Urban Air Mobility: Preliminary Noise Analysis of Commuter Operations

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This study aims to estimate potential noise levels generated due to Urban Air Mobility (UAM) commuter operations in the Northern California and the Dallas-Fort Worth regions. UAM is a concept aerial transportation mode designed to bypass ground congestion using an electric vehicle with Vertical Take-Off and Landing (VTOL) capabilities. UAM vehicles are expected to be significantly quieter than traditional helicopters, but operate on a much larger scale. Commuter travel demand will not be uniformly distributed with operations concentrated in a small geographical area such as Central Business Districts (CBD) and short time windows such as morning or evening peak periods. The objective of this study is to evaluate the aircraft noise annoyance generated by commuter UAM operations using flight trajectories developed in a previous study estimating UAM commuter demand. This study estimates the noise level from overflying UAM vehicles in a full day of operation (24 hours) and identifies areas where the noise levels may pose a challenge to future UAM operations. Noise estimation is performed at the Census Block group level using the Day-Night Level (DNL) metric. We run a parametric analysis considering two scenarios in each region: the UAM vehicle has a 10 dBA and 15 dBA noise reduction compared to the Robinson R-44 helicopter. The findings indicate a considerable difference between the 10 dBA and 15 dBA reduction scenarios. Although challenging, achieving a 15-dBA reduction compared to a 10-dBA reduction could reduce land area with DNL value above 50 dBA by 94% and highly-annoyed population by 91% in Northern California. Similarly, in Dallas-Fort Worth, achieving a 15-dBA reduction compared to a 10-dBA reduction could reduce the land area with DNL value above 50 dBA by 80% and a highly annoyed population by 85%. Lastly, we analyze the high-demand vertiport in the San Francisco Financial District in the Aviation Environmental Design Tool (AEDT) to observe the DNL contours for the varying noise performance scenarios.

I. Introduction

Community annoyance due to aircraft noise around major airports has been a topic of interest for several decades [1, 2, 3]. Studies have shown that aviation noise disrupts sleep, adversely affects children's academic performance, and increases the risk for cardiovascular disease of people living in the vicinity of airports [4]. Urban Air Mobility (UAM) technology may be deployed in the National Airspace System (NAS) in significant numbers in urban areas and it is important to evaluate the magnitude of increased noise levels due to such operations.

UAM is a proposed aerial urban transportation mode involving advanced electric Vertical Take-Off and Landing (VTOL) vehicles. The concept of urban transportation using an aerial vehicle is not entirely novel. Multiple companies offered transportation services in New York using helicopters between Manhattan and airports in the region from the mid-1950s to the late 1970s [5, 6]. Besides safety concerns, the locals opposed these operations due to the high noise level generated [7]. Companies like BLADE, Uber, and Voom offer scheduled and on-demand helicopter trips between urban centers and airports [8, 9]. Even after utilizing advanced and relatively quiet helicopters like the Bell 206L-4, these services generated noise annoyance for Brooklyn residents [10]. Helicopter services operate on a considerably smaller scale than proposed UAM concepts, which indicates that UAM could significantly impact urban noise levels and potentially contribute to community annoyance. The UAM system demand is likely to be small in the

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initial phase of deployment. However, under favorable economic conditions, the UAM system could achieve maturity requiring thousands of flights daily in the U.S. [11, 12, 13, 14, 15, 16]. Unless the vehicles are considerably quieter compared to present helicopter technology, demand is unlikely to reach such numbers unprotested from the community, especially in densely populated regions.

This study presents a preliminary assessment of noise generated from a full day of UAM operations in two major urban areas in the United States: Northern California Bay Area and Dallas-Fort Worth. While multiple studies have estimated noise impacts through trajectory and concept vehicle simulations, there has not been much work performed on the potential noise levels generated from a mature UAM system with data based on a UAM demand analysis. This study fills this gap in the literature and creates critical links between UAM forecasted demand, vehicle noise performance, and expected noise annoyance. In addition, we extend the analysis to include a high-demand vertiport in San Francisco Financial District in the Aviation Environmental Design Tool (AEDT) tool to closely observe the DNL contours for the varying noise performance of UAM vehicles.

II. Background

Yedavalli and Mooberry performed a study to understand public perception of UAM utilizing expert interviews and 1,540 survey responses across Los Angeles, Mexico City, New Zealand, and Switzerland [17]. The findings show that communities ranked noise generation as second in their top concerns (both the type of sound and volume), with UAM vehicle safety ranking first. The individual parameters producing the highest average concern from overflying UAMs across all combinations are: the resemblance between the sound of a UAM and that of a helicopter at 51%, the low flying UAMs at 51%, and the frequency of UAMs flying (100 times per hour) at 51%. The study concluded with an emphasis on noise mitigation in the UAM system design for better adoption of the mode.

Vascik and Hansman identified decreased community acceptance due to UAM noise as one of the strong scaling constraints for UAM [18]. The study identified the significant non-acoustic factors and mapped the acoustic and non-acoustic impacts of UAM operations to noise annoyance. The authors point out the challenge of representing community acceptance of aircraft noise constraints with a single metric. Furthermore, they determined the *percentage of people highly annoyed* in a community to be a salient metric for community acceptance in their proposed two-stage approach to understanding scalability limitations due to community acceptance.

Bent et al. studied the barriers associated with UAM noise that may hamper UAM vehicle entry into service and recommended high-level goals to address them [19]. The study focuses on four areas of interest: Tools and Technologies, Ground and Flight Testing, Human Response and Metrics, and Regulation and Policy. The authors recognize the importance of the human response to UAM noise for public acceptance and the success of UAM. Therefore, the study recommends the development of surrogate or other reduced order models so that designers can quickly determine the effects of design changes on noise early in the design process.

There has been a great interest and rapid development in the UAM vehicle sector from many aviation and automobile industry leaders in recent years [20, 21, 22, 23]. Polaczyk et al. summarized current technology (2019) and research in UAM [24]. Their report discusses forty-four eVTOL prototypes currently being designed and implemented. The UAM vehicle concepts vary broadly from multi-rotors, multi-rotors with fixed wings, multi-rotors with foldable wings, etc., with different passenger capacity, payload capacity, battery, etc. Aircraft noise is an intrinsic property partly influenced by various factors such as structural design, the number of rotors/engines, operational noise of rotors/engines installed, and other design factors incorporated to mitigate noise specifically. Since all design concepts have varying components and the Federal Aviation Administration (FAA) is yet to certify a UAM vehicle capable of transporting passengers safely, the aircraft noise profiles of this vehicle are a major unknown.

Glaab et al. performed system-level simulations for a fleet of notional UAM vehicles for two different scenarios in New York [25]. The noise analysis is performed with AEDT using linearly scaled-down (20% lower) version of Noise Power Distance (NPD) curves of the Eurocopter AS350D light helicopter. The first scenario analyzes trips to the airport from current heliports in Manhattan representing near case, whereas the second scenario involved "hubs" located inside Manhattan based on the assumption of "early adopters" representing a farther term use case with commuters. The study assumes the number of operations parametrically (8, 32, and 128 operations per hour) to develop DNL contours at the airports for the first scenario and at the hubs in the second scenario. Using a notional target of 50 dBA, the findings suggest that the first scenario using 32 vehicles per hour did not exceed the target value for populated areas outside the vertiport vicinity. However, with 128 vehicles per hour, the study estimated 55 dBA in the interior of Manhattan and 65 dBA near vertiports. For the farther term scenario, the study found noise levels of less than 50 dBA. While the study displays the ability to simulate a different number of operations and estimate DNL contours around vertiports, it lays little emphasis on noise generated by overflying vehicles along the route and focuses only on areas around vertiports. The parametric analysis helps understand the cause-effect relationship but does not

reflect the region's actual travel patterns. Nevertheless, the study developed a sound methodology to estimate noise levels from NPD curves available in AEDT.

