed on a 100 ft [30.48 m] radius for Griffon helicopter (from flight test data provided in AAM3) and the conceptual quadcopter and L+C aircraft (from prediction provided by NASA). Significant differences in directivity and sound level are observed with the Griffon data approximately 35 dB louder than the conceptual multirotor aircraft and the directivity patterns being different for all three vehicles due to the different propeller and rotor configurations and orientations. The sound spheres also vary in relative levels and directivity for vertical flight and transitional climb and descent operating conditions. This paper is not focused on the details of the noise source data but rather on the assessment of ground observer noise exposure by comparing the conceptual vehicles to existing helicopter flight test acoustic data.

The University of Cincinnati Advanced Mobility Propulsion Laboratory is further developing sound spheres using anechoic laboratory measurements for use in for conceptual vehicle studies beyond the scope of the quad and L+C spheres. This is an ongoing effort. The analysis presented in this paper utilizes the broadband sound hemispheres received from NASA in their original format.

NASA provided 43 hemispheres for the quadrotor and 45 hemispheres for the L+C. Each hemisphere represents a unique flight condition or operating state, denoted by airspeed, and climb angle. The sound sphere set for both vehicles consist of hemispheres for different airspeeds and reasonable climb (or descent) angles. At a lower airspeed of 10 knots, the quadrotor set includes 15 hemispheres with climb angle ranging from -45 to 85 degrees. Whereas, for the highest airspeed of 90 knots, the quadrotor set includes 3 hemispheres with climb angles of -5, 0, and 5 degrees. The AAM3 database contains 41 hemispheres/flight conditions for the Griffon.



Parameter	Quadrotor	Lift plus Cruise
Number of Rotors	4x 3-bladed rotors	8x 2-bladed lifting rotors, 1x 3-bladed pusher propeller
Gross Weight	6469 lbs	5903 lbs
Max Airspeed	109 KTAS	123 KTAS
Constant Rotation Speed	1200 RPM	2100 RPM, 7500 RPM
Operating Condition	Collective Trim	Lift only, Lift plus Pusher, Pusher only (wing-borne)

Figure 1. Vehicle Parameters for Quadrotor and “Lift plus Cruise” [11].

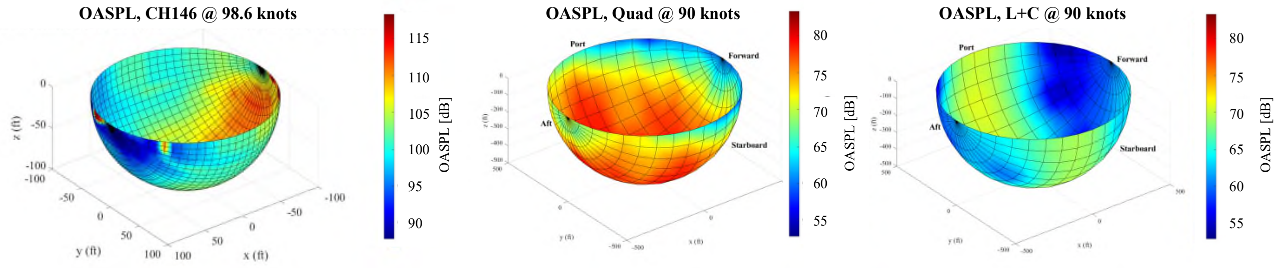


Figure 2. Sound Hemispheres for the CH-146 Griffon helicopter (from AAM3), Quadrotor, and Lift + Cruise vehicles (from NASA) at similar forward flight speeds. The CH-146 contour scale is about 35 dB higher.

There are specific modules in the AAM-CIP Tool that work on analyzing potential study area and origin destination routes based on the economic analysis. Another module in the tool focuses on generating detailed flight trajectories for AAM vehicles on those routes. The high temporal resolution of these flight trajectories is helpful in finer noise analysis in near-vertiport area. The other vehicle state variables like angle-of-attack, flight mode, climb and nacelle angle, are utilized in the simulation model during noise analysis. Figure 3 shows the flight trajectory used in this analysis, i.e., a 30-mile (48-km) cargo route between Cincinnati/Northern Kentucky International Airport (CVG) in Covington, KT, and Miami University Airport (OXD) in Oxford, OH. The climb rate in the ascending parts of the trajectory increases gradually from approximately 400 feet per minute (fpm) to a stable climb rate of approximately 900 fpm in 52 seconds. Similarly, the descent rate in the descending parts of the trajectory gradually decreases from approximately 640 fpm at the top-of-the-descent to landing in nearly 4 minutes. The vehicles climb and descend at angles of approximately 10 degrees and 7 degrees, respectively. The cruise portion has the vehicle in steady, level flight at an airspeed of 98 knots (181 kph) and altitude of 3,000 ft relative to Mean Sea Level (MSL).

