Enhanced Modeling of Aircraft Taxiway Noise, Volume 1: Scoping

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Volume 1

Scoping

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ABSTRACT

Aircraft taxi noise acoustic sensitivity studies were conducted to document the importance of the modeling elements within INM and AEDT: source noise, operations, and environmental propagation. Sensitivity studies decoupled the taxi noise into the three areas and exercised each element independently. Limited opportunistic commercial aircraft taxi operation acoustic measurements were conducted. Independent taxi flight data recorder (FDR) information was queried to determine statistical engine and aircraft operational parameters.

The sensitivity studies revealed the primary driver for prediction is source noise: level, spectra and directivity. A nominal taxi state NPD, spectral class and directivity database is suggested based on existing data augmented with measurements. There is sufficient capability in INM to support detailed taxi operations. Future improvements planned for AEDT will reduce user input burden. The propagation algorithms, primarily lateral attenuation are sufficient. Airport-specific considerations may necessitate inclusion of terrain, shielding and variable ground impedance.

The measured acoustic data and FDR data were separate; therefore one could not quantify sensitivity of taxi noise to thrust. This identifies a need for a concurrent acoustic/FDR dataset. The study suggests modeling nominal taxi state in the short term with a comprehensive long term enhanced acoustic sensitivity to thrust capability.

EXECUTIVE SUMMARY

Introduction

The objective of this scoping project was to determine the best way to model airport noise from aircraft taxi operations and to create a plan for implementation of a taxi noise prediction capability into INM in the short term and AEDT in the longer term.

A comprehensive series of acoustic sensitivity studies were conducted in order to develop a physical understanding and draw conclusions about the relative importance of the various modeling elements (source, environment, operations) within the framework of INM and AEDT. The sensitivity studies were based upon decoupling the modeling of taxi noise into the following three areas and exercising each element independently.

1. Engine source noise (level, spectra, directivity);
2. Aircraft movements and operating states (location, duration, power setting); and
3. Environment / propagation (lateral attenuation, terrain, shielding, and ground impedance).

Findings

The sensitivity studies revealed that the primary weakness for taxi noise modeling is related to item #1, engine source noise modeling. A nominal taxi state noise NPD, spectral class and directivity database can be developed using existing data and augmented with additional acoustic measurement data. The existing source directivity model in INM needs to be modified to more appropriately account for taxi operations. At present there is sufficient capability in INM to support item #2 via detailed aircraft taxi movements, from gate to runway, terminal to runway or via time in mode assignments. Future aircraft movement and queuing modeling improvements targeted for AEDT will greatly reduce the current user input burden in INM. It was found that for #3, the propagation algorithm (primarily lateral attenuation in INM), is sufficient and only site-specific airport considerations will necessitate the inclusion of terrain, shielding and / or variable ground impedance. Therefore no recommendation to always or never include such effects could be made.

Conclusions

During the course of the project, opportunistic noise measurements were conducted in order to obtain acoustic data from commercial aircraft during taxi operations for a limited number of aircraft events. Additionally, existing flight data recorder (FDR) information was queried to determine statistical information about aircraft taxi operating parameters and typical taxi operational patterns. The acoustic data and FDR data were not gathered concurrently; therefore one could not definitively determine the noise level for a particular taxi engine thrust, or the sensitivity of noise with changes in thrust. The need for concurrent acoustic and engine operating state data is an important finding of this study and is the primary reason for considering only a nominal taxi state in the short term, and the recommendation of a comprehensive long term solution seeking concurrent taxi noise and operating condition measurements for the purposes of developing an enhanced acoustic sensitivity to thrust capability for AEDT.

Suggestions

While the scoping study suggestions are applicable to both INM and AEDT, we found that taxi noise can result in a "significant impact" (DNL increase of more than 1.5 dB) under certain conditions, and hence suggest short term implementation in INM, so that an improved taxi modeling capability may be provided to the noise modeling community sooner rather than later.

The projected rough order of magnitude costs for implementing a taxi noise capability in INM alone is $220k, in INM + AEDT is $310k and in AEDT only is $240k. Included in these estimates is the approximate $130k cost for development of the various aircraft and acoustic taxi databases.

This report documents both the acoustic sensitivity studies and a technical implementation plan for a comprehensive taxi noise computational capability in INM/AEDT.

CHAPTER 1. INTRODUCTION

Historically, the analysis of airport noise has generally been limited to the flight operations of aircraft arriving and departing, as these are the operations that produce most noise, and therefore, determine the shape and size of the overall airport noise contours. Over recent years, since the phase-out of Stage 2 aircraft and the replacement of these aircraft by the quieter Stage 3 and Stage 4 models, noise exposure at most US airports has decreased significantly. Projections indicate that the noise contours from flight operations will continue to shrink as the noisier Stage 3 retrofits are retired, until later in this decade when the growth of operations will cause a leveling off and an eventual increase in exposure. Noise contours will however still be smaller than those computed for pre-2000 conditions.

It might be expected that as noise levels from flight operations decrease over time, noise exposure from ground operations (i.e., taxiing) will decrease proportionally. As such, taxiway noise would remain a relatively small contributor to airport noise. The reductions in flight noise resulting from the introduction of new engine technology are, however, not necessarily reflected in the noise at the low engine thrust settings that are typical of taxiing operations. Furthermore, as traffic grows, and airports approach capacity, the resulting ground congestion will mean that aircraft will be spending more time on the ground in hold short positions and waiting queues. Fuel heavy departing aircraft will be producing more noise as they accelerate to taxiing speed from hold short positions. The overall result is that ground operations may, in fact, become a larger contributor to airport noise, hence, the need to include them in future airport noise estimates required in Part 150 studies, master plans, Environmental Assessments (EA) and Environmental Impact Statements (EIS).

There are, of course, other sources of noise at an airport. These sources, which include taxiing, APU's, ground support and other gate operations have generally been minor contributors to the overall airport noise contours. As such, these sources have generally not been included as contributors to the airport noise contours. There are exceptions, however, such as at Boston Logan, where the nearby water surface reduces the propagation losses, and at Chicago Midway, where residential dwellings are very close to the airport boundary.

The purpose of the sensitivity work described in Chapters 1-4 in this report is to develop an approach for modeling taxiing and ground noise, and for incorporating the necessary algorithms into the INM and AEDT. In order to properly model taxi operations at airports, one must first characterize the elements of such operations and determine which features are important from the perspective of noise modeling. A holistic approach requires an understanding from the operational level (how the aircraft move from the gate to the runways, and how the bigger picture of congestion and weather affect aircraft movements) through the detailed aircraft motion level (what thrust is being used, how fast do aircraft accelerate and decelerate) and down to the source details (noise directivity, levels and spectral content).

We have approached the project in the following manner:

- Define the requirements of a taxiway model.
- Acquire noise and operations data for taxiing operations where available.
- Develop models for the source and propagation of noise from taxiing aircraft at appropriate thrust levels.

- Perform sensitivity analyses of the source and propagation models to determine the influence of model components on the acoustic predictions.
- Identify the critical components and operations that need to be included in a taxiway noise model and assess the capability of the current INM7 and AEDT Local structure to incorporate these components, and make suggestions for their inclusion.

Data and information was sought from a variety of sources including airframe manufacturers, engine companies, airlines, airports and government agencies such as NASA and DOT Volpe Center. Several examples of operations were examined in detail in order to understand and extract pertinent operational information. These examples include historical flight data recorder records from a major European airline, taxi modeling protocol and procedures approved for use in the Boston Logan Airport Noise Study, and operational scenarios developed for a benchmark emissions study under CAEP.

The findings from the sensitivity study led to a suggested system design and architecture for incorporating a taxiing noise model into INM7 / AEDT Local. At project initiation, the ACRP project review panel communicated that the first priority was to determine if a taxi noise model can be incorporated into INM 7 in the short term and if so, to determine and document the necessary acoustic modifications. The second priority was to design a taxi noise module for AEDT and identify any longer term research items. The design presented here may therefore be implemented in two steps:

- Step 1: Targeted acoustic modifications and database extensions to INM Version 7 (*1*) and
- Step 2: A taxi module for AEDT Local (*2*), which builds upon features of EDMS (*3*) including longer-term improvement recommendations for taxi noise modeling.

The taxi noise modeling system design presented in Chapters 5 and 6 incorporate maximum input flexibility providing the user with the option of selecting a suitable level of fidelity for their needs. The taxi model architecture suggested for AEDT Local has been constructed such that it is compatible with and leverages capabilities and data contained within both INM and EDMS. The Step 2 AEDT Local taxiway noise module is presented both in isolation and with the supposition that the Step 1 taxi noise modeling acoustic extensions suggested for INM 7 will also be available and implemented in AEDT Local, specifically within the Aircraft Acoustics Module. Chapter 7 gathers together the specific taxi modeling pieces and identifies a path forward.

CHAPTER 2. AIRPORT TAXIING OPERATIONS

Taxiing is the controlled movement of the aircraft under its own power on the ground. Noise levels in the community generated by taxiing aircraft will clearly depend on the operation of the aircraft. Taxiing operations encompass the movement of departing aircraft from the gate-push-back position to the assigned runway, and of arriving aircraft from the runway to their assigned gate.

Cumulative noise levels in the community will depend not only on the total time for the taxiing aircraft to reach its assigned destination, but also on the duration of each operating mode – stationary operations, moving taxiing operations at ground idle settings, and brief periods of acceleration which for some aircraft types is preceded by an increase in thrust.

Chapter 2 will explore in Section 2.1, the various rules and regulations which impact taxi ground operations. Holding queues will be discussed in Section 2.2, along with several existing tools, TAAM® and EDMS, often employed in studies for the prediction of airport delays. Section 2.3 will focus on the details of the aircraft taxiing motion, present some generalizations about aircraft behavior during taxi operation, drawn from analysis of a large flight data recorder database. Typical aircraft ground speed, engine use during taxi and nominal thrust settings during motion and holds will be presented. Section 2.4 provides a characterization of aircraft accelerations into "Gentle" and "Burst behavior and describes a technique for evaluating Breakaway thrust from FDR data. The final Section 2.5 provides a summary of engine operating state information as was compiled for CAEP as an Alternative Emissions Methodology.

2.1. FAA ATC Rules and Regulations Affecting Taxi Operations

Unlike flight operations, the taxiing process is not rigidly influenced by the FAA, so that many of the decisions on taxiing procedures are left to the airline, and ultimately to the Captain. There are some general discussions of airport operations to be found in current literature (*9*). In order to gain a better understanding of taxi procedures, and specifically to find out how both airline and FAA rules and regulations impact taxi operations, interviews were held with pilots across a variety of airlines (*4*, *5*, *6*, *7*, *8*). This section will discuss the interplay between the FAA guidance, specific airline protocols and the like.

The FAA states that a pilot should taxi at a 'safe taxi speed', so as to maintain positive control and have the ability to stop or turn where and when desired. The FAA does not designate a specific speed or power setting for aircraft taxiing operations, but local Tower personnel do prescribe the taxi pathway.

As a result, aircraft and engine operation during taxi varies from one airline to another and from one pilot to another. For instance, upon being given a slot time, a departing aircraft will be pushed back from the gate; where upon the pilot will start the No 1 engine. Depending on aircraft size and type, some airline Standard Operating Procedures (SOP) may advise pilots to taxi on one engine in order to conserve fuel and reduce emissions, but this is generally only possible for the lighter aircraft. Many pilots prefer not to use one engine because of the non-symmetrical engine wear, and because it requires a two- to four-minute run up of the second engine prior to take-off. Normally, for the first flight of the day two engines are used.

The aircraft will then briefly accelerate to taxiing speed and proceed to the end of the assigned runway. En route, taxiing may be interrupted to await ATC clearances, allow for the movement of other aircraft, or enter a departure queue due to congestion. The taxiing process will generally involve constant speed in the range 15 to 20 knots with the engine(s) at ground idle thrust, with brief accelerations for time-sensitive movements, such as crossing active runways.

The actual thrust settings are not fixed, but for ground idle are in the range of 5 to 15 percent for regular commercial aircraft, and can be up to 35 percent for regional jets, Thrusts of up to 35 percent are sometimes needed for short periods of time for accelerating from a hold-short position. On some of the lighter aircraft, such as the A320, the pilot may only have to release the brakes to taxi. FAA rules state that engine power is not permitted to exceed 45 percent on the ramp. Several airlines interviewed reported a self-imposed limit of 35 to 45 percent thrust for all taxi operations. Actual thrust settings are aircraft-dependent.

Taxiing operations at commercial airports are strongly influenced by aircraft separation standards for departing and arriving aircraft. These standards are dependent on many parameters, including the equipment available (Radar vs. Non-Radar), distances between runways, runway configurations, phase of flight, altitude, and wake turbulence separation

Departure separation must be assured by air traffic controllers. The departing aircraft can not begin their takeoff roll until the preceding aircraft has departed and crossed the runway end, or turned to avoid conflict. The above rule only applies if controllers cannot reference landmarks to determine departure distance. If controllers are able to determine departure distances, as related to landmarks on the airfield, if the two aircrafts are Category I aircraft, then a minimum distance of 3,000 feet between them must exist. If a Category II aircraft departs in front of a Category I aircraft, then 3,000 feet between them exist. If the succeeding or both aircraft are Category II aircraft, 4,500 feet must exist between the aircraft. If either aircraft, departing or preceding, is a Category III aircraft then 6,000 feet must exist between the aircraft. (Category I aircraft is a small aircraft weighing 12,500 lbs or less, with a single propeller driven engine, and includes all helicopters, Category II is a small aircraft weighting 12,500 lbs or less with a propeller driven twin-engines, and a Category III includes all other aircraft.) (*10*)

Air traffic controllers are not to issue clearances to small aircraft to taxi into position and hold on the same runway behind a departing heavy jet aircraft, due to the wake turbulence. There is a 2 minute wake turbulence hold when an IFR/VFR aircraft is departing behind a heavy jet or B757 on the same runway or a parallel runway that is separated by less than 2,500 feet.

A small aircraft landing behind a large aircraft on the same runway must be separated by 4 miles; a small aircraft landing behind a B757 must be separated by 5 miles, a small aircraft landing behind a heavy aircraft must be separated by 6 miles, a large or a heavy aircraft landing behind a B757 must be separated by 4 miles, and a large behind a heavy must be separated by 5 miles, and a heavy aircraft landing behind another heavy aircraft must be separated by 4 miles.

Runway capacity plays a role in aircraft wait times as do Visual Meteorological Conditions (VMC) and Instrument Meteorological Conditions (IMC). VMC and IMC refer to the conditions under which Visual Flight Rules (VFR) and Instrument Flight Rules (IFR) are used, respectively. A single runway configuration, during VMC, can accommodate up to 99 operations per hour for smaller aircraft and approximately 60 operations per hour for larger commercial service aircraft. The capacity of a single runway is reduced during IMC to approximately 42 and 53 operations per hour. If parallel runways exist, depending on the distance between the two runways, capacity is increased. Capacity for parallel runways that have at least 4,300 feet between the two centerlines of the runways, are double the capacity of a single runway capacity. If lateral separation between parallel runways is less than 4,300 feet and IFR conditions exist, capacity is reduced significantly. Parallel runways that are separated by less than 2,500 feet must operate, and are treated, as a single runway configuration for IFR operations.

The FAA does not designate a minimum distance that aircraft on the ground must be from each other. A safe distance should be maintained at all times. An interview with an air traffic controller (*8*) who worked in the tower at Teterboro Airport in New Jersey, indicated that distance between aircraft stopped on taxiways depends on the type of aircraft is in front of the line. If preceding aircraft is one where the engines are located on the wings such as a B737, aircraft following might be as close as 50 feet behind. A preceding aircraft whose engines are located on the fuselage or tail, such as a MD80, might have 100-150 foot of separation in between the tail of one aircraft and the nose of the following aircraft. A simple model of aircraft in a holding queue is depicted in Figure 1.

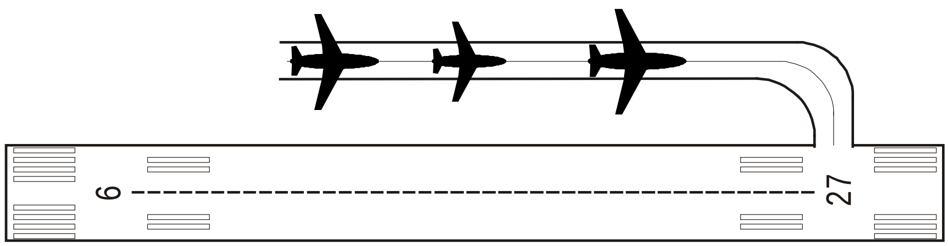

Figure 1. Single taxiway, multiple aircraft holding queue scenario.