The typical UAM vehicle is likely to be a multi-rotor with a capacity of 2-4 passengers. We use the Robinson R-44, a two-bladed, single-engine four-seat, light utility helicopter, as the baseline vehicle for this analysis. The assumption is that the UAM vehicle would likely be quieter than the R-44, but the magnitude is unknown. Uber indicated that VTOLs would initially be 15 dBA or more quieter than existing helicopters [26]. Jia and Lee studied the acoustics of a 1-passenger and a 6-passenger quadrotor Urban Air Mobility (UAM) aircraft designs in level flight based on high-fidelity Computational Fluid Dynamics (CFD) approach [27]. The study found significantly lower noise from their UAM aircraft than a traditional 4-seat helicopter (such as the Bell 430). However, the difference reduces to less than 10 dBA at 1,000 Hz, where the human ear perception of noise annoyance is important. The study concludes that a goal of 15 dBA quieter UAM than a traditional helicopter would be challenging to achieve. Eißfeldt suggests a potential reduction of 3-5 dBA from reduced tip speed, swept blades, increased blade count, or 1-2 dBA from reduced blade loading [28]. Due to the wide variation of the potential reduction in noise generated from UAM vehicles in literature, the study presented in this paper performs a parametric analysis concerning the noise profile (SEL curves) of UAM vehicles, i.e., multiple noise profiles are generated from different reduction values from baseline noise profile (SEL curves) of Robinson R-44. This analysis is performed at two reduction levels from the baseline noise profile: 10 dBA, 15 dBA.

III. Data

The analysis presented in this paper utilizes the UAM demand estimated during the commuter demand estimation study [29, 13]. The four-dimensional flight trajectories are generated after distributing daily UAM demand using departure time distribution of commuter trips extracted from the National Household Travel Survey -2017 Add-on data (see Fig 1). A flight trajectory consists of a set of waypoints generated every second, keeping track of the flight's coordinates, altitude, and timestamp. The UAM Coordination and Assessment Team (UCAT) at the National Aeronautics and Space Administration (NASA) 's Aeronautics Research Mission Directorate has defined a series of UAM Maturity Levels (UMLs) [30]. UML levels represent development levels of UAM ecosystem through density and complexity of UAM operations. This analysis uses a UAM traffic level, which corresponds to "Intermediate State" or UML-3 and UML-4 [31, 32]. In Northern California, the desired daily UAM traffic level is obtained with 100 vertiports and $1.85 UAM Cost per Passenger Mile (CPM). Fig 2 shows the two-dimensional view of all flight trajectories (5,818) with 100 vertiports placed via a demand-driven approach. The scope of the demand analysis was seventeen counties surrounding the bay area. However, the scope shrinks to five or six counties around the bay area when the demand-driven approach places the vertiports to extract maximum UAM demand for a given number of vertiports. The Concept of Operation (ConOps) in the demand analysis assumes UAM operations being independent of Air Traffic Control (ATC). Therefore, UAM flights are routed to avoid approach and departure surfaces of precision runways to avoid any conflict with aircraft operations at commercial airports [33, 34].

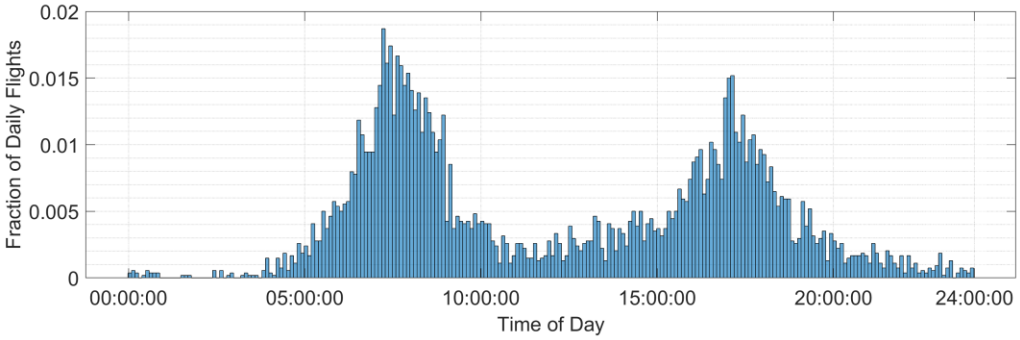

Fig 1. Distribution of Departure Times of UAM Commuter Trips

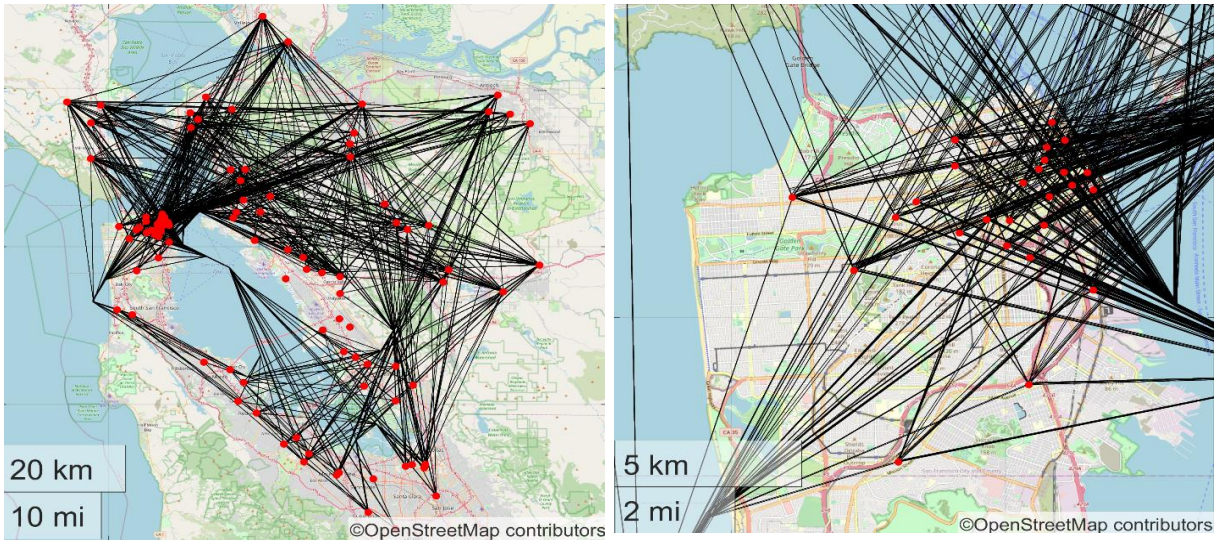

Fig 2. UAM 2-D Flight Trajectories. Left: All 100 Vertiports. Right: Focused on San Francisco CBD

Similarly, in Dallas-Fort Worth, the desired daily UAM traffic level is obtained with 75 vertiports and $1.30 UAM CPM. Fig 3 shows the two-dimensional view of all flight trajectories (5,398), with 75 vertiports placed via the demand-driven approach. The scope of the demand analysis was 12 counties surrounding the Dallas-Fort Worth area. Similar to the Bay Area, the approach and departure surfaces at Dallas-Fort Worth International Airport (DFW) and Dallas Love Field (DAL) are protected.