With a 2-second spacing, the climb, cruise, and descent sections of the modeled trajectory consist of 71, 408, 142 waypoints, respectively, totaling 621. Since all the rotors are fixed for the quadrotor, the nacelle tilt angle throughout the trajectory is 90 degrees. However, the L+C vehicle was modeled with a nacelle tilt angle of 90 degrees in climb and descent sections, and 0 degrees in cruise section when the pusher propeller is dominant.

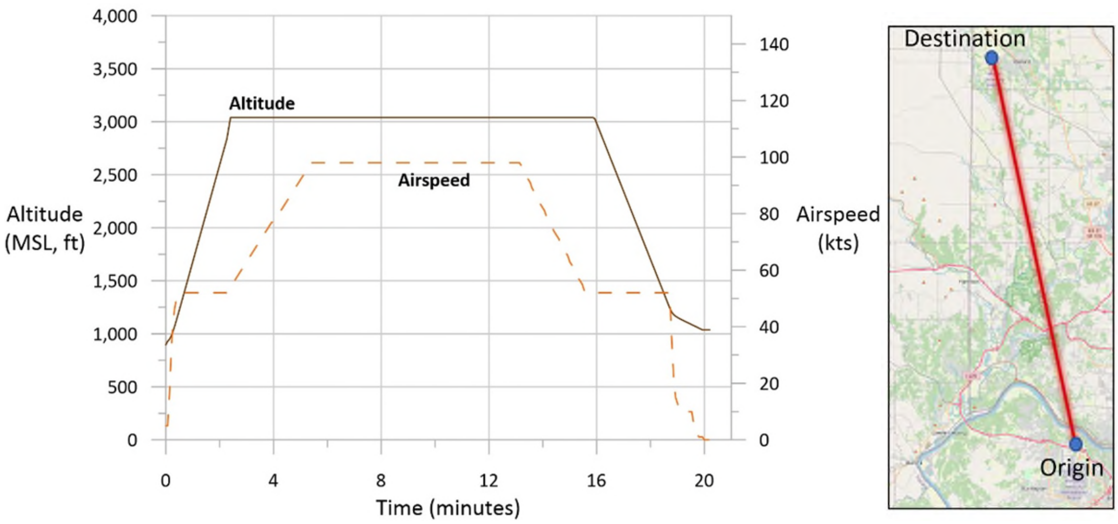


Figure 3. 2-D (Left) and Top (Right) Views of the Flight Trajectory.

The 30-meter resolution National Elevation Data (NED) from the U.S. Department of Agriculture (USDA) – National Geospatial Center of Excellence was the source of the elevation data used in this analysis [14]. Similarly, the impedance data was gathered from the Multi-Resolution Land Characteristics (MRLC) Consortium – National Land Cover Data 2019 (NLCD) at the same 30-meter resolution [15].

We modeled standard atmospheric weather conditions, i.e., 59 degrees Fahrenheit (15 degrees Celsius) and 70 percent Relative Humidity. No wind or temperature gradients were assumed.

The methodology for this framework was developed with focus on quick, efficient, and credible noise exposure calculation. Figure 4 shows the three modules built for the noise estimation framework of the AAM CIP tool. All modules in the framework were scripted in Python 3.9 [16].

The Preparation module creates the setup for the time simulation in AAM3. The study setup includes preparing prospective noise grid, elevation grid, and impedance (or land cover data). Once the study setup is complete, the Processing module processes the flight trajectories, input data, and output requirements to create input files for the time simulation. The time simulation is performed in AAM3 computing several noise exposure metrics for the input receptor set. These metrics include unweighted and A-weighted SEL (L_{AE}), and A-weighted Maximum Sound Level ($L_{A,max}$).