In summary, when considering ATC Rules and Regulations affecting taxi operations and based on the wide variability seen in practice of operational procedures, both in terms of pilot discretionary decisions and regulatory/safety requirements, it was not possible to draw any general taxi operational guidelines such as minimum separation distances, speed limits or the like.

2.2. Holding Queues

Queuing time refers to the amount of time aircraft executing departures wait to depart from the runway or aircraft executing arrivals wait to cross active runways as they travel from the runway to a terminal. As mentioned in Chapter 1, a myriad of things may impact the travel of an aircraft between a gate and a runway.

- FAA guidance and rules;
- Weather;
- Airport Congestion;
- Runway Capacity; and
- Crossing over active runways.

Often runway queues consist of parallel taxiways with multiple aircraft holding. As one can imagine the prediction of the interaction between the runways, terminal and taxi operations can be quite complex, especially for larger airports. Simplified time in mode modeling may rely on data sources for total taxi times, as is commonly employed for emissions assessments, and may include FAA maintained databases. For example Boston Logan International Airport's Annual

Environmental assessment (*11*, *12*) bases Aircraft taxi-times on data obtained from the FAA Aviation System Performance Metrics (ASPM) database (*13*) for 2006. For Boston, aircraft taxi-times for 2006 averaged 25.32 minutes, an increase of less than 1 percent from 2005.

Another source of time information is the ICAO guidelines (*14*) for emissions calculations. These specify 26 minutes total taxi time (taxi-in + taxi-out). These 26 minutes are broken down into 9 minutes taxi-in and 17 minutes taxi-out. This reference time is applied also within the Emissions and Dispersion Modeling System (EDMS) (*15*).

The alternative to the aforementioned two taxi time data sources is the prediction of taxi times based on simulation which take into account the aforementioned issues. Such analysis can a sophisticated model such as the Total Airspace and Airport Modeler (TAAM®) (*16*) or the queuing component of EDMS (*15*).

TAAM® is a very high fidelity tool capable of simulating complex scenarios and is currently being used for airport modeling. We utilized TAAM® because of the opportunity to leverage a concurrent Wyle noise study at a major US International airport thereby utilizing realistic aircraft taxiing movements including aircraft congestion queuing for this study.

EDMS, an emissions model for assessing air quality around airports, is being incorporated into AEDT. The queuing engine within EDMS consists of an Airside Delay Model (WWLMINET) in conjunction with a sequencing model. The primary modes of operation for EDMS, inventory and dispersion, require significantly different input data and model considerably different level of detail for aircraft operations. Further information on EDMS can be found in Appendix D.

In the remainder of this chapter the aforementioned tools and the potentially symbiotic analyses which can be performed in support of emissions and taxi noise prediction will be addressed in subsequent sections.

2.2.1. Total Airspace and Airport Modeler (TAAM®)

TAAM®, a time-based simulation and modeling tool (*16*) is an application for the simulation of airspace and airport operations. It is a gate-to-gate system that models the entire airside and airspace environment in detail, including pushback, runways, terminals, en-route and oceanic airspace. TAAM® is often employed to evaluate the efficiency, capacity, and safety of airspace and airport operations. TAAM® simulates aircraft movements in detail in fast-time, facilitating quicker results and cost efficiencies. TAAM® is not a noise model, but its results can provide some sample test cases for use in activities developing and assessing various fidelity taxi operation modeling scenarios.

In subsequent sections of this report, we will be leveraging the results of a TAAM® analysis performed for a major International US Airport. This TAAM® analysis utilized input associated with air traffic procedures, weather and operational constraints and predicted a set of complex taxi movements for the average day of the peak month of existing operations. The intent of the analysis from which this dataset is being leveraged, was to calculate estimated capacity metrics, add proposed noise abatement alternatives, and assess their effect on capacity of the a major US International airport. The TAAM® model provides aircraft type, taxi track (segments of each route), numbers of operations and queue times.

A TAAM® simulation can also provide modeled taxi routes and unimpeded taxi times and delays (i.e., additional taxi/queue time) separately for arrivals and departures, by route segment. Unimpeded aircraft ground times are measured as the un-interrupted time from gate to lift-off for departures, and un-interrupted time from touch-down to gate for arrivals. This unimpeded time is the amount of time it would take the aircraft to traverse its taxiing route if it were the only aircraft in the simulation. The unimpeded taxi movements were not considered in this study; however this TAAM® capability is noted here because it could be utilized for those airports surrounded by communities where taxi noise and impeded taxi/queuing time can dominate and be of significant concern.

2.2.2. EDMS and the WWLMINET Queuing Module

EDMS predicts air quality inventory and also models emission dispersion around airports. In the future users of AEDT will be able to simultaneously model noise and emissions impacts. The two different types of EDMS computations along with the input data and outputs has some applicability to taxi noise modeling in that both emissions and noise modeling requires knowledge of the aircraft operations, specific airplane and engine performance as well as detailed motions the aircraft employ in the airfield.

Within EDMS, for computation of an annual emissions inventory, the user-specified taxi time option may be used. This option, which requires summary data about the airport operations (emission sources and annual activity for each source) may not be used for dispersion analysis. The methodology employed for prediction of annual emissions inventory does not consider any kind of geometric distribution of the emissions sources. Hence, for emissions inventory computations within EDMS, the user is not required to provide an airport layout. The question naturally arises as to whether such a summary assessment of emission sources (aircraft spent in various modes of operation, taxiing and holding) could be useful for aircraft taxi noise modeling. This subject is addressed later in Chapter 4.

Dispersion modeling requires knowledge of detailed aircraft movements. Within EDMS this higher fidelity input option may be used to calculate an annual emissions inventory in addition to providing data critical for dispersion modeling using AERMOD (*17*) thus, in addition to the aircraft schedule, the future AEDT user will be required to provide the following:

- Detailed airport layout (gates, taxiways, runways, etc.);
- A set of taxipaths connecting gates to runways and runway exits to gates;
- Airport configurations;
- Hourly weather; and
- Location of receptors.

Each operation (departure or arrival) is characterized, among the others, with its assigned gate and its expected (scheduled) operation time. Based on the weather input file, EDMS identifies the most appropriate airport configuration for each hour, which further identifies: 1) the airport runway capacity and 2) the aircraft runway distribution (based on the aircraft weight class).

EDMS allows users to identify one (1) taxi path for each gate-runway pair (departures) and runway-exit-gate (arrivals). Therefore, each departure gets assigned a unique taxi path when the appropriate gate-runway pair is identified. Also, each arrival operation gets assigned a unique taxi path when the appropriate runway-exit-gate pair is identified. EDMS then models the movements of individual aircraft along the taxi paths.

In summary, the timing of aircraft in holding queues is affected by a multitude of factors including FAA rules, weather, congestion and capacity. Empirical or modeling data from EDMS and TAAM® and ultimately AEDT are suitable sources for such queuing information. Based on the complexity of taxi operations, especially at larger airports we found that we could not provide a generally applicable recommendation for queuing time determination nor a particular level of fidelity with which taxiing queuing should be modeled.

2.3. Typical Taxi Behavior: Ground Speed, Engine Use and Thrust

During an aircraft's travel between gates and runways, a series of different operating states might be encountered. These include stationary operations, moving taxiing operations at ground idle settings, and brief periods of acceleration which for some aircraft types is preceded by an increase in thrust.

An examination of flight data recorder (FDR) information from a major European airline was used to generate some statistical generalities about vehicle taxi operating behavior, including aircraft taxiing speeds, engine use and operating states / thrust levels. The FDR data include 1 year of operational data from a major European carrier (flagship plus their affiliate regional carriers) and include all operations, from gate to runway to air to runway to gate, across a multitude of international airport pairs. Since it's a European carrier there are more European airports represented than US airports, but the data can be considered generally applicable to US domestic operations as well. It is important to note that this comprehensive dataset covers only the operational half of the situation – the noise half is not covered since concurrent taxi acoustic data was not gathered during any of these operations.

Subsequent sections will delve into the subject of taxiing aircraft acceleration after a stop (excluding on-runway and takeoff acceleration) and breakaway thrust. Simple queries were employed in the prediction of the parameters presented below. Appendix E contains expanded information about the analysis algorithms.

To develop the summary data, the flight record was split into operational segments from gate to gate: departure, enroute flight and arrival. This included segments such as parked at the gate, pushback, taxi to the runway (including any holding queues encountered), and departure operation on the runway. On the ground FDR data is spaced 5 seconds apart while enroute data incorporates a logarithmic time spacing algorithm. The departure segment was further examined and aircraft with "rolling departures" were separated from those who "held" at the end of the runway before departing. The next segment was the runway takeoff, followed by the enroute flight segment. At the destination region, the records were split up to include approach up to the touchdown point along with the runway deceleration period. Segments where the aircraft had left the runway and was on a taxiway (regardless of speed) are included as part of the taxi for an arrival. The aircraft at the gate was considered part of the taxi segment up until the time when the fuel flow was reported as zero for all engines. Operations at the gate while engines were spooling down (and thrust / operating state parameters were reported as non-zero) were not included in the taxi segment. Subsequent examination of the average operational parameters for stationary portions (or holds) included this stationary gate portion of the taxi operation.

The departure taxi segment and the arrival taxi segments were assessed separately. An assessment of the use of engines expressed as a function of total taxi time was performed in order to determine whether single or multiple engine operations could be a factor in taxi analysis. Stationary segments were defined as those with reported ground speed less than 1 knot and moving segments those with speeds at or above 1 knot. During these stationary and moving segments average ground speed and thrust parameters were obtained from the FDR data. Table 1 itemizes the average and standard deviation of ground speed during departure and arrival taxi operations. One would expect that taxi speeds immediately after leaving the runway on arrivals to be greater than those for departing aircraft as is indicated in the average and standard deviation of ground speed (Table 1). Table 2 summarizes the percentage of time each engine is operating during the various taxi operations. For this analysis, an operation is defined as those records when the fuel flow for at least one engine is greater than zero. The engine operating state parameters as reported in the FDR data is presented in Table 3. The definition and units of the engine operating state parameters are:

- N1avg: N1, average (all engines, percent of maximum) at start of event;
- %Thrust: percent of maximum thrust at start of event;
- EMS Thrust: EMS thrust per engine, averaged over all engines at start of event, lbs; and
- EMS enhanced: EMS enhanced thrust per engine, averaged over all engines at start of event, lbs.

In summary, an examination of a comprehensive flight data recorder dataset yielded some statistical information about historical commercial aircraft ground speeds, engine use and thrust settings. Such data could be applied by noise modelers to their specific analyses. Engine operating parameters were computed for a range of aircraft types and categorized into arriving and departing operations as well as during moving as well as stationary periods. This section provides some of the numerical basis from which subsequent sensitivity studies will draw.

TABLE 1 Ground Speeds for Taxiing Operations

Ground Speed - Moving Aircraft, Departures		
Aircraft	**Average Ground Speed (knots)**	**Standard Deviation GS (knots)**
A319	9.26	3.34
A320	9.10	2.92
A321	9.39	3.31
A330	10.05	3.32
A340	9.26	2.98
B757	8.87	2.28
B767	11.13	3.13
B777	8.97	3.18
RJ100	9.14	3.57
RJ85	8.23	3.08

Ground Speed - Moving Aircraft, Arrivals		
Aircraft	**Average Ground Speed (knots)**	**Standard Deviation GS (knots)**
A319	11.72	3.27
A320	11.08	3.27
A321	11.28	4.67
A330	13.07	3.21
A340	9.88	2.92
B757	13.23	2.68
B767	12.65	2.60
B777	11.45	2.26
RJ100	14.10	4.44
RJ85	14.67	4.77

TABLE 2 Engine Use for Taxiing Operations

Engine Use - Stationary, Departure Taxi Operations								
Aircraft	Average %1eng	Standard Dev.%1eng	Average %2eng	Standard Dev %2eng	Average %3eng	Standard Dev %3eng	Average %4eng	Standard Dev %4eng
A319	2.40	5.47	97.40	5.68	0.00	0.00	0.00	0.00
A320	3.30	7.62	96.60	7.85	0.00	0.00	0.00	0.00
A321	2.10	3.56	97.80	3.85	0.00	0.00	0.00	0.00
A330	9.60	14.93	90.30	15.12	0.00	0.00	0.00	0.00
A340	1.20	7.25	7.10	15.86	3.20	5.70	88.20	21.51
B757	5.10	5.58	94.70	5.86	0.00	0.00	0.00	0.00
B767	17.10	15.24	82.70	15.38	0.00	0.00	0.00	0.00
B777	7.30	14.01	92.50	14.14	0.00	0.00	0.00	0.00
RJ100	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00
RJ85	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00

Engine Use - Stationary, Arrival Taxi Operations								
Aircraft	Average %1eng	Standard Dev.%1eng	Average %2eng	Standard Dev %2eng	Average %3eng	Standard Dev %3eng	Average %4eng	Standard Dev %4eng
A319	3.00	15.13	96.90	15.21	0.00	0.00	0.00	0.00
A320	1.10	7.63	98.80	7.77	0.00	0.00	0.00	0.00
A321	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00
A330	4.40	19.42	95.50	19.50	0.00	0.00	0.00	0.00
A340	1.00	8.60	1.70	10.36	1.20	10.07	95.90	19.35
B757	1.20	10.87	98.70	10.87	0.00	0.00	0.00	0.00
B767	0.60	5.39	99.30	5.44	0.00	0.00	0.00	0.00
B777	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00
RJ100	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00
RJ85	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00

Engine Use - Moving, Departure Taxi Operations								
Aircraft	Average %1eng	Standard Dev.%1eng	Average %2eng	Standard Dev %2eng	Average %3eng	Standard Dev %3eng	Average %4eng	Standard Dev %4eng
A319	11.20	19.54	88.60	19.41	0.00	0.00	0.00	0.00
A320	9.30	18.39	90.60	18.27	0.00	0.00	0.00	0.00
A321	8.70	16.10	91.10	15.99	0.00	0.00	0.00	0.00
A330	11.30	14.72	88.50	14.75	0.00	0.00	0.00	0.00
A340	1.80	2.98	7.20	8.74	1.40	1.88	89.20	10.83
B757	2.80	4.51	97.10	4.76	0.00	0.00	0.00	0.00
B767	6.60	9.73	93.30	9.90	0.00	0.00	0.00	0.00
B777	10.50	10.87	89.40	10.92	0.00	0.00	0.00	0.00
RJ100	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00
RJ85	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00

Engine Use - Moving, Arrival Taxi Operations								
Aircraft	Average %1eng	Standard Dev.%1eng	Average %2eng	Standard Dev %2eng	Average %3eng	Standard Dev %3eng	Average %4eng	Standard Dev %4eng
A319	0.40	2.85	99.50	2.99	0.00	0.00	0.00	0.00
A320	1.10	6.28	98.70	6.46	0.00	0.00	0.00	0.00
A321	0.00	0.53	99.90	0.62	0.00	0.00	0.00	0.00
A330	1.70	11.23	98.20	11.36	0.00	0.00	0.00	0.00
A340	0.50	3.05	1.70	10.09	0.10	0.68	97.50	11.04
B757	0.40	3.60	99.50	3.72	0.00	0.00	0.00	0.00
B767	0.50	7.36	99.40	7.36	0.00	0.00	0.00	0.00
B777	0.00	0.18	99.90	0.25	0.00	0.00	0.00	0.00
RJ100	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00
RJ85	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00

TABLE 3 Engine Operating Parameters for Taxiing Operations

Engine Operating Parameters - Stationary, Departure Taxi Operations								
Aircraft	Average N1average	Standard Dev. N1avg	Average %Thrust	Standard Dev %Thrust	Average EMS Thrust	Standard Dev EMS Thrust	Average EMS Enhanced	Standard Dev EMS Enhanced
A319	19.42	1.41	8.41	1.18	1975.24	278.42	1975.24	278.42
A320	19.16	1.29	7.45	1.34	2011.77	361.01	2011.77	361.01
A321	20.06	1.55	6.15	1.15	1843.61	345.29	1843.61	345.29
A330	21.16	3.08			3845.13	2484.18		
A340	19.50	4.73			2210.70	1027.83		
B757	20.47	1.51	2.68	0.67	1077.75	268.58	1077.75	268.58
B767	23.78	2.66	5.74	1.24	3565.83	772.65	0.00	0.00
B777	19.89	2.30	4.86	0.86	5615.41	989.00	0.00	0.00
RJ100	22.67	1.80	21.70	1.99	1518.85	139.30	0.00	0.00
RJ85	22.32	1.59	21.44	1.71	1500.55	120.04	0.00	0.00