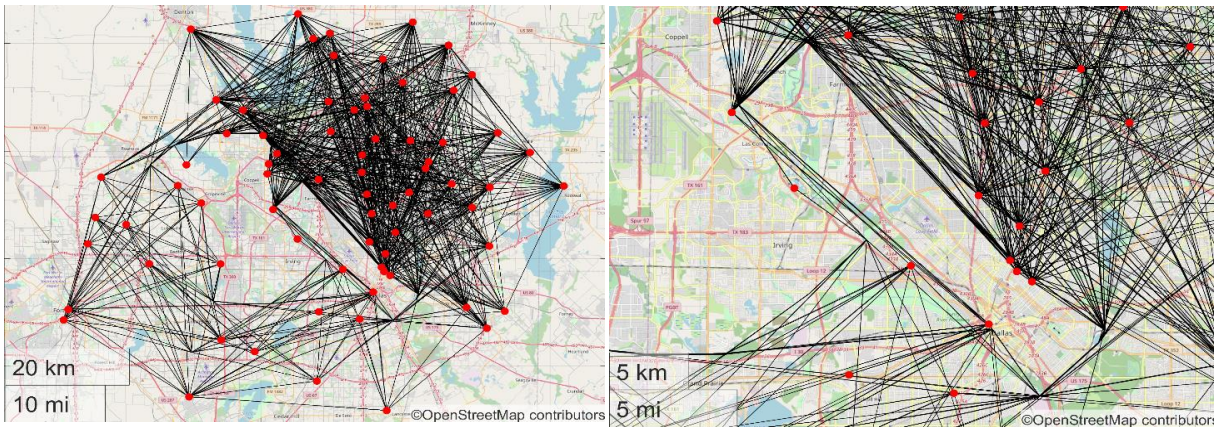

Fig 3. UAM 2-D Flight Trajectories. Left: All 75 Vertiports. Right: Focused on Dallas CBD

IV. Methodology

Noise generated by a flying event (flyover, approach, departure) is measured in Sound Exposure Level (SEL). SEL is a single event metric that combines the acoustic energy generated by an event accumulated in one second. The AEDT tool developed by the Federal Aviation Administration (FAA) contains NPD curves for several airplanes and helicopters in their database. NPD curves model the variation in SEL with the distance of measuring point, i.e., noise generated by an event at a certain distance. NPD curves vary by event type, i.e., they are different for approach, departure, and flyover. Moreover, different NPD curves apply to different engine types. Using the baseline NPD curves of R-44, UAM vehicle NPD curves are developed for different reductions. Fig 4 shows the NPD curves developed from R-44 for all three operations (approach, departure, and level-fly) and the assumed NPDs for UAM vehicles for two scenarios (10 dBA and 15 dBA levels of noise reduction).

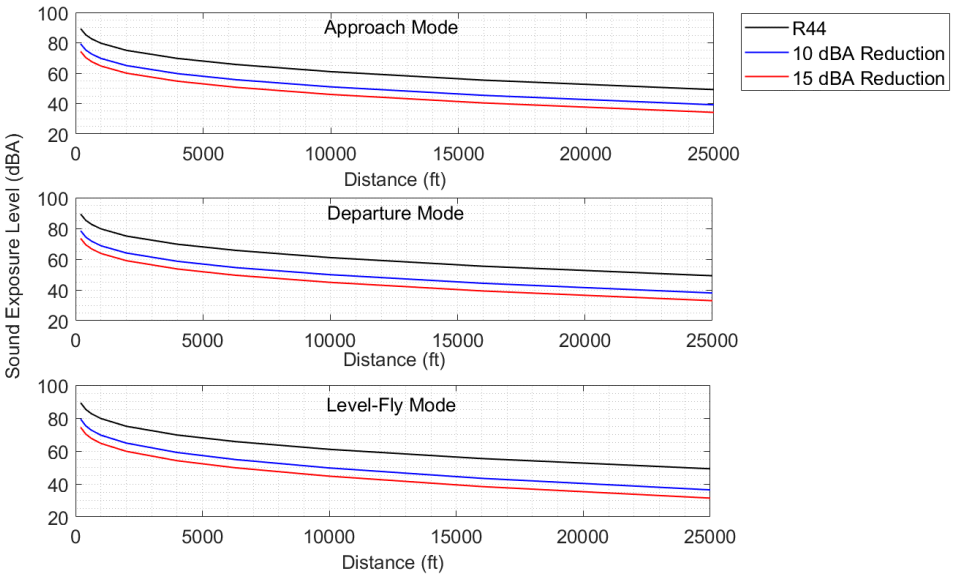

Fig 4. Noise Power Distance Curves of R44 and UAM for Different Modes

Fig 5 illustrates the workflow adopted for Census Block Group level noise analysis. The steps or data sources outlined in red are found to have the most decisive influence on final DNL values or annoyance levels. The following subsections explain the DNL noise metric and annoyance level estimation in detail.

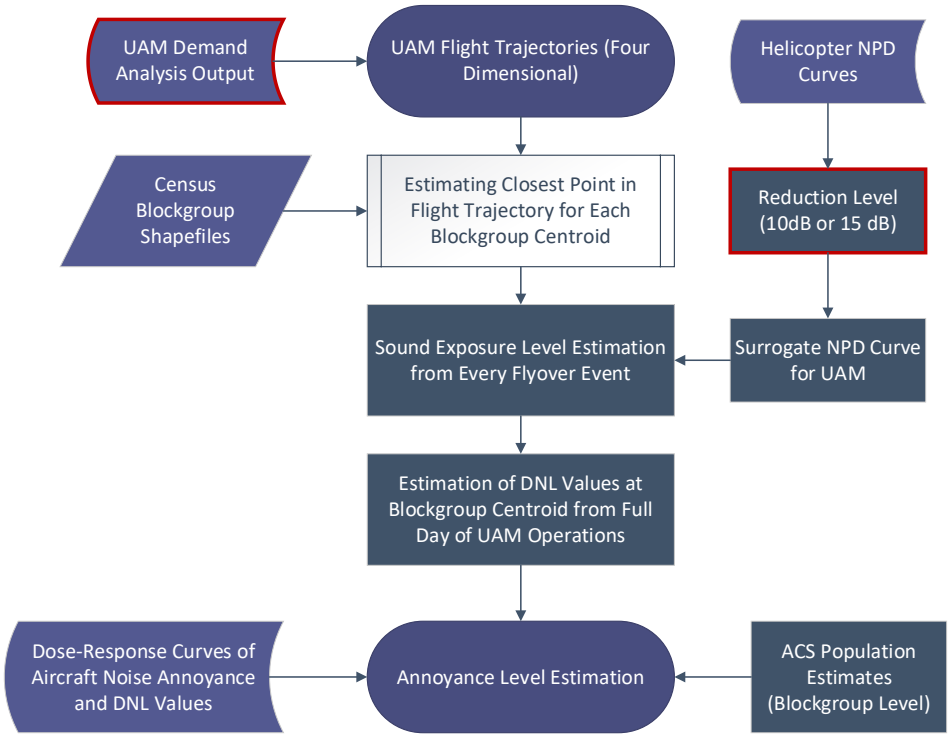

Fig 5. Adopted Workflow for Blockgroup Level Noise Analysis

A. Estimation of Block Group Level DNL Values

There are 7,106 and 4,158 block groups in the Northern California and Dallas-Fort Worth study area. For every Block Group, taking the population centroid as the representative point, SEL generated by each flying event is calculated. It is assumed that the flight trajectory's closest point is the most impactful part of the event. Therefore, the