Table 1. Processing Modules of the Noise Estimate Framework.

Module	Duties
Preparation	• Define study area • Collect and prepare ground elevation and impedance data
Computing	• Process and convert input trajectory • Generate AAM3 input file • Run AAM3
Post-Processing	• Process AAM3 outputs • Calculate cumulative metrics and generate noise contours

A Post-Processing module takes the noise exposure output from AAM3, i.e., L_{AE}, from a single flight and with the number of events, converts L_{AE} to Day-Night Average Sound Level (DNL), via Equation 1:

$$DNL = L_{AE} + 10 \times \log_{10}(N_{day} + 10 \times N_{night}) - 49.4, \quad dB \tag{1}$$

N_{day} is the number of daytime (7:00 am to 9:59 pm) events. N_{night} is the number of nighttime (10:00 pm to 6:59 am) events.

The noise computational grids are developed dynamically based on the latitude and longitude extents of the flight trajectory being processed. A buffer of 10,000 ft (3 km) is added to the lateral extents to estimate the extent of the 45 dB DNL contour. A rectangular grid is then generated based on the input spacing. The framework has been tested for varying grid size of 500 ft (152 m) to 5,000 ft (1,524 m). Usually a coarser grid [~2,000 ft (610 m) spacing] is used for the full trajectory simulation, whereas a finer grid [~500 ft (152 m) spacing] is deployed for the near-vertiport analysis. The analysis presented in the paper has utilized a finer grid of 500 ft (152 m) for the full trajectory with the goal of achieving smoother and precise contours.

4. RESULTS AND DISCUSSION

For 300 daytime unidirectional operations (20 operations per daytime hour), Figure 4 shows a comparison of the resultant DNL contour bands from the framework for the quadrotor, L+C and the Griffon on the route/profile shown in Figure 3. The Griffon had the largest DNL footprint [80.6 sq. miles (209 sq. km)] i.e., area of the 45 dB DNL contour(s), of the three vehicles, followed, in order, by the L+C [2.9 sq. miles (7.5 sq. km)] vehicle and quadrotor [2.1 sq. miles (5.4 sq. km)]. The quadrotor and L+C vehicle both produced DNL less than 45 dB for their cruise segment. The Griffon's cruise segment produced DNL between 55 dB and 65 dB. The comparisons of DNL are only for sake of demonstrating the flexibility of the framework. For true environmental comparisons, we understand the flight profiles of these three vehicles would not likely be identical. For example, the arrival/departure profiles at the destination/origin areas would likely significantly vary between the three vehicles because of each vehicle's VTOL times and their typical transitions to/from cruise flight.

AAM3 runtimes averaged 90 minutes for each vehicle for the full trajectory [500 ft (152 m) grid spacing].