Engine Operating Parameters - Stationary, Arrival Taxi Operations								
Aircraft	Average N1average	Standard Dev. N1avg	Average %Thrust	Standard Dev %Thrust	Average EMS Thrust	Standard Dev EMS Thrust	Average EMS Enhanced	Standard Dev EMS Enhanced
A319	17.37	3.98	8.62	2.20	2026.47	516.45	2026.47	516.45
A320	17.51	3.04	7.72	1.89	2083.66	510.60	2083.66	510.60
A321	18.21	3.82	6.78	1.97	2034.77	591.40	2034.77	591.40
A330	21.51	4.25	5.80	4.46	3947.56	3035.05	2815.96	3582.02
A340	19.20	3.93	6.38	2.85	2590.74	839.84	1516.45	1520.39
B757	19.64	2.50	1.39	0.87	560.33	347.74	560.33	347.74
B767	26.79	1.56	6.09	4.47	3781.28	2777.72	0.00	0.00
B777	21.41	0.91	5.46	0.43	6312.84	496.08	0.00	0.00
RJ100	17.51	6.52	16.54	6.41	1157.97	449.01	0.00	0.00
RJ85	18.03	5.69	17.06	5.45	1194.22	381.76	0.00	0.00

Engine Operating Parameters - Moving, Departure Taxi Operations								
Aircraft	Average N1average	Standard Dev. N1avg	Average %Thrust	Standard Dev %Thrust	Average EMS Thrust	Standard Dev EMS Thrust	Average EMS Enhanced	Standard Dev EMS Enhanced
A319	19.56	3.34	9.20	1.92	2162.66	451.69	2162.66	451.69
A320	19.71	3.29	8.22	1.85	2220.48	498.40	2220.48	498.40
A321	20.32	3.13	6.89	1.43	2066.97	429.37	2066.97	429.37
A330	22.28	3.30			4261.80	2792.32		
A340	20.45	4.08			2407.10	1008.95		
B757	23.28	2.20	3.73	1.01	1500.41	405.07	1500.41	405.07
B767	26.14	1.71	6.58	1.14	4085.75	708.94	0.00	0.00
B777	20.08	1.94	5.16	0.77	5960.23	884.92	0.00	0.00
RJ100	25.49	2.45	24.61	2.47	1722.56	172.80	0.00	0.00
RJ85	24.59	2.11	23.85	2.38	1669.50	166.76	0.00	0.00

Engine Operating Parameters - Moving, Arrival Taxi Operations								
Aircraft	Average N1average	Standard Dev. N1avg	Average %Thrust	Standard Dev %Thrust	Average EMS Thrust	Standard Dev EMS Thrust	Average EMS Enhanced	Standard Dev EMS Enhanced
A319	19.94	1.05	9.89	0.70	2323.04	164.33	2323.04	164.33
A320	19.62	1.38	8.70	1.32	2350.02	355.09	2350.02	355.09
A321	20.72	1.55	7.62	0.57	2284.95	169.66	2284.95	169.66
A330	23.15	2.23	6.56	4.26	4459.99	2892.61	2886.91	3742.11
A340	20.03	2.55	7.04	2.54	2862.06	555.44	1672.96	1585.15
B757	22.29	1.79	3.34	0.61	1341.46	245.01	1341.46	245.01
B767	27.17	2.13	6.65	0.89	4130.46	549.77	0.00	0.00
B777	21.53	0.45	5.48	0.31	6336.52	359.74	0.00	0.00
RJ100	23.84	6.19	22.85	6.16	1599.68	431.08	0.00	0.00
RJ85	23.44	6.67	22.55	6.63	1578.58	463.89	0.00	0.00

Note: Some A330 and A340 Departure values were erroneous in the FDR database and removed.

2.4. Accelerating Aircraft and Breakaway Thrust

A measure of the aircraft acceleration following a hold was obtained by examining flight data recorder information from a major European Airline. A full description of the analysis process may be found in Appendix E. A hold was defined as any period during which the aircraft speed (as reported by the ground speed indicator in the FDR data) was less than 1 knot. The cause of the hold (wait to cross a runway, queue hold due to traffic, hold after pushback etc…) could not be determined or catalogued. Figure 2 shows the acceleration values for all aircraft types where the acceleration "bursts" (5 and 10 second duration) display a distinctly higher longitudinal acceleration value. The corresponding Maximum % Thrust parameter for these data records is given in Figure 3. The Maximum Thrust was determined by searching through the time records during the stationary period immediately preceding the acceleration event through the acceleration event itself, and extracting the maximum value of the indicated thrust parameter. It is presumed that these particular acceleration events are due to the application of breakaway thrust and hence a significantly higher, yet shorter duration acceleration region than those other events with very low values of acceleration (less than .05 g) which tend to linger for long times. The resolution of the source FDR files used in this analysis all contained a 5 second time spacing, hence the discrete time intervals in the figures in this section.

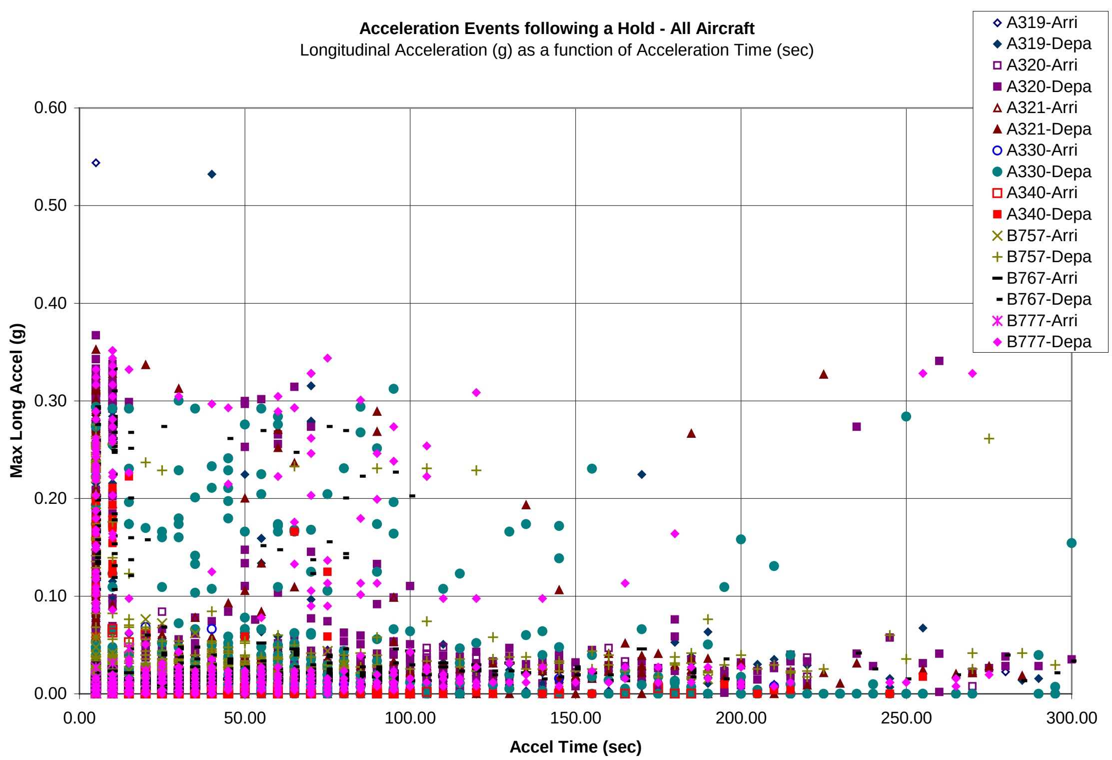

Figure 2. Acceleration events following a hold – all aircraft.

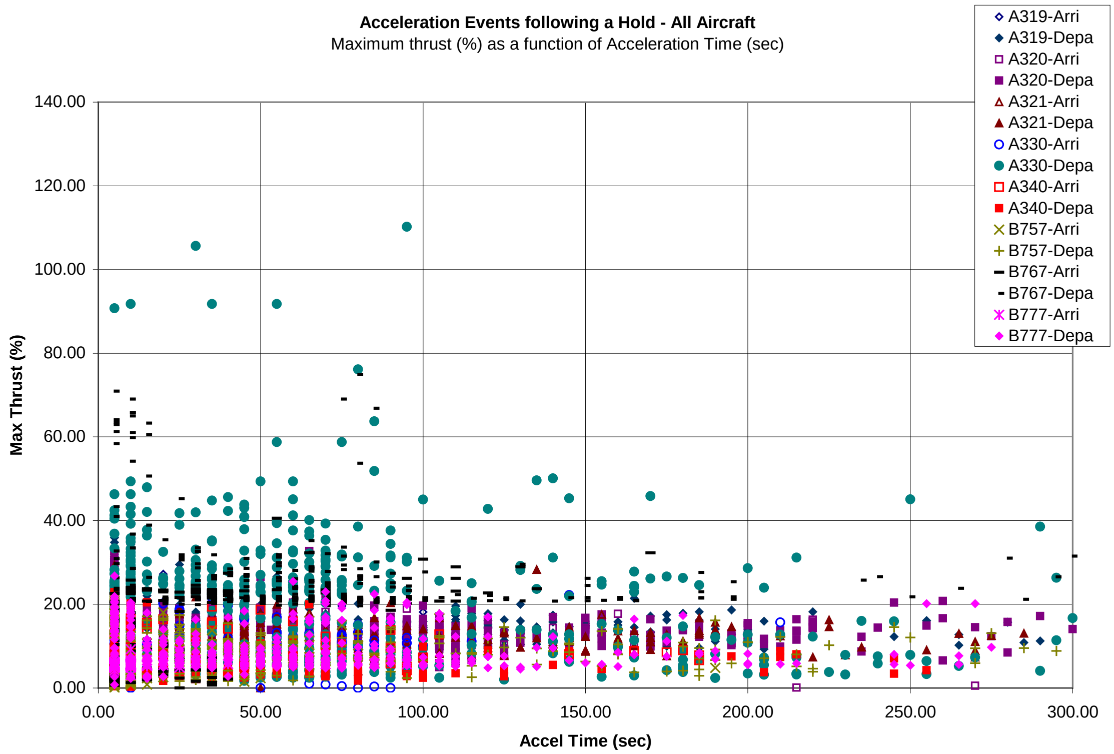

Figure 3. Thrust (% maximum) for the acceleration events following a hold – all aircraft.

The increase in thrust required to overcome static friction is referred to as breakaway thrust. During thrust measurements conducted by Wyle (see Appendices A, B and C) the following aircraft behavior was observed:

In general the commercial jet aircraft spool up their engines to a higher thrust setting and achieve a "new steady state" (as evidenced by the acoustic spectral trace) after which the pilots release the brakes and the aircraft begins moving. A short period of time later the pilots bring the engines back down to the idle setting.

For the purposes of this analysis the aforementioned behavior will be utilized but the applicability of this taxi operation generalization should be verified, possibly by conducting further interviews with pilots, performing additional acoustic measurements of breakaway thrust at other airports for a wide variety of aircraft and airlines, and by examining in more detail flight data recorder information from which engine operating state, aircraft location and speed can be reliably obtained.

The data presented in Figure 2 was filtered to capture two distinct operation types: 1) Short Bursts of acceleration (15 seconds or less) where presumably breakaway thrust is applied and 2) "Gentle" longer slower accelerations (below 0.1g) where brakes are released from which it can be inferred that minimal thrust changes are employed. Accelerations below .01g were removed from the analysis. These two groupings are in essence those events clustered near the axes as shown in Figures 4 and 5. The corresponding Thrust values are provided in Figures 6 and 7 for 'Burst" and "Gentle" accelerations respectively. More detail about the processing algorithms employed in this analysis can be found in Appendix E.

The key acceleration findings are summarized in Table 4. For these same events, the pertinent thrust parameters were obtained. Occasionally, especially for the A340 the high thrust values are possibly a failure of the flight segment separation logic and indicative of the erroneous inclusion of a rolling takeoff. Due to licensing restrictions we were not able to delve into the FDR time histories for these events and subsequently improve the algorithms, so those events were deleted from the analysis. Also during some of the events, particularly for the A330 and A340, inconsistencies between the various reported FDR thrust parameters was noted. These spurious records, present also in the 'raw' FDR dataset, were also deleted from the analysis presented here. A series of graphics with the acceleration and breakaway thrust events separated by aircraft type may be found in Appendix E.

The FDR data included the following data fields which we utilized in this analysis: N1-average-%, defined as "N1: average (all engines, percent of maximum) at start of event, units of %" and thrust-ave-percent defined as "thrust, percent of maximum at start of the event, units of %". These parameters was averaged over the duration of the identified holding event to obtain the nominal values and then the multiple events were averaged together and are therefore referred to in Table 4 and 5 as the average of the avg-%-thrust.

In summary, an examination of a comprehensive flight data recorder dataset yielded some statistical information about historical commercial aircraft application of thrust following holds. Events following a hold were categorized into burst or gentle acceleration periods whereby statistical thrust values were computed.

TABLE 4 Engine Operating Parameters for Taxiing Operations

Aircraft Type	Arri / Depa	Operation Type	Avg. Accel Time (s)	Avg. N1avg	Avg. N1Max	Avg. avg %Thrust	Avg. max %Thrust	Avg. Max Long Accel (g)	# Events
A319	A	Burst	5.00	14.88	15.58	8.01	8.50	0.29	2
A320	A	Burst	8.33	18.40	20.45	7.21	8.44	0.03	6
A321	A	Burst	7.00	18.56	18.71	6.88	6.94	0.03	5
A330	A	Burst	7.31	21.89	23.80	5.82	6.27	0.01	13
A340	A	Burst	9.50	22.77	25.88	8.07	9.69	0.03	10
B757	A	Burst	6.68	18.85	20.50	-	-	0.02	95
B767	A	Burst	8.00	26.10	27.31	4.61	11.88	0.01	25
B777	A	Burst	9.27	21.04	22.10	5.23	5.73	0.01	41
A319	D	Burst	6.63	28.24	36.07	15.61	21.24	0.20	92
A320	D	Burst	7.07	27.93	35.79	13.74	18.68	0.20	121
A321	D	Burst	6.07	28.80	35.45	12.74	16.69	0.18	61
A330	D	Burst	8.00	40.07	54.75	10.44	16.58	0.15	95
A340	D	Burst	7.50	29.52	41.41	8.57	14.04	0.14	34
B757	D	Burst	7.27	35.58	44.34	10.29	14.30	0.15	75
B767	D	Burst	8.17	41.16	57.39	14.19	28.82	0.18	71
B777	D	Burst	8.17	31.14	40.96	9.45	13.02	0.15	101

Aircraft Type	Arri / Depa	Operation Type	Avg. Accel Time (s)	Avg. N1avg	Avg. N1Max	Avg. avg %Thrust	Avg. max %Thrust	Avg. Max Long Accel (g)	# Events
A319	A	Gentle	104.41	17.85	26.12	8.71	14.17	0.02	17
A320	A	Gentle	115.47	15.32	23.89	6.64	11.30	0.03	43
A321	A	Gentle	54.76	22.08	27.72	7.89	11.41	0.03	21
A330	A	Gentle	32.20	24.32	29.84	8.76	11.49	0.02	25
A340	A	Gentle	29.44	23.28	29.09	8.50	11.40	0.02	18
B757	A	Gentle	12.41	19.70	21.94	-	-	0.02	106
B767	A	Gentle	41.84	21.94	27.73	4.55	16.35	0.02	98
B777	A	Gentle	17.50	21.19	22.66	5.24	5.89	0.01	54
A319	D	Gentle	71.53	23.07	27.90	10.87	14.49	0.02	334
A320	D	Gentle	70.02	22.46	26.77	9.42	12.22	0.03	547
A321	D	Gentle	70.63	23.39	28.18	8.22	11.53	0.03	248
A330	D	Gentle	59.65	27.27	32.93	6.46	9.18	0.02	103
A340	D	Gentle	48.94	23.38	31.10	5.22	8.68	0.03	17
B757	D	Gentle	67.99	27.38	33.84	5.14	8.95	0.04	296
B767	D	Gentle	74.26	27.64	29.86	6.84	22.62	0.02	291
B777	D	Gentle	68.46	22.89	25.80	5.98	7.16	0.02	343

Note: Some B757 %Thrust values were erroneous in the FDR database and removed.