waypoint in the flight trajectory closest to the concerned Block Group centroid is selected to determine the SEL. Fig 6 shows an example of the closest point in the trajectory to a Block Group population centroid. A flight trajectory is made from 3-dimensional waypoints (blue) and population centroid is denoted by the red dot. The NPD curve selection depends on the relative position of the selected waypoint in its trajectory, i.e., if the closest waypoint is during the approach phase of the flight, the approach NPD curve is selected.

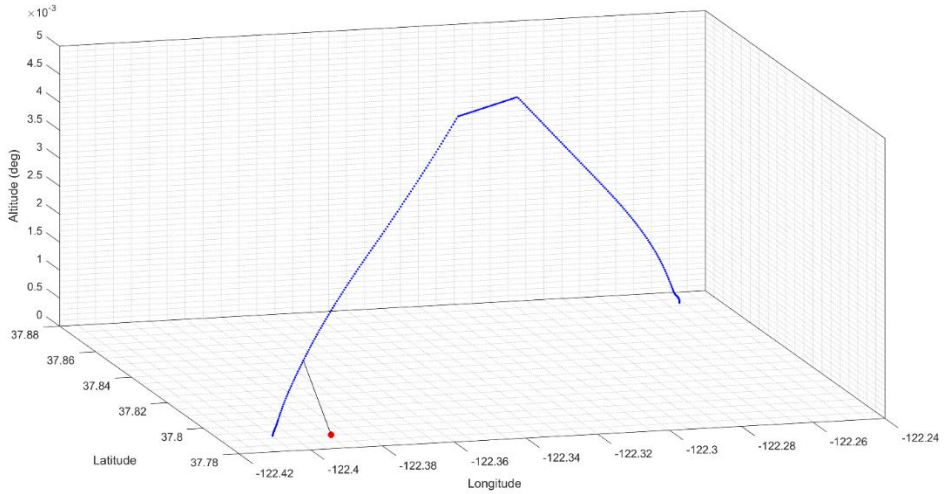

Fig 6. Example of Closest Point in the Flight Trajectory

Furthermore, the combined metric used to understand the noise generated by all the flying events in a day is the Day-Night Average Sound Level (DNL). Equation 1 calculates the value of DNL value at each Block Group centroid due to all flying events combined.

$$L_{DN} = 10 \log \left[\frac{1}{T} \sum_{i=1}^{N} 10^{\frac{(SEL_i + W)_i}{10}} \right] \quad (1)$$

$$L_{DN} = Day - Night\ Sound\ Level\ (dBA)$$
$$SEL_i = Sound\ exposure\ level\ associated\ with\ the\ i^{th}\ flyover$$
$$T = Reference\ Time\ (86{,}400\ seconds\ in\ a\ day)$$
$$W = 10\ if\ Operation\ is\ during\ Night\ (10\ PM\ to\ 7\ AM)$$

B. Estimation of Annoyance Levels

Human annoyance levels are estimated from DNL values for better interpretation of noise levels generated. Annoyance summarizes people's adverse reactions towards the noise that causes interference with speech, sleep, and the desire for a tranquil environment [35]. The noise was recognized as an environmental pollutant in l950's, and since then, several social surveys have been conducted to understand the societal impact of noise. Schultz developed one of the first dose-response relationships between noise exposure and subjective responses from eighteen social surveys on noise annoyance worldwide [36]. FAA's current noise policy uses the updated dose-response curves developed by Schultz. Miedema and Oudshoorn modeled the distribution of noise annoyance with the mean varying as a function of the noise exposure measured in DNL or Day-Evening-Night-Level (DENL) [37]. They fitted the model to data from several noise annoyance studies and developed a polynomial approximation of these relationships, which can be used for practical applications.

FAA undertook a multi-year research effort to quantify the impacts of aircraft noise exposure on communities around commercial service airports in the United States (U.S.) [38]. In this effort, their research team performed the Neighborhood Environmental Survey targeting communities around airports with at least 100 daily jet operations and where at least 100 people exposed to DNL higher than 65 dB and between 60 dB- 65 dB each. They analyzed "highly annoyed" responses and associated DNL to generate dose-response curves for each individual airport and a national dose-response curve. Their findings revealed that substantially more people are highly annoyed for a given DNL aircraft noise exposure level compared to previous studies. Therefore, we used the national dose-response relationship

to estimate the fraction of the "Highly Annoyed" population at the Census Block Group level. The logistic relationship is shown by equation 2. Further, we used the American Community Survey (ACS) Population Estimates [39] to estimate the number of annoyed people at the Census Block Group level.

$$\text{Percent HA} = \frac{100\exp(-8.4304 + 0.1397DNL)}{1 + \exp(-8.4304 + 0.1397DNL)} \quad (2)$$

C. Generation of DNL Contours using AEDT

The second part of the analysis involves developing noise contours around the busiest vertiport, located in the San Francisco Central Business District (CBD), from a full day of operations. The DNL contours provide a better understanding of noise propagation at the vertiport level and could be conducive to planning noise-mitigation techniques on the operations front. The operations (landing and take-off) are simulated in AEDT 3c, and noise contours are examined closely. The vertiport in the San Francisco district is generated as a heliport in the AEDT scenario. The UAM equipment is generated from Robinson R44 Raven/Lycoming O-540-F1B5 equipment in the AEDT database but with a modified noise profile based on the reduction level scenario (10-dBA or 15-dBA). Multiple flight tracks are generated from analysis of popular azimuths in arrival and departure flight trajectories. A receptor grid of 300 latitudinal and 300 longitudinal points separated 0.05 nm with vertiport in the center is generated for the analysis. Based on the arrival and departure times of the UAM flights, hourly-binned operations are created in the AEDT environment. A full day of operations is simulated to estimate DNL levels at each receptor, which are then used to develop noise contours around the vertiport.

V. Results

The estimated Block Group level DNL values and annoyance levels are presented in this Section. In addition, both metrics' results are compared to understand better the impact of vehicle noise performance on noise level generated from a full day of operation.