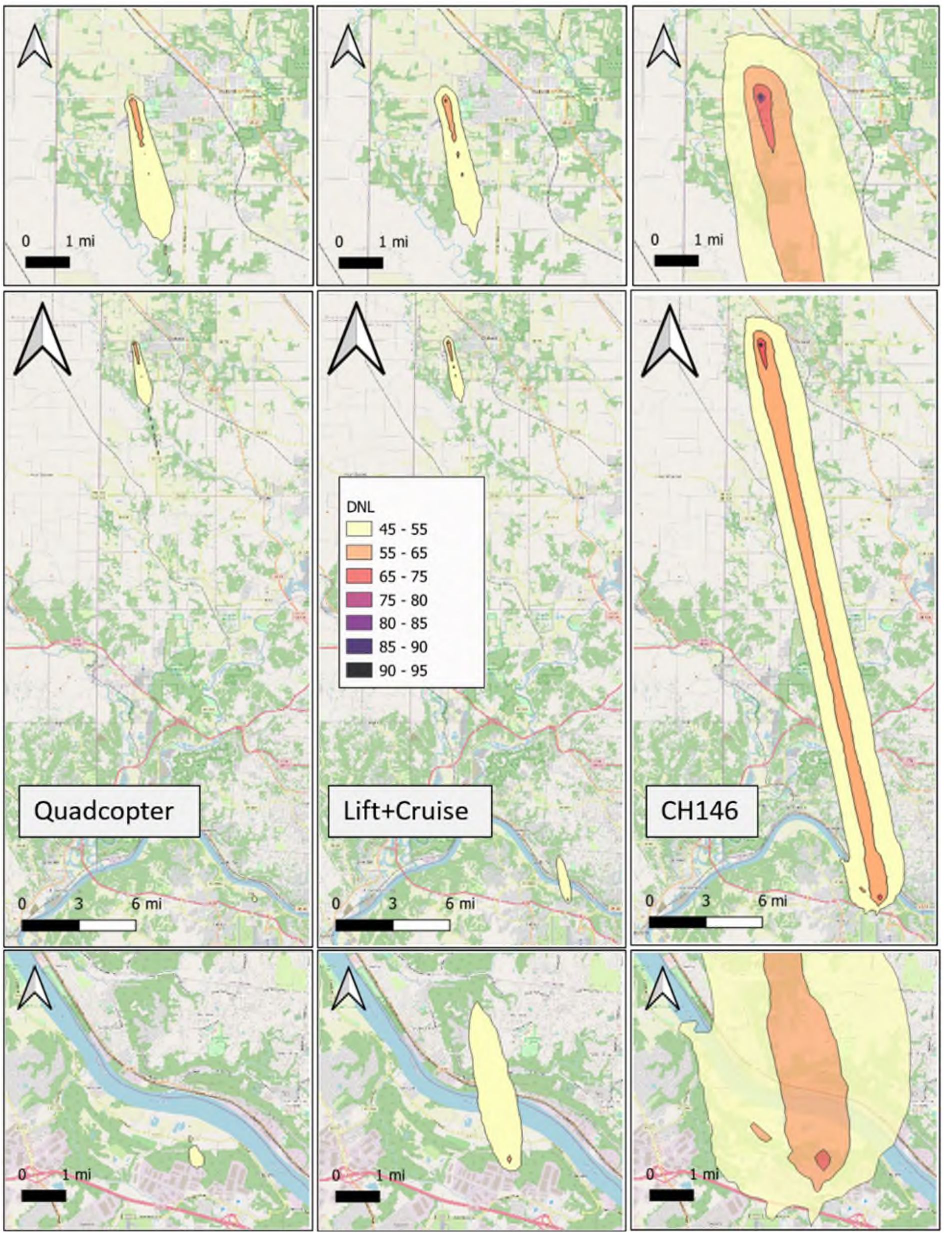


Figure 4. DNL Bands for AAM vehicles (Quadrotor and L+C), compared to Bell CH-146 Griffon Helicopter. The top and bottom panels zoom-in on Descent and Climb phase, respectively. The middle panels capture the entire flight's noise exposure.

5. CONCLUSION AND RECOMMENDATIONS

A noise estimation framework for AAM vehicles has been built for the AAM CIP tool. The framework leverages the credible computing capabilities of AAM3, which allows for proper acoustic characterization of AAM vehicles as sound sources via sets of spectral hemispheres. The framework allows for the estimation of noise exposure from AAM operations.

Although scripts were written to process the input/output for AAM3 helping to make the framework more efficient, the 90-minute runtimes for AAM3's time-based simulation did not facilitate the goal for "quick" results. Runtimes can likely be decreased by segmenting the noise grids further (beyond the three analyzed here) and optimizing the noise grid sizes for those segments. However, segmenting and optimizing would come at the expense of processing complexity. More research is needed to determine whether the 2-second time spacing is too coarse for the areas near takeoff and landing. Reducing the time spacing would increase AAM3 runtimes.

More research is also needed to determine whether computing cumulative noise exposure from multiple AAM operations would be more quickly and easily facilitated with AAM3's MOM. Analyzing multiple operations with SOM means creating scripts to add/merge noise grids, whereas MOM would require flight routes and profiles to be converted from point-to-point representation to vector/segment specifications.

We intend the AAM CIP tool to eventually compute population and housing units within the DNL bands to provide context to the DNL exposure. For routes in California, Community Noise Equivalent Level (CNEL) would be computed in addition to DNL. Also, we anticipate the final tool to use local average daily weather conditions or averages for the region being analyzed, vice standard atmospheric conditions.

6. ACKNOWLEDGEMENTS

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