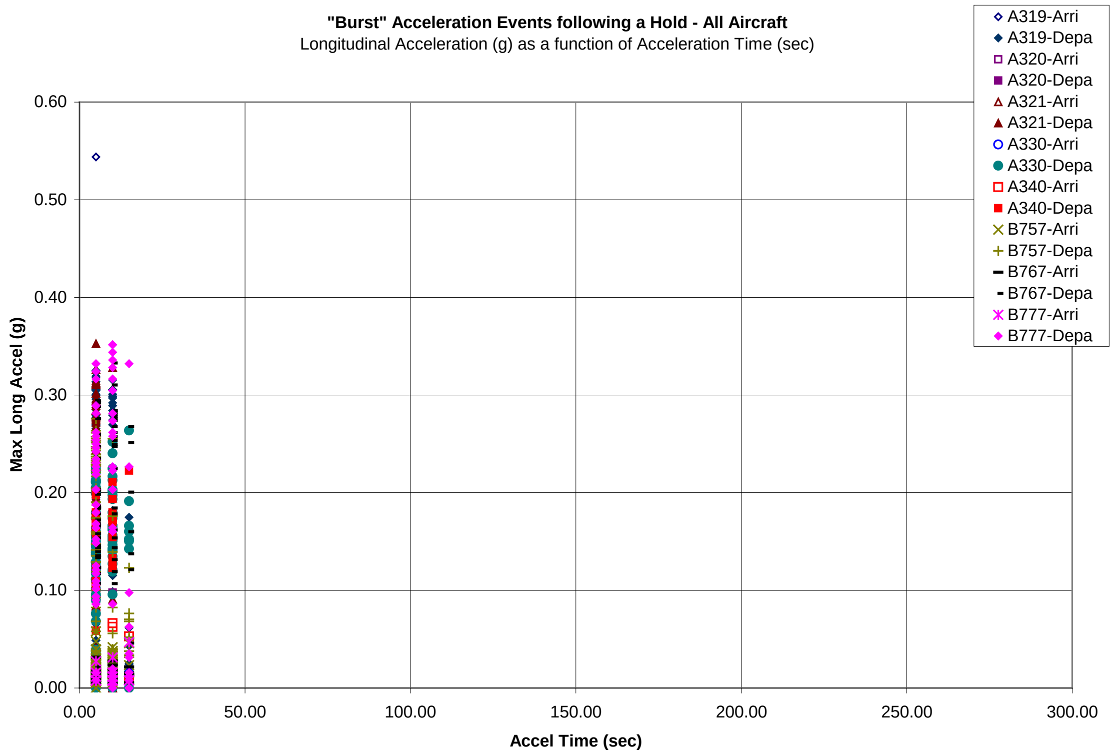

Figure 4. "Burst" acceleration events following a hold – all aircraft.

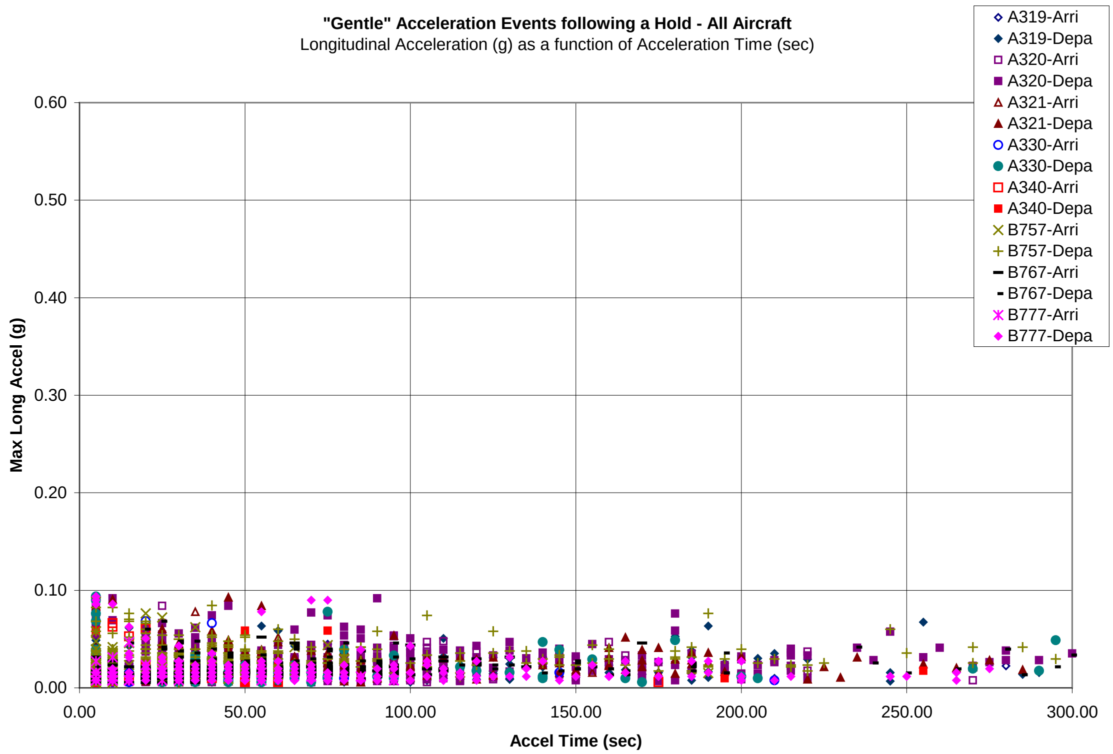

Figure 5. "Gentle" acceleration events following a hold – all aircraft.

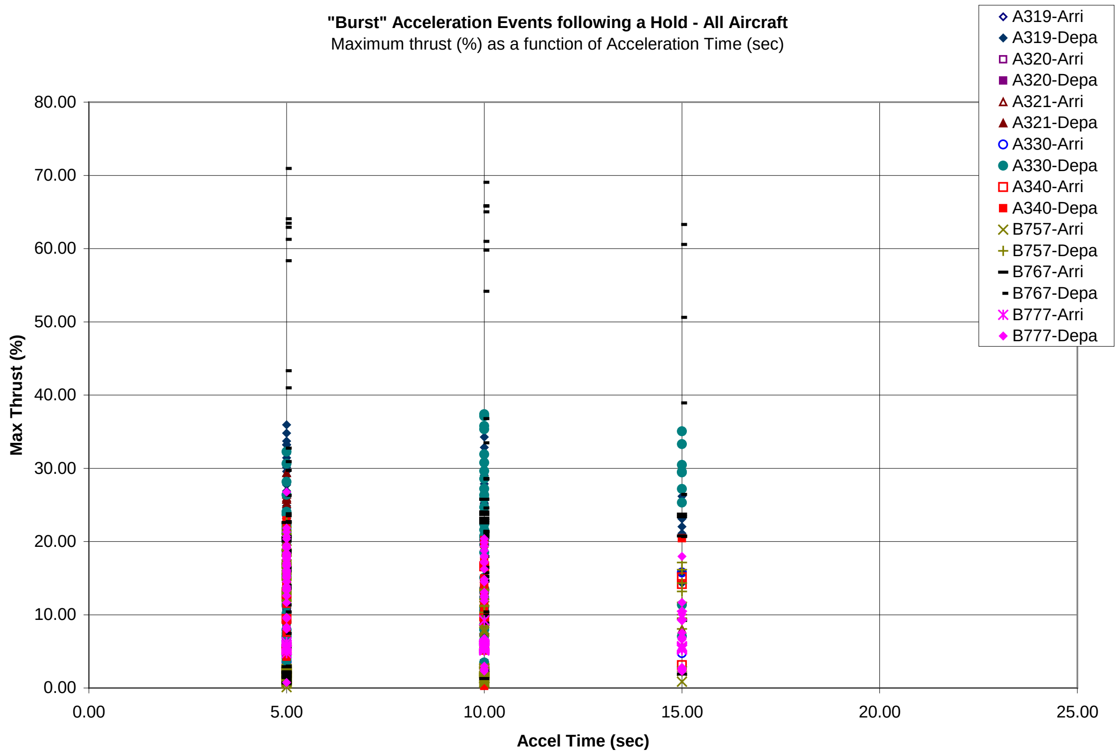

Figure 6. "Burst" acceleration event thrust (% maximum) following a hold – all aircraft.

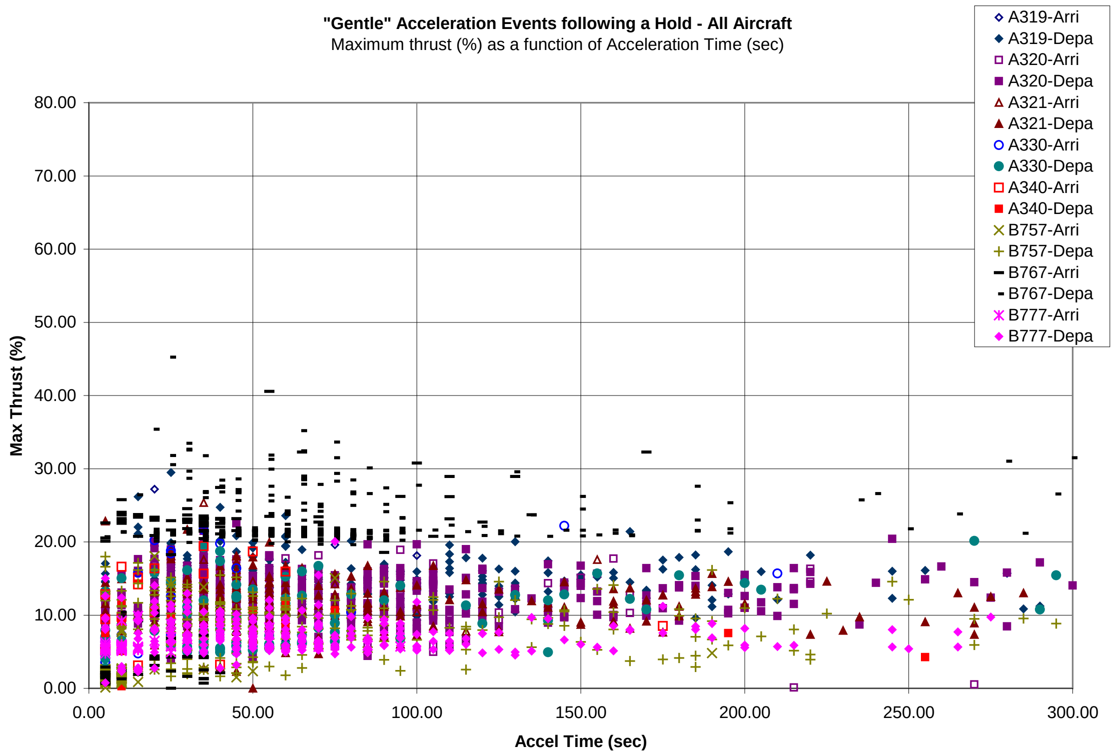

Figure 7. "Gentle" acceleration event thrust (% maximum) following a hold – all aircraft.

2.5. CAEP Alternative Emissions Methodology

For taxi noise assessments, one critical question is that of the engine thrust setting during idle and taxi conditions. Consistency in future analyses using AEDT for both noise and emissions would dictate the use of a common dataset describing the aircraft operations.

In Air Quality assessments, 7% of full rated power from the ICAO certification procedures is currently used to model the idle and taxi power setting for aircraft operations. In 2006, the Committee on Aviation Environmental Protection (CAEP) Alternative Emissions Methodology Task Group presented results from a number of surveys of power settings used during normal taxi operations (*18*).

Across a wide range of commercial aircraft, an analysis of fuel flows determined that the actual thrust levels used were approximately 5% to 6% of the maximum rated engine output with some Rolls Royce engines being operated in the 3% to 5% range.

The recommendation from the study (*18*) which is under consideration by Working Group 3 is to modify the current ICAO standard of utilizing a nominal 7% thrust (*14*) to instead utilize fuel flow for emission assessments, or in situations where actual fuel flows are not available to instead use 5% of the ICAO Databank Rated Output thrust level. Based on the emissions certification specifications %Foo is the ICAO "Rated Output" at sea level static conditions.

Figure 8, from reference (*18*), summarizes the taxi and idle power data measured during several projects executed at London's Heathrow and Gatwick airports (*19*, *20*, *21*). In addition to assessing idle settings, the studies identified the breakaway thrust level used in practice by some aircraft.

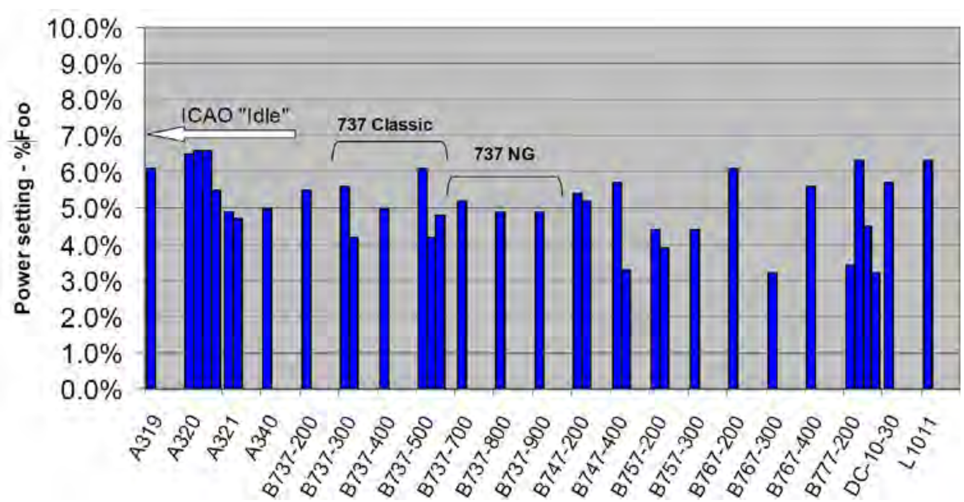

Figure 8. Recorded idle / taxi settings for a number of aircraft and air carriers (*18*).

Figures 9, 10 and 11, also from reference (*18*), indicate the sensitivity of breakaway thrust for the B747-400 (RB211), the B777-236 (GE90-76B) and the B777IGW-236 (GE90-76B) to aircraft mass, expressed as a percentage of maximum takeoff mass. Breakaway thrust values were not reported for other aircraft (*18*).

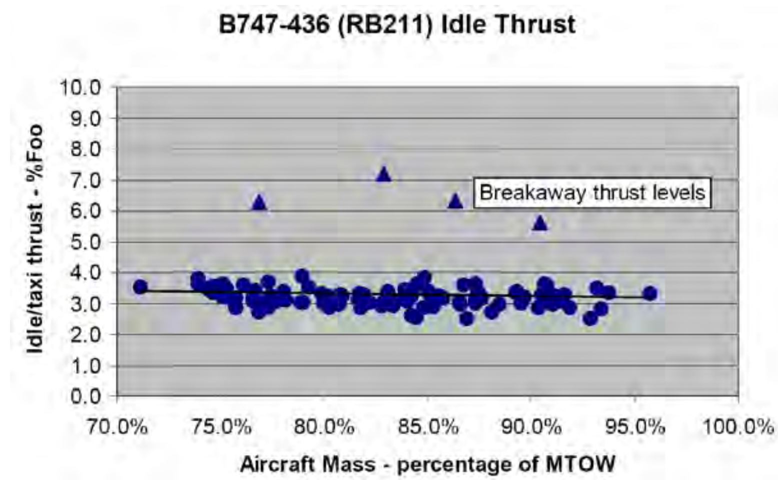

Figure 9. Recorded idle settings for the B747-400 as a function of % TOGW (18).

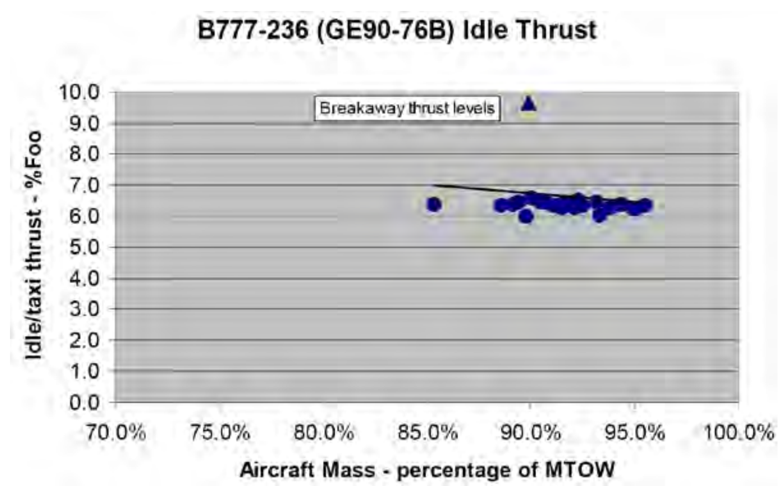

Figure 10. Recorded idle settings for the B777-236 (GE90-76B) as a function of % TOGW (18).