A. Northern California

Fig 7 displays the spatial distribution of DNL values for both scenarios; the map on the left represents the 10-dBA reduction scenario, and the map on the right represents the 15-dBA reduction scenario. As suspected, high DNL values are observed in the San Francisco CBD due to the high concentration of UAM demand. It was found from the demand analysis that high employment density (especially high-income earners), high congestion levels, and costly parking costs resulted in high UAM demand for San Francisco CBD [13]. In the 10-dBA reduction scenario, the Financial District's DNL value reaches 63 dBA, with several block groups in the CBD region experiencing DNL values above 50 dBA. Besides San Francisco CBD, DNL values of 50 and above are observed all around the bay, in San Jose CBD and Oakland CBD. The DNL values drop significantly in the 15-dBA reduction scenario all around the region. DNL levels drop below 60 dBA in the Financial District and below 50 dBA in most of the CBD. DNL values have also dropped considerably all around the bay and on the east side of the bay. Due to the detouring of UAM around the approach and departure surfaces of precision runways at commercial airports, the block groups falling below the protected surfaces have a low noise level. However, it should be noted that expected UAM noise would be in addition to existing noises due to aviation, industry, ground transportation, etc.

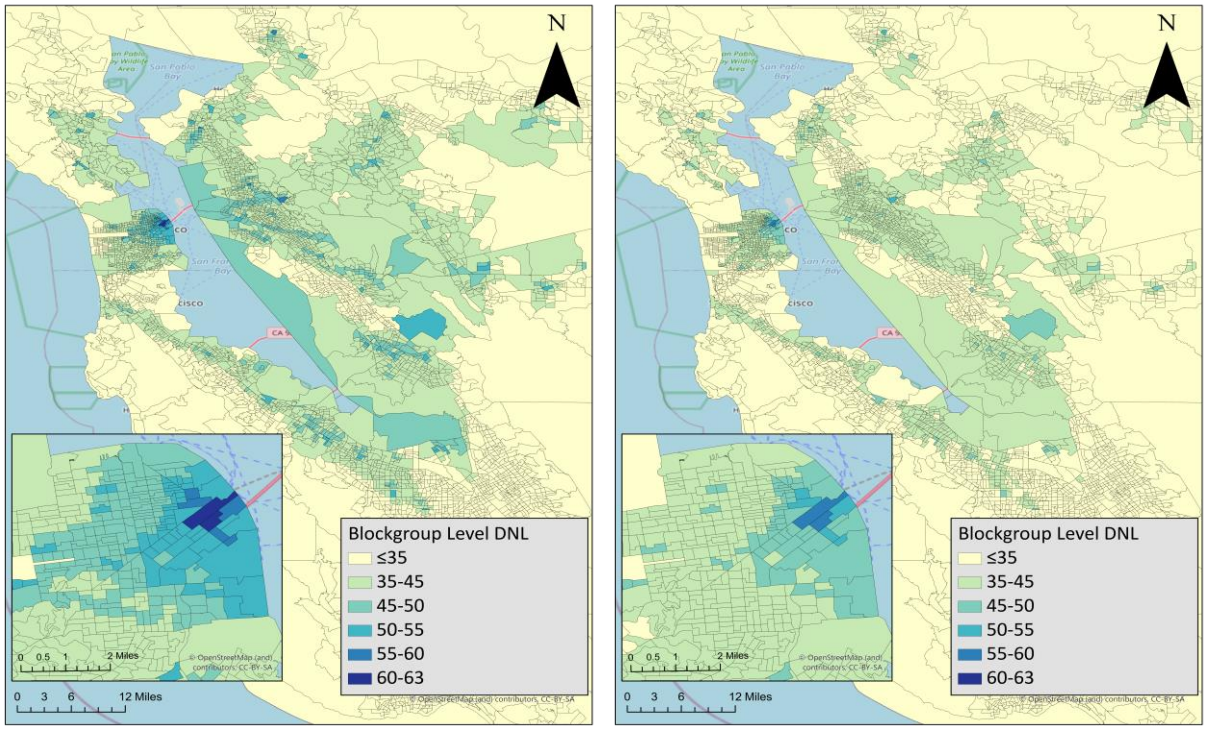

Fig 7. Spatial Distribution of DNL Values in dBA. Inset Focuses on San Francisco CBD. Left: 10 dBA Reduction Scenario. Right: 15 dBA Reduction Scenario.

The percentage of the Highly Annoyed population is calculated using the estimated DNL values. Fig 8 shows and compares the Highly Annoyed population's spatial distribution for both the reduction scenarios. As expected, the majority of the highly annoyed population is in San Francisco. For the 10-dBA reduction scenario, the highly annoyed population can be found in significant numbers (>500 per blockgroup) near San Jose CBD, Oakland CBD, Mountain View, Cupertino, Dublin, Antioch, San Rafael, and Livermore. However, the highly annoyed population drops substantially in the 15-dBA reduction scenario than the 10-dBA reduction scenario. In the 15-dBA reduction scenario, very few block groups have more than 200 highly annoyed people.

It should be noted that achieving a 15 dBA reduction compared to a helicopter could be challenging for UAM vehicle designers. Since the demand scenario analyzed in this study belongs to an intermediate maturity level (expected in the late-2020s), achieving a 15 dBA reduction maybe possible in that timeframe. Moreover, the noise level generated in the region could be reduced substantially if a 15 dBA reduction is achieved. Table 1 compares the DNL values and annoyance level output for both scenarios. If the noise levels of future UAM vehicles achieve a 15 dBA reduction, the land area affected by noise could decrease by 80%. The total highly annoyed population would be reduced by 80%.

Table 1: Comparison of DNL values and Annoyance levels for both Scenarios (Northern California)

DNL Category	**Area under Influence (sq. mi.)**		**Population under Influence**		**Highly Annoyed Population**	
Reduction Scenario	10 dBA	15 dBA	10 dBA	15 dBA	10 dBA	15 dBA
45-50 dBA	97.0	22.7	657,946	159,270	87,126	21,828
50-55 dBA	22.7	1.15	159,270	12,844	38,435	2,870
55-60 dBA	1.15	0.32	12,844	3,317	4,699	1,209
60-63 dBA	0.32	0	3,317	0	1,776	0
Total	**121.2**	**24.2**	**833,377**	**175,431**	**132,036**	**25,907**

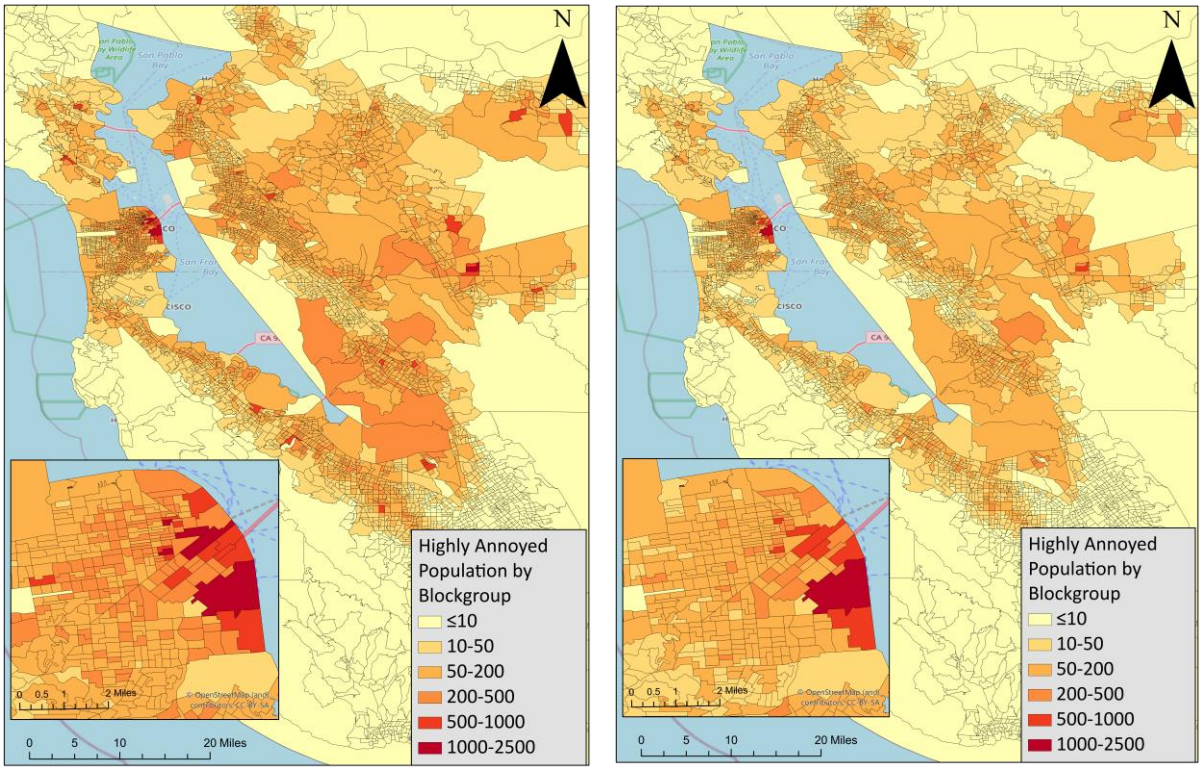

Fig 8. Spatial Distribution of Highly Annoyed Population. Inset Focuses on San Francisco CBD. Left: 10 dBA Reduction Scenario. Right: 15 dBA Reduction Scenario.

B. Dallas-Fort Worth

Fig 9 illustrates the spatial distribution of Block Group level DNL values for both the scenarios; the map on the left represents the 10-dBA reduction scenario, and the map on the right represents the 15-dBA reduction scenario. For the 10-dBA reduction scenario, high DNL values could be observed in Dallas CBD, Carrollton, Lewisville, Plano, Duncanville, Mesquite, and Dallas suburbs. Compared to the Bay Area, the generated noise is spatially more distributed in Dallas-Fort Worth and relatively smaller levels in the CBD region due to lesser concentration. Moreover, a significant part of Dallas downtown falls under the protected surface of DAL. For the 15-dBA reduction scenario, like the Bay Area, the DNL values drop substantially compared to the 10-dBA reduction scenario. A limited number of block groups have DNL values of more than 45 dBA.

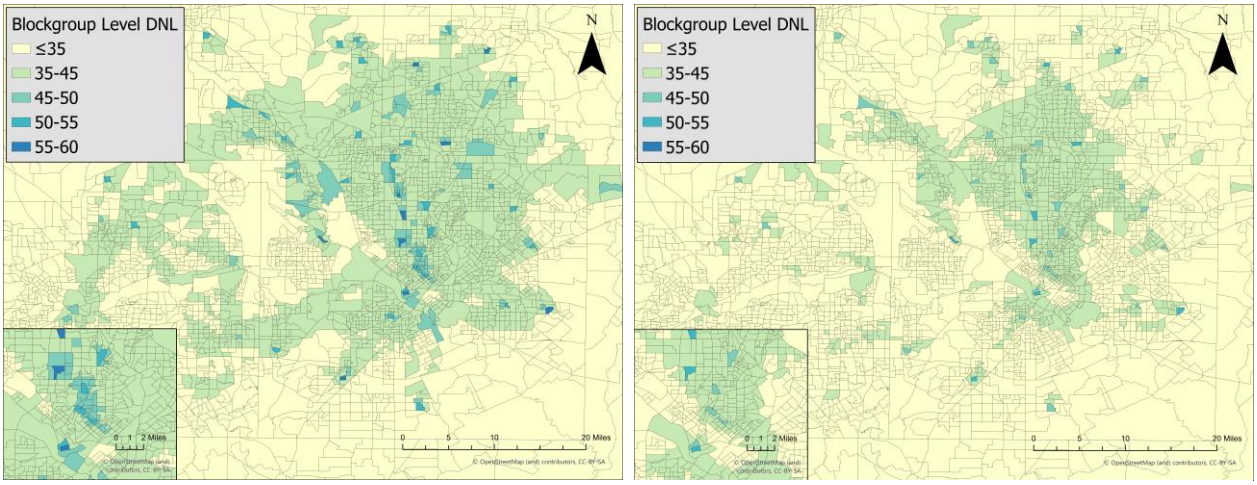

Fig 9. Spatial Distribution of DNL Values. Inset Focuses on Dallas CBD. Left: 10 dBA Reduction Scenario. Right: 15 dBA Reduction Scenario.

Fig 10 compares the spatial distribution of the highly annoyed population by Census Block Group. Dallas-Fort Worth has a smaller population density compared to Northern California. With lower DNL values, the total number of highly annoyed people is significantly less than the Bay Area for a similar UAM maturity level. For the 10-dBA reduction scenario, the Census Block Groups with more than 250 highly annoyed people can be found near major feeder vertiports, forming a circular pattern around the Dallas CBD. The same block groups can also be observed distinctively in the 15-dBA reduction scenario but with fewer highly annoyed populations. The annoyance caused in the 15-dBA scenario is significantly lower than the annoyance in the 10-dBA scenario. Table 2 compares the DNL values and annoyance level output for both scenarios. Suppose the reduction level could be increased from 10 dBA to 15 dBA. In that case, the area under the influence could decrease by 78%. The total population under the influence could reduce by 72%. The total highly annoyed population could reduce by 74%.

Table 2: Comparison of DNL values and Annoyance levels for both Scenarios (Dallas-Fort Worth)

DNL Category	**Area under Influence (sq. mi.)**		**Population under Influence**		**Highly Annoyed Population**	
Reduction Scenario	10 dBA	15 dBA	10 dBA	15 dBA	10 dBA	15 dBA
45-50 dBA	50.6	11.2	188,688	58,284	24,832	8,776
50-55 dBA	11.2	2.8	58,284	14,514	15,252	3,121
55-60 dBA	2.8	0	14,514	0	5,145	0
Total	**64.6**	**14.0**	**261,486**	**72,798**	**45,229**	**11,897**