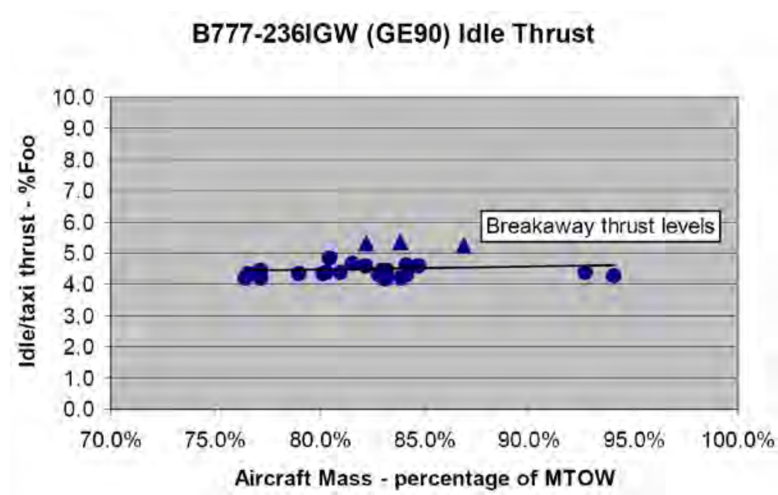

Figure 11. Recorded idle settings for the B777-236IGW (GE90-76B) as a function of % TOGW (18).

Additionally, some information was provided about the variation due to taxiing with less than all engines operating (*18*). This indicated that for most aircraft types an increase in thrust was required to perform the taxi operation (Figure 12) with active engines on twin engine aircraft requiring greater thrust increases than those with four engines.

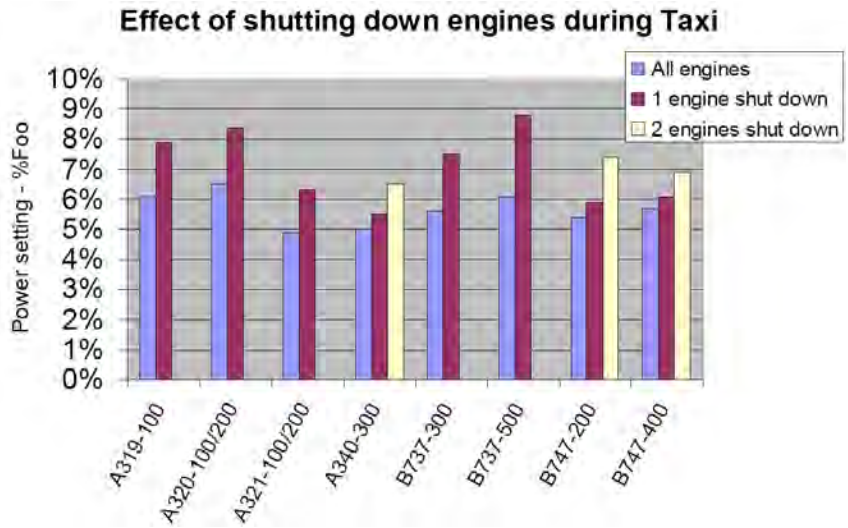

Figure 12. Recorded power settings for the taxi with fewer than all engines operating.

In summary, an examination of a recent CAEP working group study (*18*) provided some additional generalized engine operating state parameters for a range of commercial aircraft types, specifically empirical taxi engine settings, breakaway thrust for a limited number of aircraft and the impact of shutting down engines during taxi operations on the remaining operating engine state.

2.6. Relative Contributions of Ground Operations and Flight Noise

The scope of the current study is to propose approaches for modeling taxi noise, not to determine whether or not taxi noise should be modeled within the context of flight operation noise. It is not appropriate to make a blanket conclusion on the importance of taxi modeling relative to flight operation modeling because such judgments depend heavily on the specific situation. However, it was requested that we include a realistic example of the relative contributions between a consistent set of ground and flight operations. We leave it to the readers to draw their own conclusion as to the relative importance. Figure 13 presents the results of a Dicerno™ noise analysis which modeled taxi, APU and flight operation noise based on acoustic simulation predictions for taxi, auxiliary power units, ground power units and ground support equipment along with flight noise. Figure 14 itemizes the number and type of operations modeled in this particular study. The ground operations are consistent and represent a geometric distribution and duration required to support the cited number of flight operations.

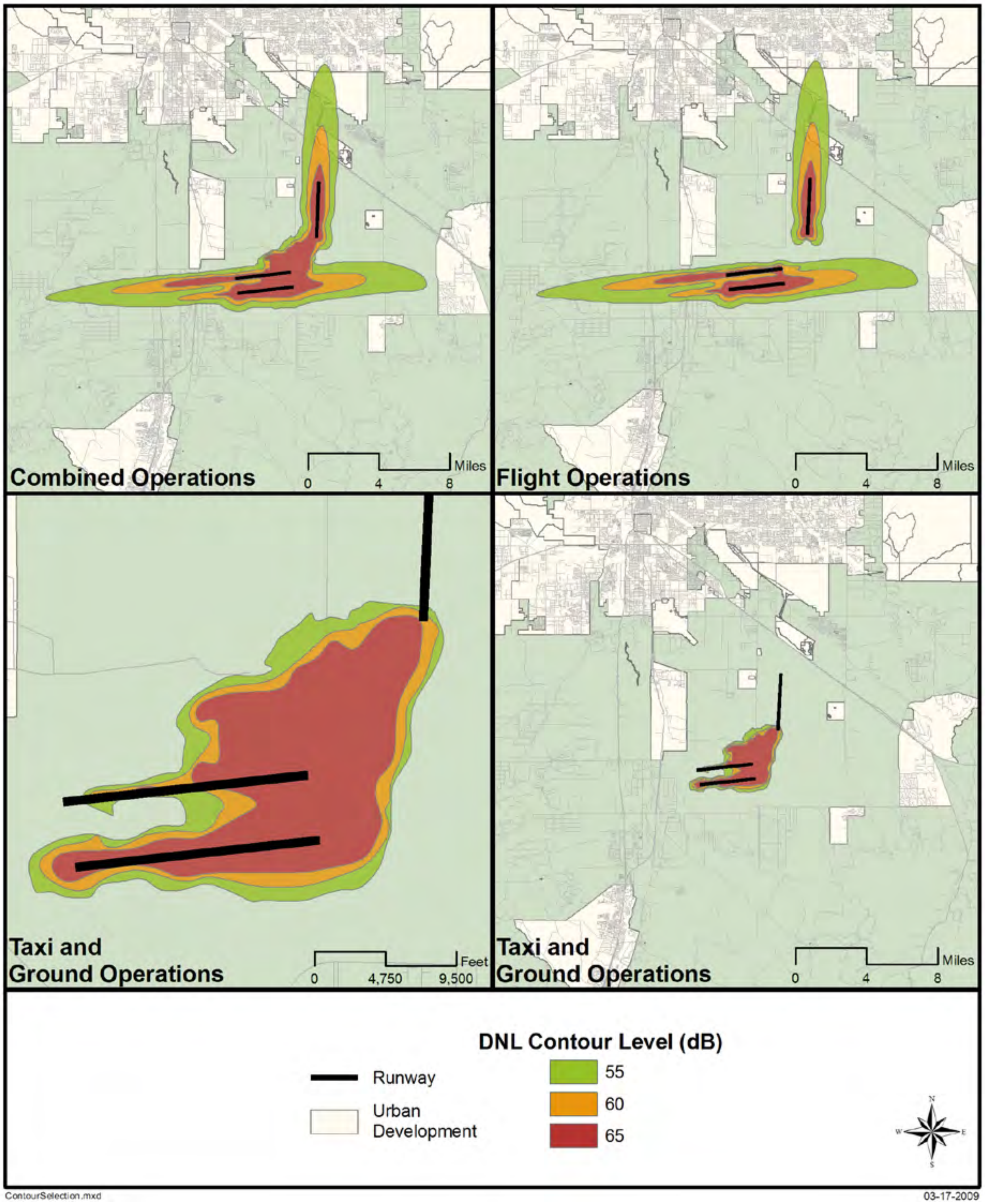

Figure 13. Ground operations and flight operations compared and combined.

INM Aircraft Type	Annual Operations					
	Departures			Arrivals		
	Day (7 am - 11 pm)	Night (11 pm - 7 am)	Total	Day (7 am - 11 pm)	Night (11 pm - 7 am)	Total
B737-700	39,642	4,557	44,199	40,098	5,012	45,110
B747-400	1,376	3,734	5,110	4,717	2,752	7,469
B767-300	10,819	6,642	17,461	10,498	4,150	14,648
B767-400	8,885	228	9,113	8,430	1,595	10,025
B777-200	2,506	1,595	4,101	3,190	683	3,873
B777-300	1,367	228	1,595	1,367	228	1,595
A319	25,289	2,734	28,023	26,884	2,734	29,618
A320	38,959	6,835	45,794	38,275	5,240	43,515
A330	10,708	1,595	12,303	10,024	2,050	12,074
A340	12,986	2,962	15,948	13,442	2,278	15,720
EMB145	116,420	19,593	136,013	114,370	18,682	133,052
EMB14L	38,731	4,784	43,515	40,326	6,151	46,477
Grand Total	**307,688**	**55,487**	**363,175**	**311,621**	**51,555**	**363,176**

Figure 14. Modeled flight operations.

In summary, the relative contribution of taxi noise with flight operation noise can be seen in the DNL contours under typical commercial airport situations. The degree of importance ground operations has on the overall noise environment at an airport is site specific and subject to interpretation.

2.7. Environmental Factors: Terrain, Buildings, Ground Cover

Airports and the surrounding communities are often urban in nature and frequently contain high-rise buildings in addition to terminals, hangers and other forms of acoustic shielding on or adjacent to airport property. The geometric proximity of these features, specifically if they block the line of sight between a taxiing aircraft and a receptor, can have a significant impact on the noise contours. Ground cover also impacts sound propagation. Water is considered an acoustically hard surface and sound traveling over bodies of water does not attenuate as rapidly as sound traveling over grassy or forested terrain. Due to the wide variety of site specific conditions it is not be possible to draw a firm conclusion to always or never include building shielding or ground cover in taxi noise analysis. Some examples of propagation effects considering environmental factors such as buildings and ground cover are described in this section.

An acoustic simulation study was performed using NMSim for a series of annual commercial flight operations at an International airport taking into account the effect of building shielding on sound propagation. While this study modeled only flight operations, they did include the on-runway portion of the operations. The geometric arrangement of the airport is such that the predominant impact to the contours on either side of the runways is from aircraft directly on the runway or at an altitude below the height of the nearby buildings. The noise modeling shown here utilizes a simple Maekawa shielding (line of sight blockage) model and with buildings modeled as a series of thin screens, as is supported by this theory. Figures 15 and 16 contrast the CNEL noise contours from all operations both without and with the building effects included. All annual operations are included in this comparison and building outlines modeled are drawn in yellow. Figures 17 and 18 contrast the CNEL noise contours from only the top 10 contributors for analyses with and without building effects included. A time sequence of still images from a single arriving flight is shown in Figure 19.

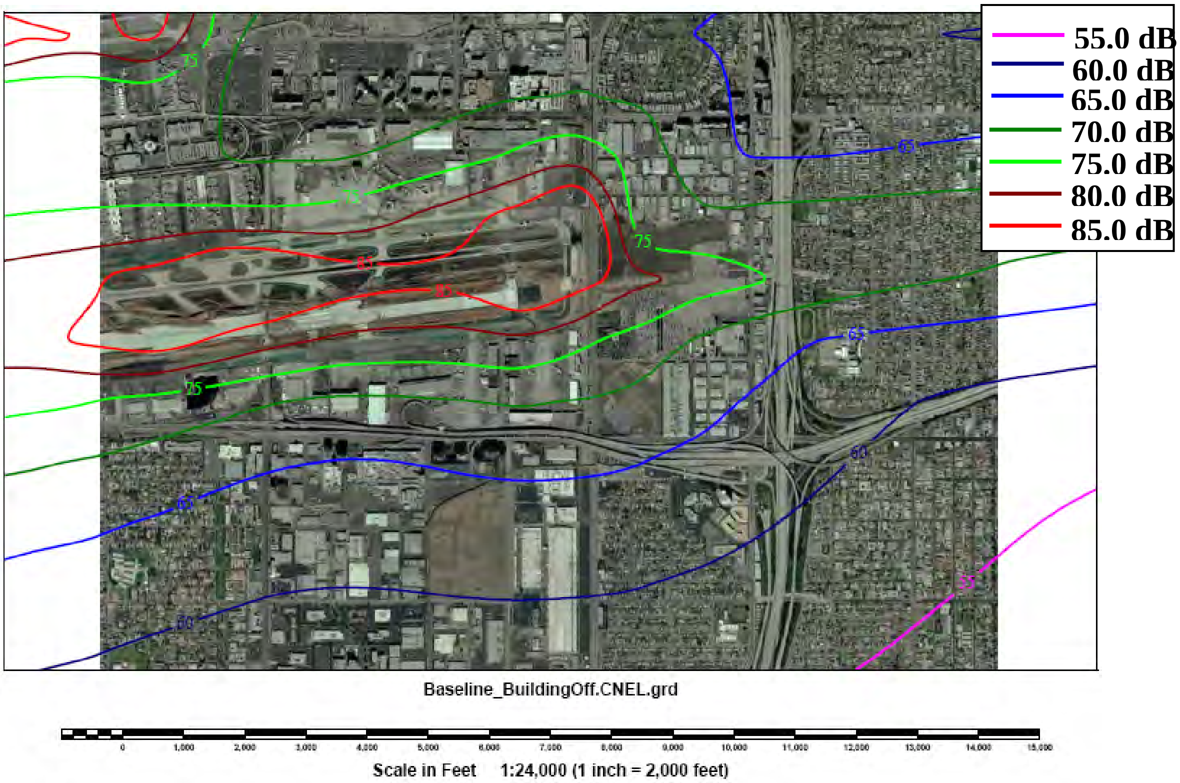

Figure 15. Flight operations, no building shielding.

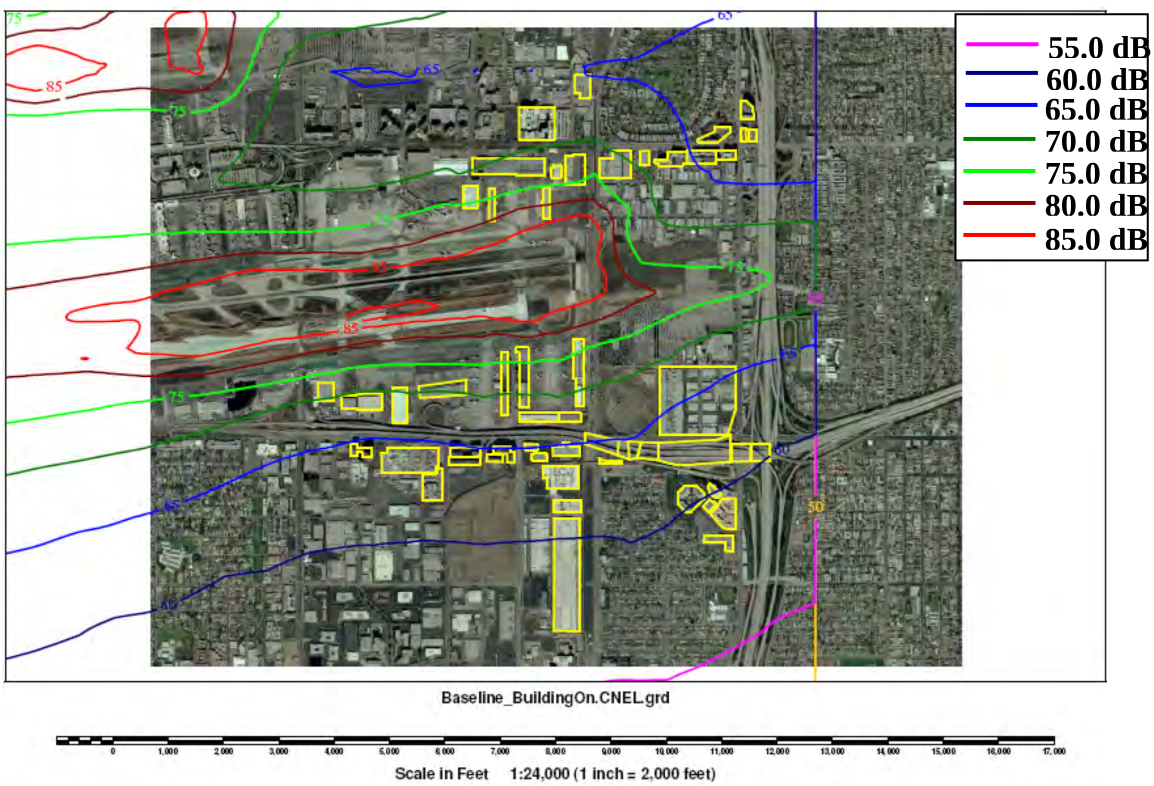

Figure 16. Flight operations, with building shielding.

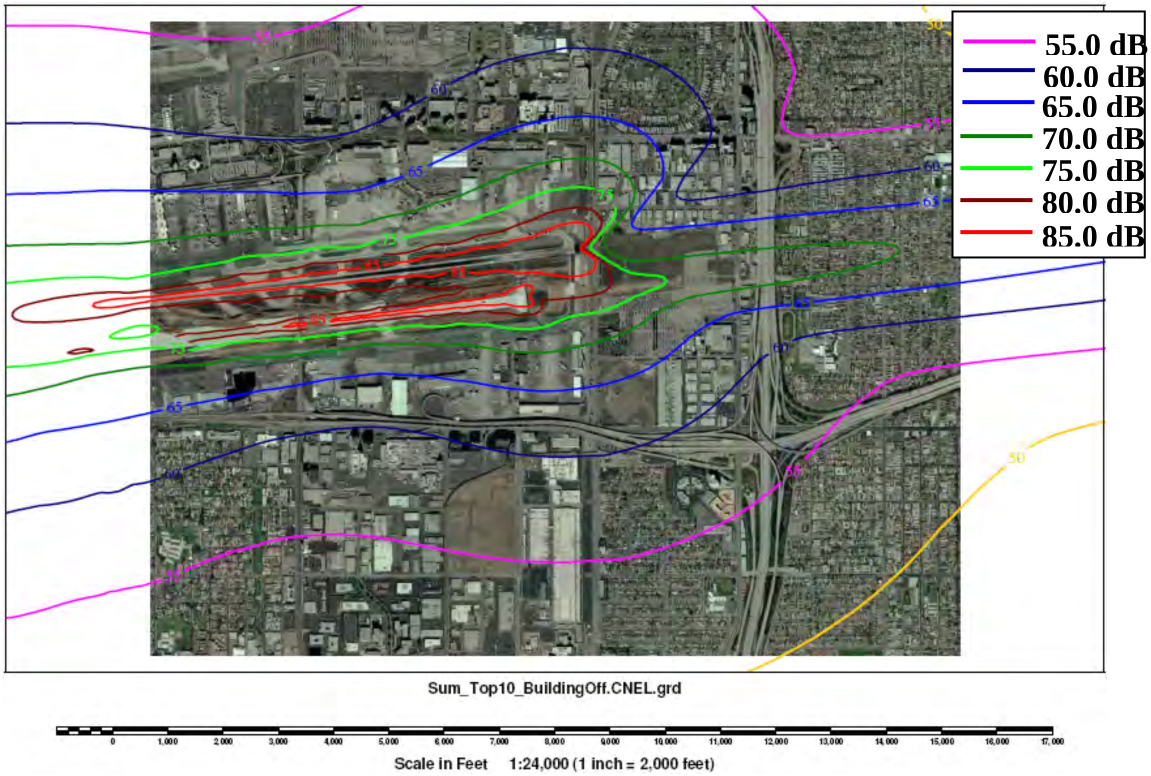

Figure 17. Flight operations, no building shielding, top 10 contributors.

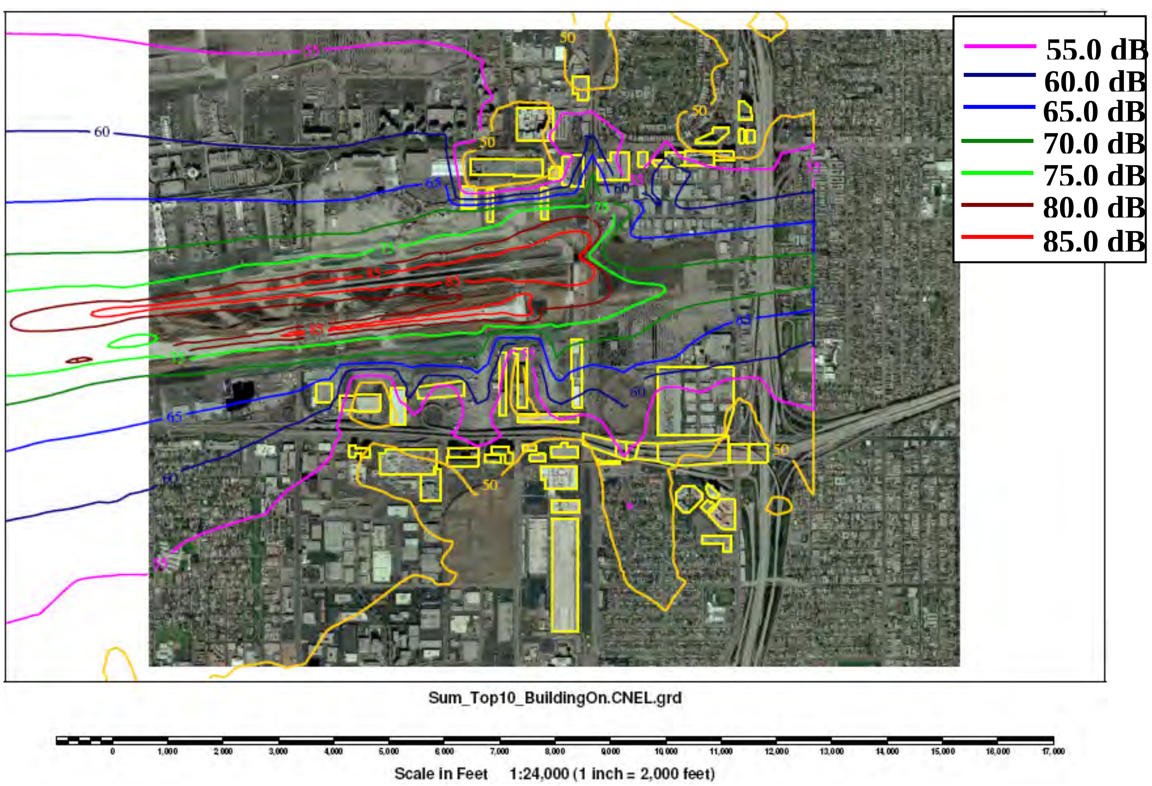

Figure 18. Flight operations, with building shielding, top 10 contributors.

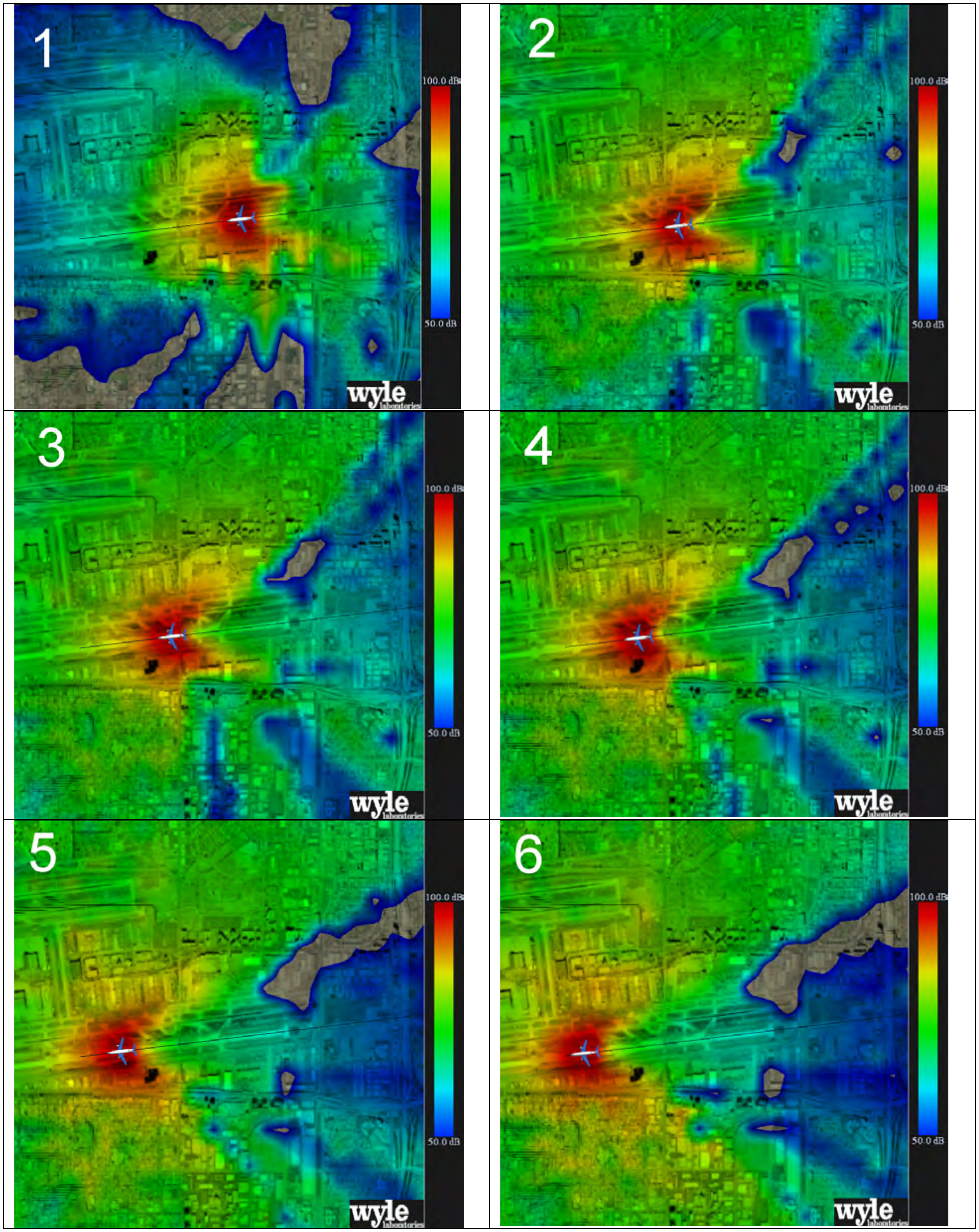

Figure 19. Series of acoustic simulation SEL (dB) contours with building shielding for a single approach operation at different times.

A measurement project was conducted in 2004 for the US Navy (*22*) in order to assess the effects of aircraft sound propagation over water. Measurements of 349 commercial aircraft departure operations at Ronald Reagan Washington National Airport & Bolling Air Force Base were obtained for elevation angles from 4^{o} – 6^{o}. PASSEUR Radar data for flight tracks and profiles were obtained for the measurement period. A list of the acoustic events and range of aircraft types is given in Table 5. A DC reference acoustic measurement SEL was used to determine vehicle Thrust setting. Figure 20 shows the geometric layout of the runway, flight track, Potomac River and microphone positions.

The primary objective of the study was to experimentally determine suitable ground impedance parameters for representing the surface of the water as an acoustically hard surface using the DoD Integrated model; NOISEMAP 7. NOISEMAP 7 and INM are similar in that they are both integrated noise models, however INM contains source lateral directivity adjustments while NOISEMAP does not. Additionally, NOISEMAP has the capability to propagate over acoustically hard or soft terrain. It is the predicted changes between propagation over ground and water which illustrate a nominal 2 dB effect of ground impedance on sound propagation for sources at low elevation angles (Table 6).

In this study, the recorded SEL at the microphone on the airport side of the river was used to determine the source conditions (thrust) of the departing aircraft. The radar data provided the aircraft's airborne trajectory while a video system recorded the aircraft rotation and liftoff. The results presented in Table 6 illustrate the predicted propagation effects over water. Here the lateral source characteristics for aircraft with wing and tail mounted engines were adjusted from the original study based on the INM lateral directivity difference. Aircraft with fuselage mounted engines are 1.5 dB quieter in the plane of the wing than aircraft with wing mounted engines. One can see in Table 6 that the over water propagation accounts for approximately a 2 dB increase in SEL compared with propagation over acoustically soft ground for the geometric arrangement at DCA and for this particular group of operations.

TABLE 5 Measured Aircraft Events

ICAO ID (Radar Data)	Modeled Aircraft Type	Modeled Engine Type	Engine Location	INM Rotation Airspeed (knts)
A319	A319	V2522	Wing	141
A320	A320	CFM56-5A-1	Wing	149
B733	B-737-300 B2	CFM56-3B-2	Wing	152
B734	B-737-400	CFM56-3C-1	Wing	160
B735	B-737-500	CFM56-3B-1	Wing	151
B737	B-737-400	CFM56-3C-1	Wing	146
B738	B-737-400	CFM56-3C-1	Wing	161
B752	B-757-200-PW	PW2037	Wing	142
CRJ1	CL-601	TF CF34-3A	Tail	164
CRJ2	CL-601	TF CF34-3A	Tail	164
DC93	DC-9-30QN9 (Q)	JT 8D(AC-LINED)	Tail	146
E135	CL-600	TF ALF502L	Tail	164
E145	E145	AE3007	Tail	125
F100	F10065	TAY 650-15	Tail	146
MD80	MD-81	JT 8D-209/217	Tail	146

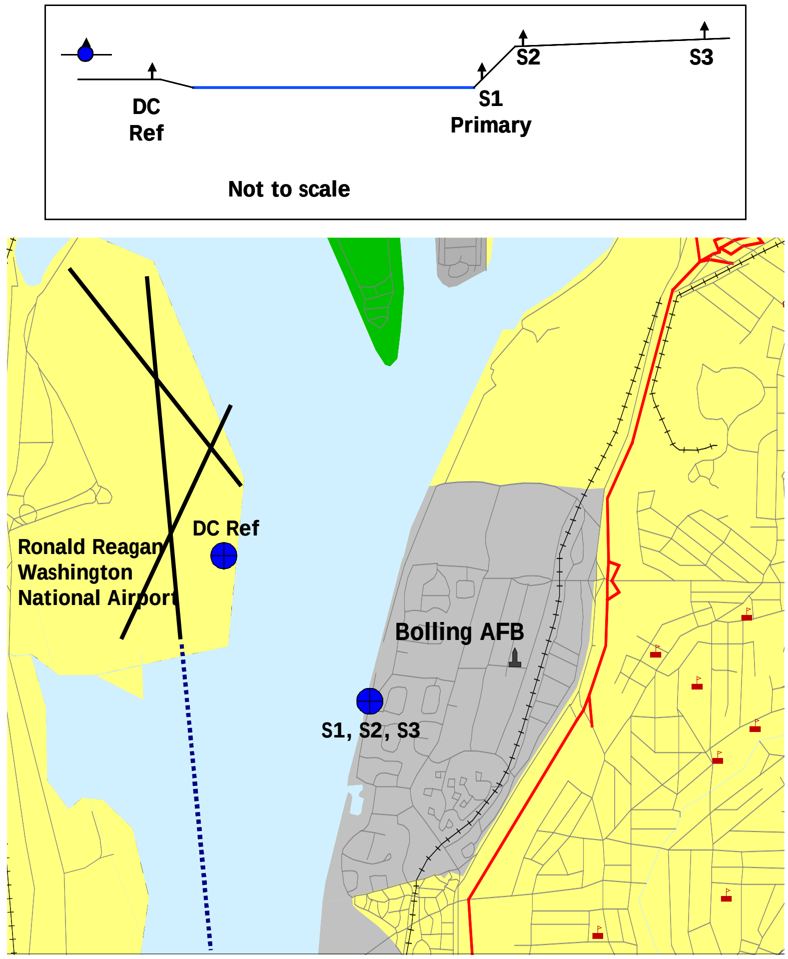

Figure 20. Over water propagation measurement configuration.

TABLE 6 Predicted Differences in SEL over Ground and Water for all Flight Operations

(Predictions modified based on INM source lateral directivity for Wing / Fuselage Engines)

Measured SEL – Calculated Over Water SEL (Predictions exactly match Reference SEL)			**Over Water Pred. SEL – Over Ground Pred. SEL (dB)** (Consistent Set of Operations with different ground characteristics)		
Site S1	**Site S2**	**Site S3**	**Site S1**	**Site S2**	**Site S3**
-0.8 ± 0.3 dB	-1.2 ± 0.3 dB	-2.15 ± 0.3 dB	-2.2 ± 0.3 dB	-2.0 ± 0.3 dB	-1.5 ± 0.3 dB

In summary, the impacts of shielding due to buildings and terrain and propagation over hard and soft ground (such as would be encountered at an airport adjacent to a body of water) are apparent in the noise contours. However, due to the wide variety of site specific conditions it is not be possible to draw a firm conclusion to always or never include these effects for taxi noise analysis.