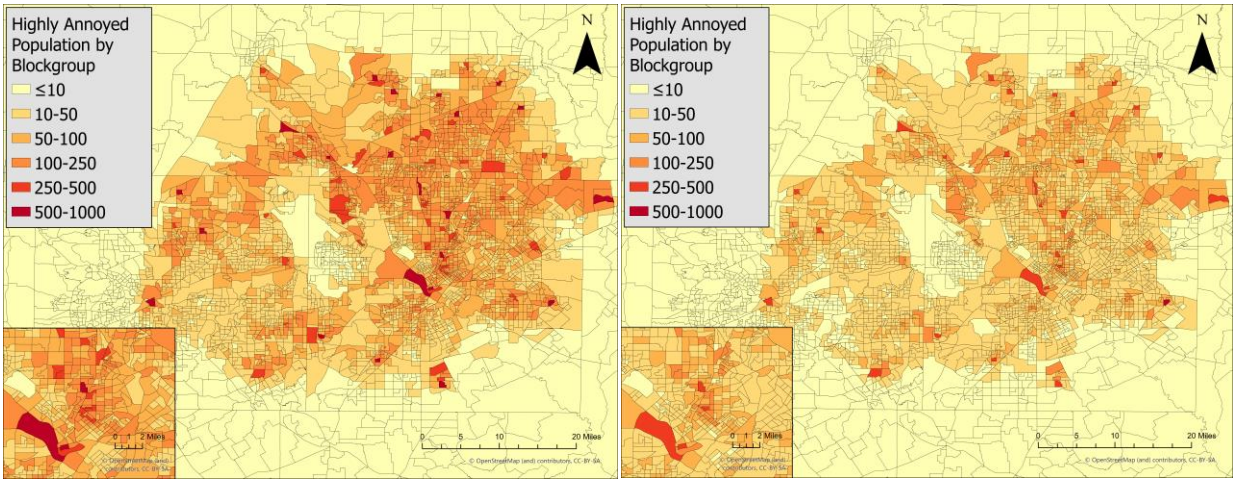

Fig 10. Spatial Distribution of Highly Annoyed Population. Inset Focuses on Dallas CBD. Left: 10 dBA Reduction Scenario. Right: 15 dBA Reduction Scenario.

C. Results of Vertiport Level Analysis in AEDT

A full day of simulation at the Financial District vertiport in AEDT consists of 458 arrivals and an equal number of departures. Fig 11 (left panel) shows the first and last three-mile segment of all departures and arrivals, respectively. Fig 11 (right panel) displays the distribution of arrival and departure times of operation at this vertiport. This vertiport has a unique operation schedule because no commuters live near that vertiport who wants to commute to other parts of the region using UAM. Therefore, all of the arrivals are concentrated in the morning hours when commuters are flowing into that vertiport. All the departures are concentrated in evening hours when the same commuters return. The analysis in this paper only considers passenger-carrying operations. However, such an unbalanced operations schedule leads to many repositioning flights (i.e. deadheading), as observed in Rimjha and Trani [40]. They found that the 0.9 repositioning departures and 0.85 repositioning arrivals are required of every passenger arrival and departure, respectively. Considering repositioning operations would significantly inflate the noise levels generated from operations at this vertiport. The DNL contours presented in this Section are generated from passenger-carrying operations only.

UAM routes are designed to detour approach and departure surfaces at commercial airports following the shortest path. All the traffic to/from any place south of SFO detours around protected surfaces of 1-19 runways at SFO; thus, there is a heavy concentration of flight trajectories on that path. Similarly, a significant portion of flights to/from the

other side of the bay detours around the protected surface at 12-30 runway at Oakland International Airport (OAK), causing a concentration of flight trajectories on that path. The heavy concentration of flight trajectories on both paths will influence the shape of noise contours significantly. DNL calculation considers nighttime operations (10 PM to 7 AM) to be more onerous and, therefore, artificially increases noise level measurements for night operations by 10 dB. Out of 916 operations, 15.2% of operations occur during nighttime hours.

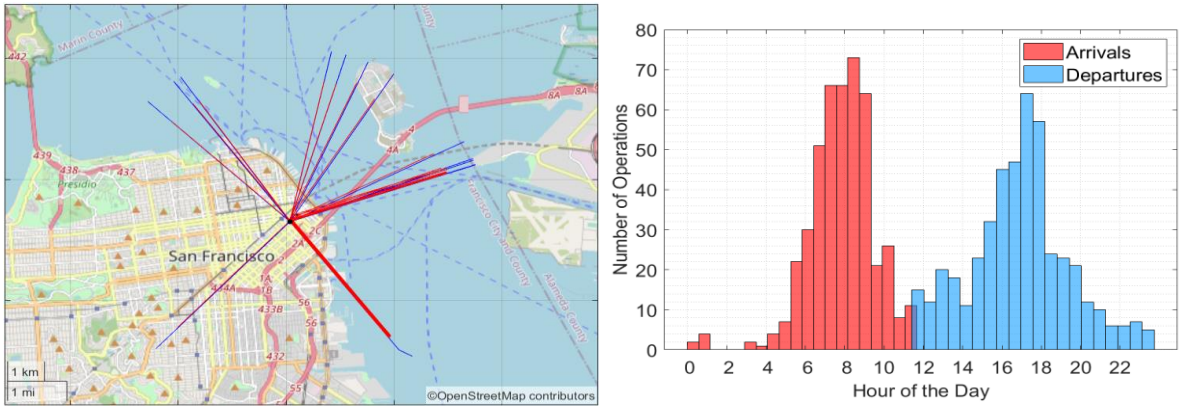

Fig 11. Flight Operations at Financial District Vertiport. Left: Flight Trajectories of Departures (Blue) and Arrivals (Red). Right: Time of Operations.

Fig 12 illustrates the DNL contours developed from a full day of operations at the Financial District vertiport. The varying concentration of flight trajectory defines the shape of noise contours around the vertiport. Unsurprisingly, the basic shape of noise contour is concentric circles, and it has concentration-based elongated spikes along the flight tracks. The length of elongation depends on the reduction scenario too. DNL contours for the 10-dBA reduction scenario encompass a significantly large area than DNL contours for the 15-dBA reduction scenario. The 45 DNL contour extends at least 1.2 miles and 0.75 miles in all directions for 10-dBA and 15-dBA reduction scenarios, respectively. The length along flight tracks is greater in the 10-dBA scenario and extends across the bay. Table 3 summarizes the comparison of DNL contours from both the reduction scenarios. In contrast to 10-dBA reduction scenario, the area under 45, 55, 65, and 75 DNL contour in 15-dBA reduction scenario shrink by 83%, 53%, 50%, and 48%, respectively. The population exposed under each DNL contour is estimated using the population exposure functionality in the AEDT tool based on Census Data. The highly annoyed population is further calculated from the exposed population and national dose-response curve discussed in Section IV-B. In contrast to the 10-dBA reduction scenario, the highly annoyed population under 45, 55, 65, and 75 DNL contour in the 15-dBA reduction scenario reduce by 74%, 64%, 58%, and 66%, respectively.

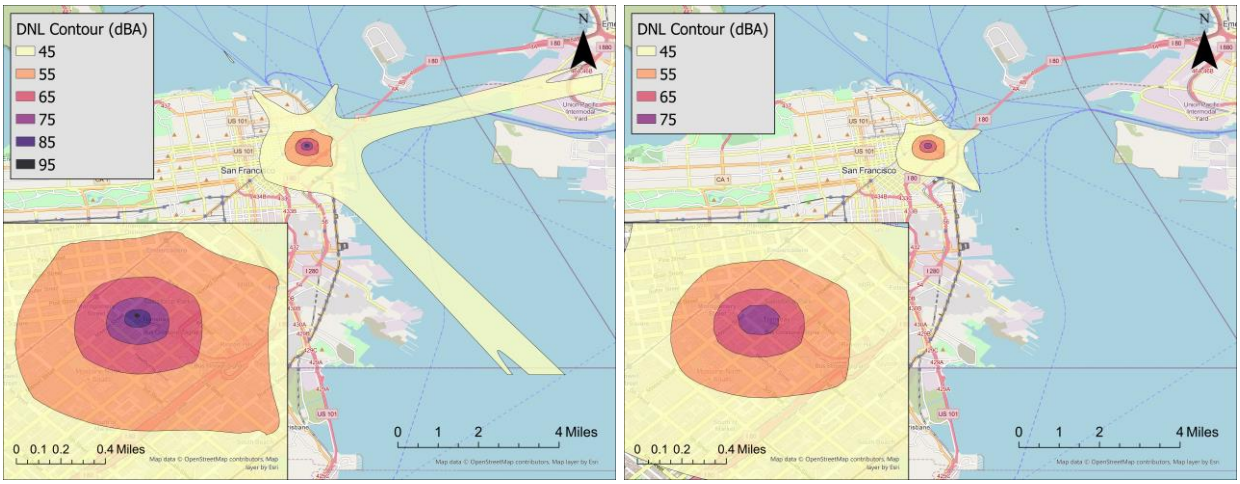

Fig 12. DNL Contours from Operations at Financial District Vertiport. Left: 10 dBA Reduction Scenario. Right: 15 dBA Reduction Scenario.

Table 3: Comparison of DNL Contours from both Reduction Scenarios

DNL	Area under DNL Contour (sq. mi.)		Population under DNL Contour		Highly Annoyed Population	
Reduction Scenario	10-dBA	15-dBA	10-dBA	15-dBA	10-dBA	15-dBA
45	10.89	1.81	110,811	28,764	21,133	5,485
55	0.70	0.33	11,655	4,213	5,687	2,055
65	0.16	0.08	1,596	677	1,267	537
75	0.03	0.0155	272	93	256	87
85	0.006	-	2	-	2	-
95	0.0002	-	-	-	-	-

San Francisco CBD has a high employment density. Although current regulations in 14 CFR Part 150 Airport Noise Compatibility do not address noise levels below 70 dB in commercial zone [41], high noise levels could cause nuisance to employees as people are now more sensitive to aviation noise [38]. Moreover, we have only considered in detail a single vertiport and passenger-carrying operations. With multiple vertiport and repositioning flights, noise levels in CBD may reach higher levels. Therefore, the impact on the daytime population should also be considered. Daytime population from ESRI demographics [42] is analyzed inside DNL contours for both reduction scenarios, as shown in Fig 13. The finest resolution of the daytime population is census tracts which are unfortunately too big for individual contour analysis. Therefore, we calculated the daytime population under 45 DNL outer boundary for both reduction scenarios. The daytime population of 22 census tracts encompassed by 45 DNL boundary is 379,527 for 10-dBA reduction scenarios. Whereas in the 15-dBA reduction scenario, the daytime population inside the 45 DNL boundary is 207,256, 45% lower than that of the 10-dBA scenario.

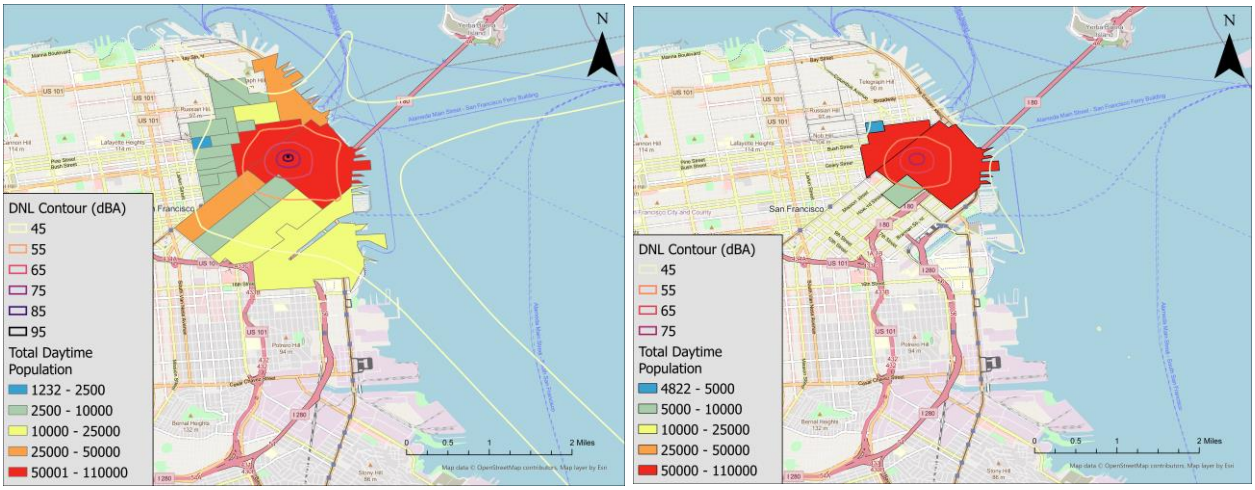

Fig 13. DNL Contours and Daytime Population. Left: 10-dBA Reduction Scenario, Right: 15-dBA Reduction Scenario

VI. Conclusions

This paper presents a framework to estimate noise levels from a full day of UAM operations in Northern California and Dallas-Fort Worth regions. UAM flight trajectories are derived from an output of mature-state demand analysis. Using Robinson R44 as a surrogate UAM vehicle and modifying its NPD curves, Block Group level DNL values are estimated for two reduction scenarios (10-dBA and 15-dBA). According to the current state of knowledge, 10-dBA reduction from the traditional helicopter is achievable, but 15-dBA reduction could be challenging. Noise results from both scenarios are compared to understand the impact of extra 5-dBA reduction. In Northern California, the area and under influence (>45 DNL) decreases by 80% and population under influence decreases by 79%, on increasing reduction level from 10 dBA to 15 dBA. In Dallas-Fort Worth, the area and under influence (>45 DNL) decreases by 78% and population under influence decreases by 72%, on increasing reduction level from 10 dBA to 15 dBA.

The Highly Annoyed population is estimated from DNL values for every scenario for a better interpretation of results. The total highly annoyed population is calculated using the national dose-response curve from Neighborhood

Environmental Survey and ACS 5-year population estimates at the block group level. In Northern California, the total highly annoyed population for the 10-dBA scenario is estimated at 132,036, which reduces by 80% on increasing the reduction level to 15-dBA. Similarly, in Dallas-Fort Worth, the total highly annoyed population for the 10-dBA scenario is estimated at 45,229, which reduces by 74% on increasing reduction level to 15-dBA.

A vertiport level analysis was performed in the AEDT tool to develop DNL contours from UAM operations at Financial District vertiport in San Francisco. The area, population, and daytime population under DNL contours significantly change based on the reduction levels. The shape of the DNL contour is influenced by geographic travel patterns and airspace restrictions. The findings indicate that a massive reduction in the noise footprint of UAM operations is observed on an increasing reduction level. Therefore, achieving reduction levels close to 15-dBA is recommended for mature state operations.

The results presented in this paper only consider passenger-carrying operations. We believe a significant fraction of repositioning operations would be required to serve commuting demand. Considering repositioning operations is recommended for future studies as that would increase noise footprint. Since the noise performance of the UAM vehicle is not available at the time of this analysis, we assumed noise reductions of 10 dBA and 15 dBA compared to the Robinson R44 light helicopter. Future research should use the noise performance of UAM vehicles once the exact noise profiles are known. Noise level estimation could also be improved by simulating the operations for an entire network in the AEDT tool, which would be computationally expensive.

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