CHAPTER 3. MEASURED AIRCRAFT TAXIING SOURCE NOISE CHARACTERISTICS

This Chapter summarizes the available measured aircraft taxi and static noise data. A blend of acoustic measurements of varying fidelity, complexity and breadth will be examined and pertinent acoustic signature data will be summarized. This measurement data is vital for guiding development of a realistic taxi noise modeling techniques and for determining viable low thrust NPD data for use within the framework of INM7. Where possible, data from the multitude of sources have been compared to one another. The spectral data presented here are normalized to 70dB at 1000 Hz, as are the spectral classes in INM.

3.1. Taxi / Idle Condition Measurement Data Sources

3.1.1. T. F. Green State Airport (PVD) Taxi Measurement Data

Aircraft taxiway noise was measured at T. F. Green State Airport (PVD) on March 24, 2008. Taxiway noise, SEL (dBA) for 7 aircraft operations, ranging from a small propeller aircraft to 737-700s was measured as the aircraft passed by the microphone setup (Table 7). Details of the T. F. Green measurements may be found in Appendix B. Run up Measurements made at T.F. Green previously are also cited below.

TABLE 7 Summary of TF Green Noise Taxi Events

Aircraft	Carrier	Plane Type	Speed (knots)	Time Start	Time Stop	dt	SEL	notes
1	-	small prop	-	11:01:39	11:02:31	52	68.6	did not have camera
2	Continental Express	Regional Jet	-	11:05:58	11:06:47	49	83.6	did not have camera, either a ERJ-145, ERJ-135 or CRJ200LR
3	Southwest	737-700	22.79	12:23:16	12:24:37	81	91.8	
4	US Airways Express	Embraer 170	17.82	12:35:56	12:37:14	78	93.4	
5	Southwest	737-700	19.37	13:10:53	13:12:07	74	88	
6	US Airways Express	Embraer 170	11.79	13:34:41	13:35:50	69	90.6	
7	Continental Express	Embraer ERJ-145	12.17	13:38:27	13:40:02	95	88.9	
Sound level meter placed 71.57 meters from centerline of taxiway								
Ambient levels around 45 dB: noise from other planes at gates								

3.1.2. Milwaukee Airport (MKE) Static Run up Noise Measurement Data

A limited amount of run up measurement data was obtained at Milwaukee Airport (*23*) from static run up measurements of a DC-9 at idle conditions, made along two radials situated approximately 40^o and 135^o off the nose of the aircraft (Table 8). Details of the Milwaukee Measurement Program may be found in reference (*23*).

TABLE 8 DC-9 Run up Measurements at T. F. Green Airport

D(ft)	Angle(deg)	Free Field (dBA)	Lmax - Avg
3161	40	61.3	53
2525	40	64.25	55.5
925	40	78.1	72
500	40	86.3	86
2846	135	73.6	76.5
1775	135	79.05	88.5
886	135	87	94.5
500	135	93.7	98.5

3.1.3. Ronald Reagan Washington National (DCA) Taxi Measurement Data

Aircraft taxiway noise was measured at Ronald Reagan National Airport (DCA) on June 30, and July 3, 2008. Sound level meters and a video system were deployed in order to obtain noise levels, aircraft speed, and positional information. Accessible measurement locations were selected in conjunction with airport operations personnel based on the prevailing weather conditions and active runway configuration. On June 30 and July 3, 2008, Wyle measured the taxiway noise of 47 and 35 aircraft operations, respectively, ranging from regional jets to 737-700s.

A total of 47 taxiway pass-by events were measured on 30 June 2008. From that dataset 20 were found to be free of extraneous noise such as arriving or departing operations. All events were arrivals taxiing from the runway to the terminal. From these measurements we were able to obtain directivity information.

Subsequent measurements were made on 3 July 2008 to measure taxiway and holding block idle and acceleration noise. . From that dataset 16 were found to be free of extraneous noise such as arriving or departing operations. Unfortunately due to the amount of traffic during this measurement period, we were unable to obtain data from a single aircraft accelerating from a stop. There were only three brief times when only one aircraft was in the holding block. This measurement dataset will be useful for validation of a future taxiway model, however at present due to a commingling of noise events with various aircraft in the holding block at the same time, the data could not be used directly to extract a single noise event.

Measurements of MD-88s were made covering a speed range from 8 to 23 knots and normalized to 150 ft. Radius. The data indicates no apparent speed sensitivity in the taxiing noise (Figure 21). It was noted that B737s and A319s all had CFM56 engines and resulted in similar directivity curves (Figure 22). The general trend for all engines, including the regional jets (Figure 23) indicates a significant high frequency (3 kHz) content at 30^o directivity (measured from the nose of the aircraft), and higher noise levels from the inlet (30^o) than from the exhaust (120^o).

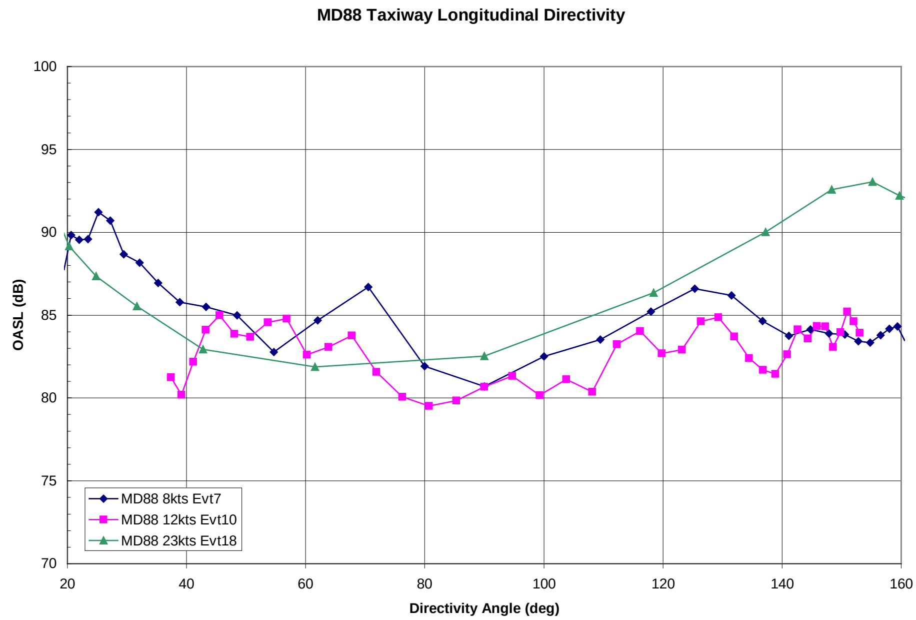

Figure 21. MD88 longitudinal directivity for 8 – 23 knot taxiing speeds.

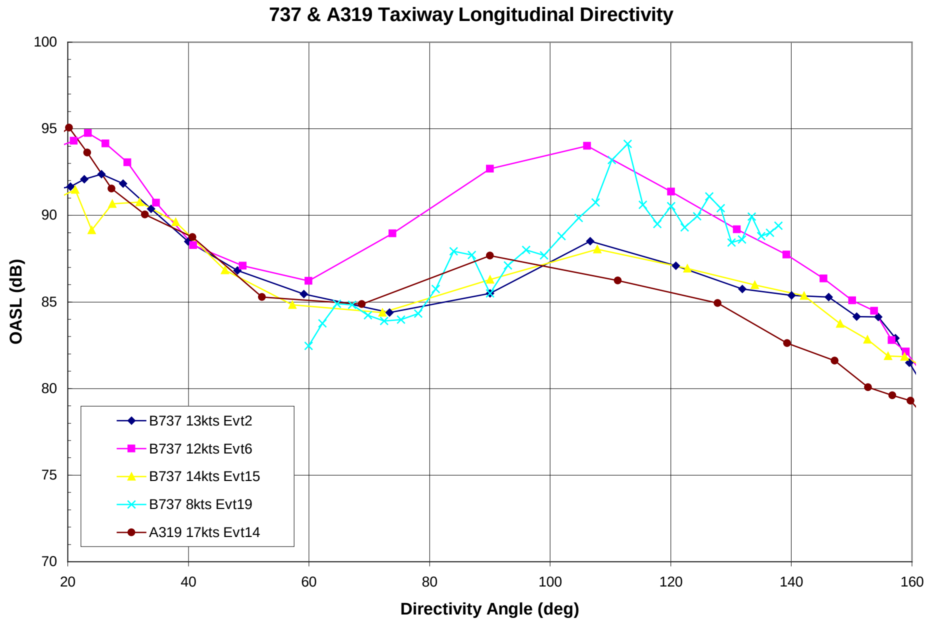

Figure 22. B737 and A319 directivity normalized to 150 ft radius.

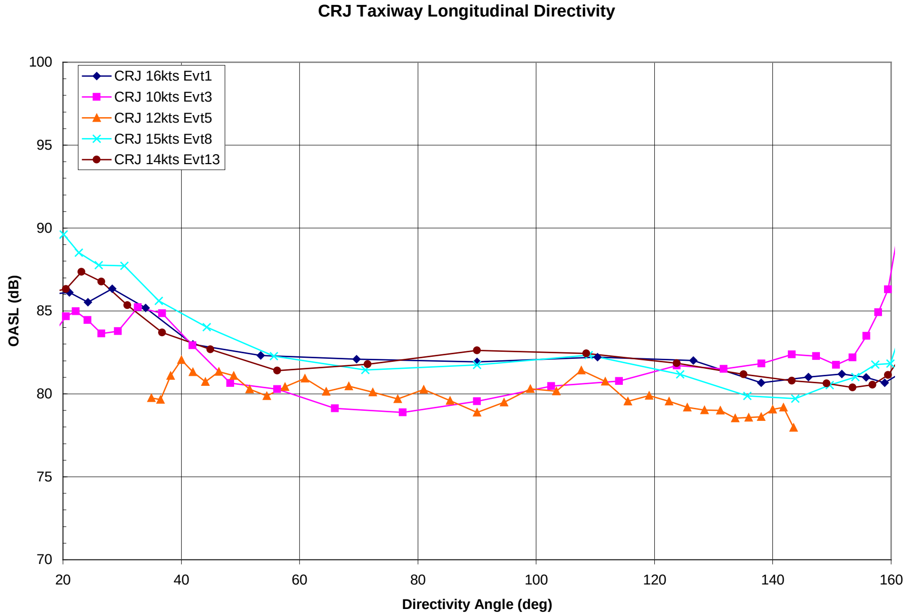

Figure 23. CRJ directivity normalized to 150 ft radius.

3.1.4. Static Engine Idle Data

Pratt and Whitney provided spectral directivity data for three engines covering a range of nominal thrusts: 20,000 lbs to 100,000 lbs. Engine 1 is near the low end, engine 2 is about the middle, and engine 3 is near the top end of the thrust range. The data is sea level static, free field, acoustic standard day conditions at 150 ft radius on a polar arc from 5 degrees off the inlet to 160^{o} off the inlet. Data was obtained from a static test stand with an inlet control device in place provides data with ‘clean’ flow entering into the engine inlet. The inlet control device is designed to minimize the distortion of the air stream and avoid entrainment of ground plane vortices, atmospheric turbulence, and vorticity caused by flow over the test stand structure. These devices have been optimized to provide a simulated in-flight environment.

There are some tones present in the dataset provided by Pratt and Whitney. It is the opinion of the engine manufacturer that these tones are quite high in amplitude relative to other engine sources and "unstable." That is, they are generally not repeatable if the points are acquired again later on. Also it is possible to encounter non-rotor related tones in the spectra at these low power conditions.

SAE has provided an Aerospace Information Report documenting methods for controlling distortion of inlet airflow during static testing (*24*). The effectiveness of ICD conditioning on entrained airflow has been demonstrated to eliminate the majority of blade pressure fluctuations on inboard compressor stations. Towards the tips of the blades there are still differences between in flight and static test + ICD data. These variations are on the order of 3-7 dB and span the entire frequency range with slightly more variation at the lower frequencies (below 3000 Hz). Given the boundary layer along the inner edge of the inlet, one would expect that a certain amount of radiated noise from fluctuating blade pressures to be present under all operating conditions, on the ground, with or without an ICD, or while in flight.

To use the test stand data for estimating taxiing noise levels it is necessary apply a correction from the SAE AIR to account for the acoustic difference between clean (ICD) and distorted (no ICD) airflow. One would therefore expect that engine measurements for taxi operations to be about 3 to 7 dB higher than ICD measurements, with a 3 dB difference above 6 kHz and a 7 dB difference below 3 kHz. The spectra of ground effect taxi operations due to ground vortex ingestion can be quite different from the flight idle spectra or engine test stand spectra obtained when using an inlet control device. Unfortunately data comparing back to back measurements with and without an ICD were not available.

3.1.5. Madrid Taxi Measurement Data

A comprehensive measurement program at Madrid-Barajas Airport, Spain (*25*, *26*), was conducted by the Universidad Politenica de Madrid obtaining a significant amount of measurement engine taxi noise data. This published dataset is based on in-situ measurements of 240 taxi events at nominal taxi speed, representing a wide variety of aircraft, listed in Table 9.

TABLE 9 Aircraft Measured at Madrid-Barajas Airport under Taxiing Conditions

A310-300	B717	MD-82	ATR-72-500
A-319	B737A (-300, -400, -500)	MD-83	CFJ
A-320	B737B (-600, -700, -800)	MD-87	DHC8Q3
A-321	B747	MD-88	Fokker 50
A-340-300	B757-200		
	B767		

Measurements were obtained in the form of 1 second time histories at five locations along taxiway. From these measurements sound power was determined according to ISO 3740 and ISO 9613. Data obtained includes a nominal spectra and directivity for each engine class in units of sound power level based on ISO 3740 based method.

Key findings in this report are:

- Overall sound power level by aircraft (AC) family (type);
- Spectral directivity of various jet AC families;
- Low (<200 Hz), mid (200-1250 Hz), and high (>1250 Hz) frequency directivity for propeller AC;
- Propeller AC demonstrate similar directivity irrespective of aircraft type;
- Jet AC demonstrate different directivity depending on aircraft type (engine config., size, etc.);
- Determined line source sound power level spectra (63-8k Hz) for studied taxiway;
- Most AC moved at constant speed of about 8-12 m/s (18-27 mph, 26-39 ft/s, 15-23 knots); and
- Average speed was 10.2 m/s (23 mph, 33 ft/s, 19.8 knots).

3.1.6. IAD Directivity and Breakaway Thrust Measurement Data

A characterization of breakaway thrust from taxiing aircraft noise was successfully made based on measurements conducted at Washington Dulles International Airport (IAD). This type of event occurs when certain aircraft, often very large jets, increase engine power in order to overcome static friction and begin to roll. Breakaway thrust has been determined to be apparent and distinguishable from normal taxi noise through measurement and analysis. For an Airbus A320-232 and a Boeing B757-222 breakaway thrust noise has been quantified from a stop-and-go taxi operation for each vehicle as they stopped to wait for a plane in front of them to take off. The microphone used for analysis was located at a directivity angle of 50° as measured off the nose of the aircraft.

The A320-232 was found to exhibit an increase of un-weighted overall sound pressure level of 4 dB over the course of 10 seconds. The static aircraft spooled up its engines from idle power to begin roll, maintained an increased thrust level for 10 seconds, then spooled-down its engines while rolling to the runway.

The B757-222 had an A-weighted increase of 7 dB, and maneuvered slightly differently from the A320 in that the increased thrust was only maintained for 1 second. However, the spool-down behavior of these particular engines may lend itself to require less time of maintained increased thrust. This is evident in the B757 spectrogram by the gentle spectral slow down.

In summary, measurements were conducted to acquire noise source levels of taxiing aircraft. The report reviewed other taxi source noise databases and identified a considerable variation between measured values. Static engine idle data was evaluated and the use of an ICD to simulate in-flight conditions precludes the adoption of such low thrust acoustic data for taxiing aircraft. Insufficient information about the particular taxi operation (specifically lack of engine operating state data) prevented the identification and quantification of plausible explanations for these discrepancies between datasets. It also precluded an empirical based determination of acoustic – thrust sensitivity. This is one of the key findings of this analysis and leads directly to the recommendation that a more comprehensive taxi noise measurement program which captures concurrent acoustic and FDR data.

3.2. Source Directivity

3.2.1. Lateral Directivity

The aircraft lateral directivity utilized in INM may be applied in the creation of 3D noise spheres as are used in AAM for detailed simulation noise modeling. Figure 24 from the INM manual (*1*) shows the lateral directivity corrections for wing and fuselage mounted engine configurations in both polar and Cartesian plot formats.

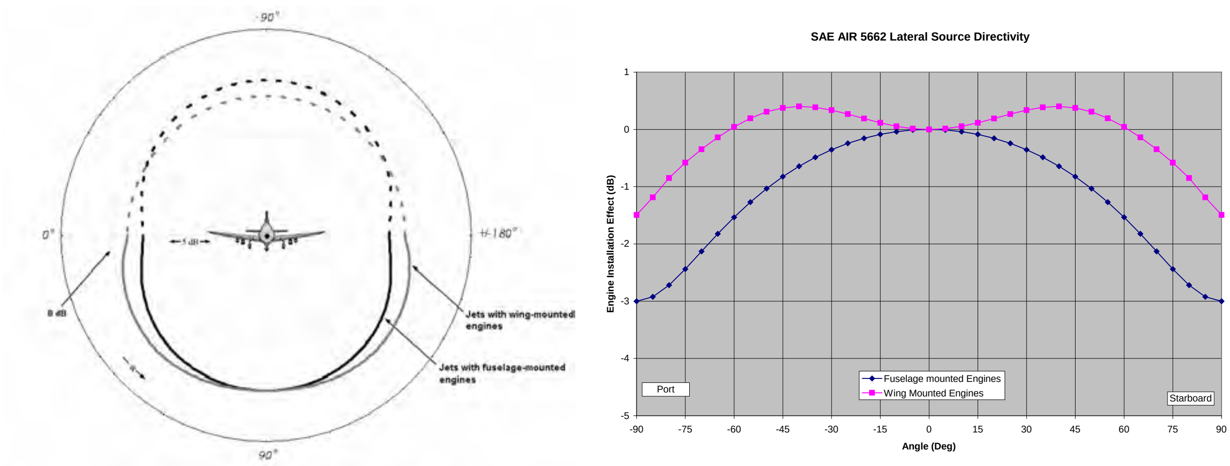

Figure 24. Aircraft lateral directivity applied to 3D noise spheres.

A series of steps were taken to create 3D Noise Spheres for use in Wyle's Advanced Acoustical Model (AAM) (*27*), a simulation model. The INM NPD curve for a B737-700 at Approach power using 3000 lbs thrust was matched by building an omni-directional 3D sphere containing the INM NPD Spectral class simulating an infinite flight and linearly offsetting it by a fixed amount in each band in order to best fit the NPD data at all distances. The inability to match the slope at the larger distances is due to different absorption models. INM's absorption method is based on SAE ARP 866A (*28*) while AAM's absorption based on ANSI standards (*29*). Since this project is assessing taxi noise at regions closer to the airfield the NPD data was readjusted in order to better match the INM at distances of 5000 ft or less.

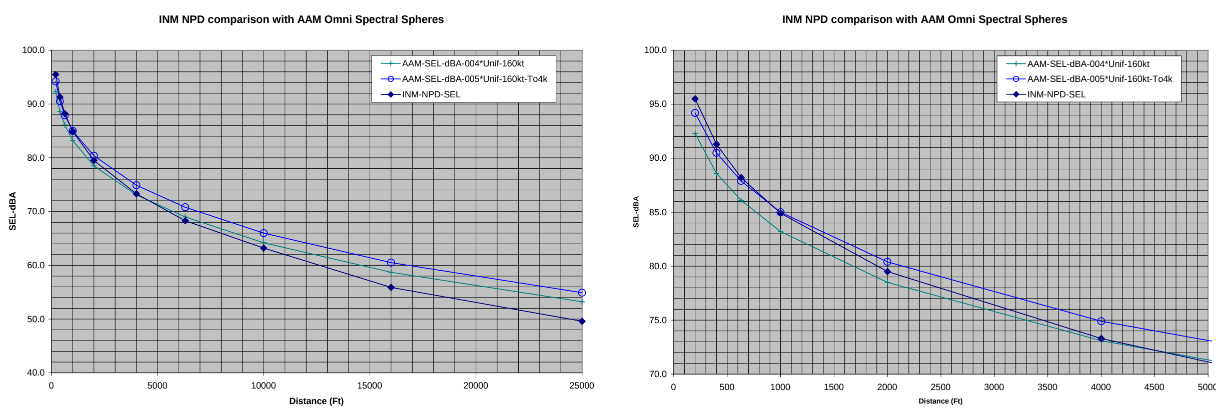

Figure 25. B737-700 AAM omni directional sphere
a) best match all distances and b) best match under 5000 ft.

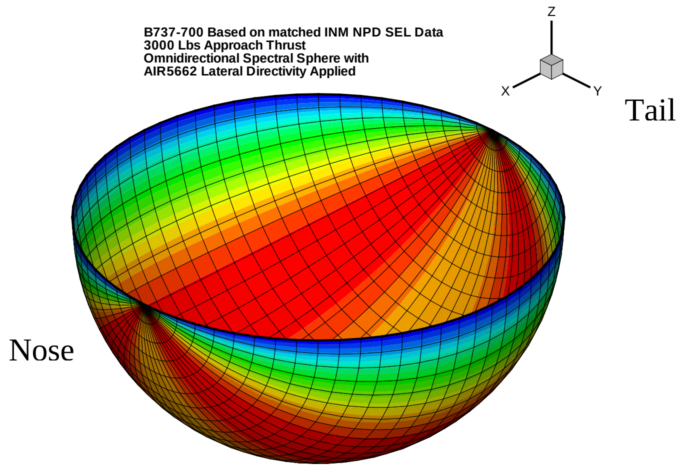

Figure 26. B737-700 AAM 3D source - omni directional sphere with SAE lateral directivity applied.

One of the manifestations of applying only lateral directivity to a sphere, due to the geometric topology, is an increase in noise in the front and rear of the spheres. While INM does not need to consider this implication since it uses an integrated approach to modeling (an entire segment of SEL data applied to a ground mesh at one time), it shows the importance in simulation modeling of coupling the lateral directivity with the longitudinal directivity. Figure 27 compares the ground noise predictions made using AAM of a sphere that is omni directional with a sphere containing only lateral directivity. One of the obvious implications of the lateral-only directivity on the sphere is the fore and aft spikes in the contour predictions. These are due to purely geometric considerations and show up when a line connecting source and receiver intersects the higher amplitude areas on the sphere near the nose and tail. The second implication can be seen in the size of the contours at large distances from the source location. Lateral directivity has a maximum reduction in the base omni directional sphere in the plane of the wings. This can be seen as a reduced contour area for very low propagation angles. Figure 28 contains a view in closer to the operation, spanning an area of +/- 10,000 ft. Because of the formulation of the lateral directivity adjustment, a uniform integrated 3D energy level is not maintained at the sphere. This is a primary contributor to the difference in the size of the contour levels (application of lateral directivity reduces the contour areas) both at the long and short propagation distances. For flight operations it is important to preserve L_{max} and SEL directly overhead; for taxi and ground operations levels directly under the aircraft are not of concern.

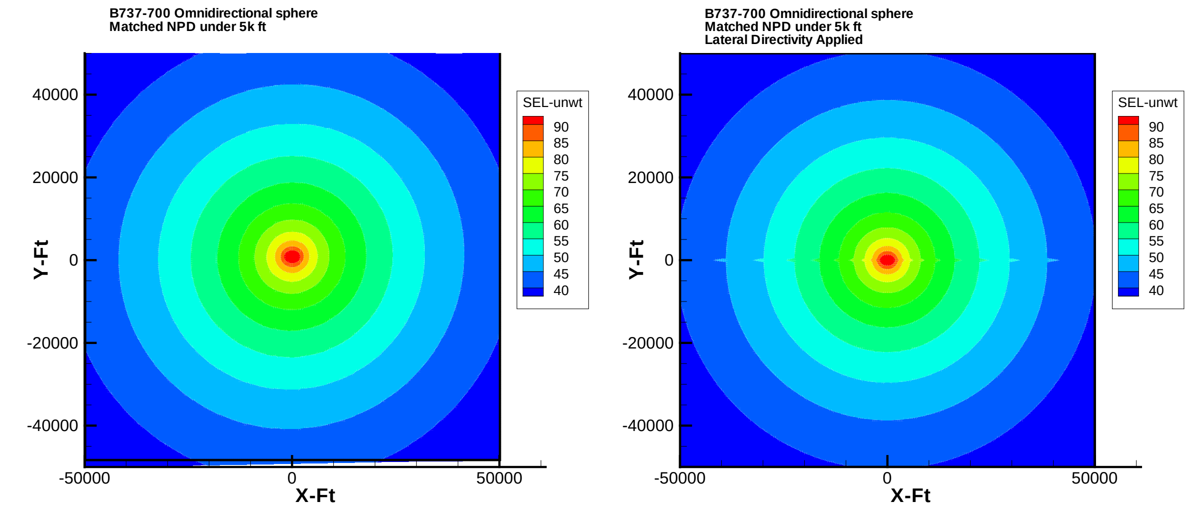

Figure 27. B737-700 AAM ground contour predictions with omni and lateral directivity spheres (+/- 50 k ft).

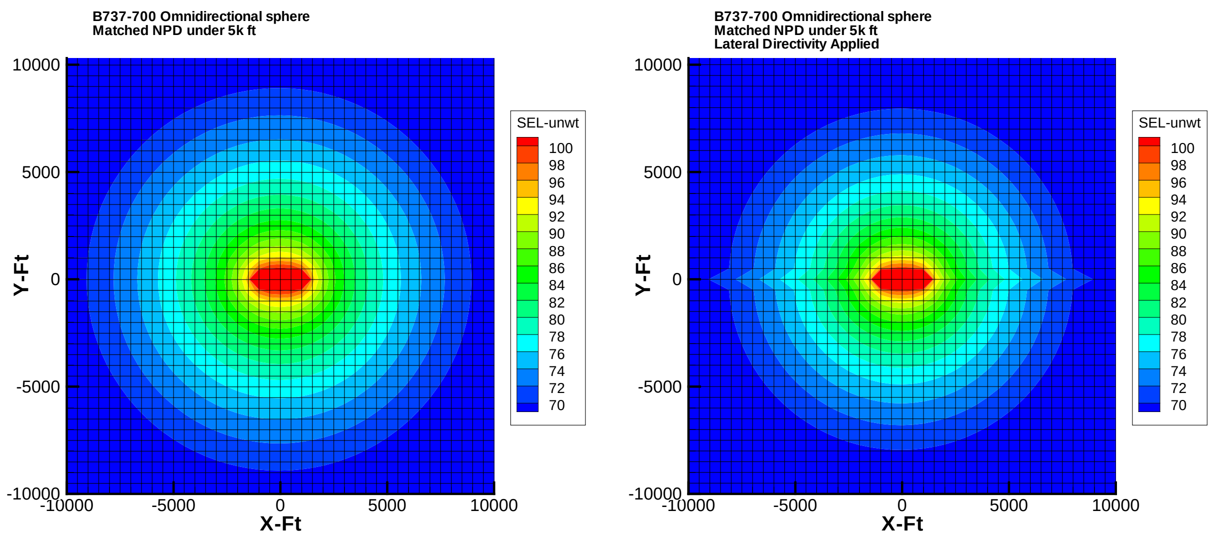

Figure 28. B737-700 AAM ground contour predictions with omni and lateral directivity spheres (+/- 10k ft).

3.2.2. Longitudinal Directivity

3D spheres were created that incorporate longitudinal directivity as obtained from measurements in addition to the lateral directivity discussed above. An assessment of longitudinal directivity was obtained by comparing several data sources: measurements performed at Washington National Airport, directivity data obtained from static engine testing provided by a major engine manufacturer and datasets obtained from published reports. Continuing with the B737-700 assessment and including data for an Airbus A319, due to the common engines types, one can obtain a nominal longitudinal directivity (Figure 29). The selected normalized directivity is also shown in Figure 30 as implemented in the sphere. During the measurements and flight recorder data was not available so the thrust of the engines is unknown, and could be contributing to the differences between the various directivity curves. Details of the measurement data analysis process is provided in Appendices A, B and C.

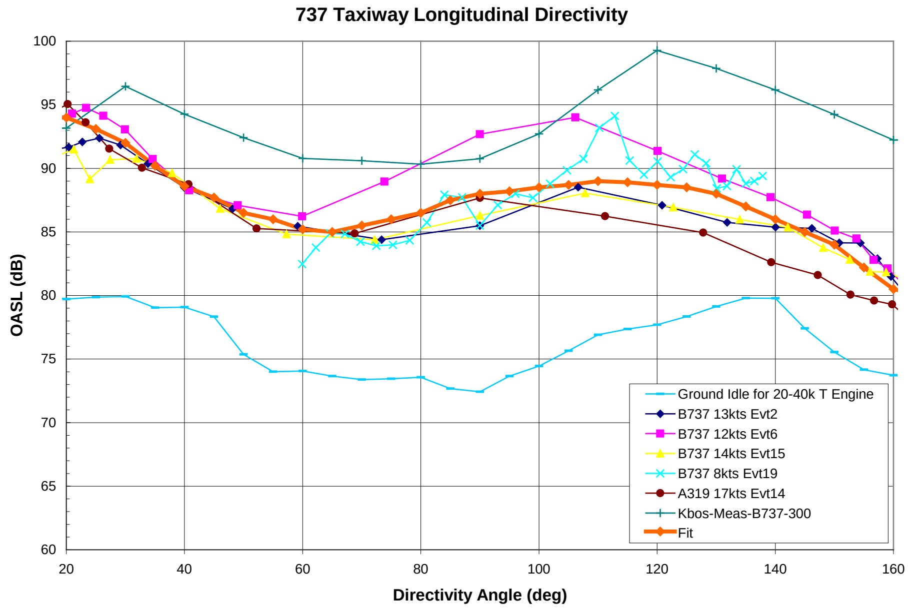

Figure 29. B737-700 measured longitudinal directivity – all available data.

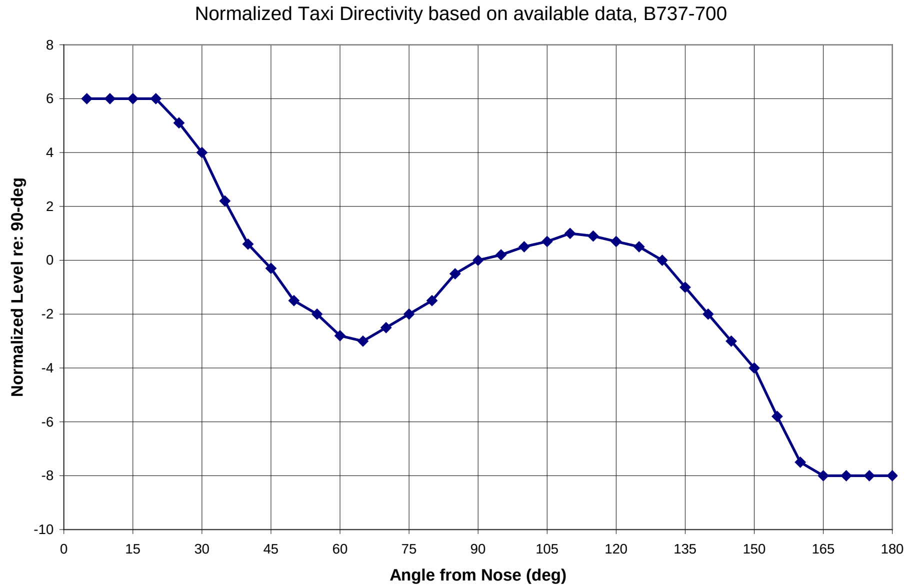

Figure 30. B737-700 normalized longitudinal directivity.

For comparison, the measured longitudinal directivity for a Bombardier CRJ aircraft is given in Figure 31. Details of the measurements and process of correcting the taxi data to free field standard day conditions directivity at 150 ft are provided in Appendix A. One of the primary differences between the 737 and the CRJ directivity is the marked increase of noise in both the front and rear of the CRJ. The measured data was depropagated using the ART technique (*27*) which takes advantage of a known geometrical and temporal relationship between source and receiver. Since vehicle tracking information could not be independently obtained, we relied on video instrumentation and scaling based on the vehicle length in order to determine a nominal taxi speed. This constant speed was then applied to obtain the temporal relationship between source and receiver. For the smaller CRJ aircraft one would expect its speed to inherently have more variability than the larger B737. It is likely that discrepancies between actual and presumed source location can cause greater uncertainty in the forward and aft portions of the longitudinal directivity evaluation so directivity data at the extremes, near the nose and tail were not included.

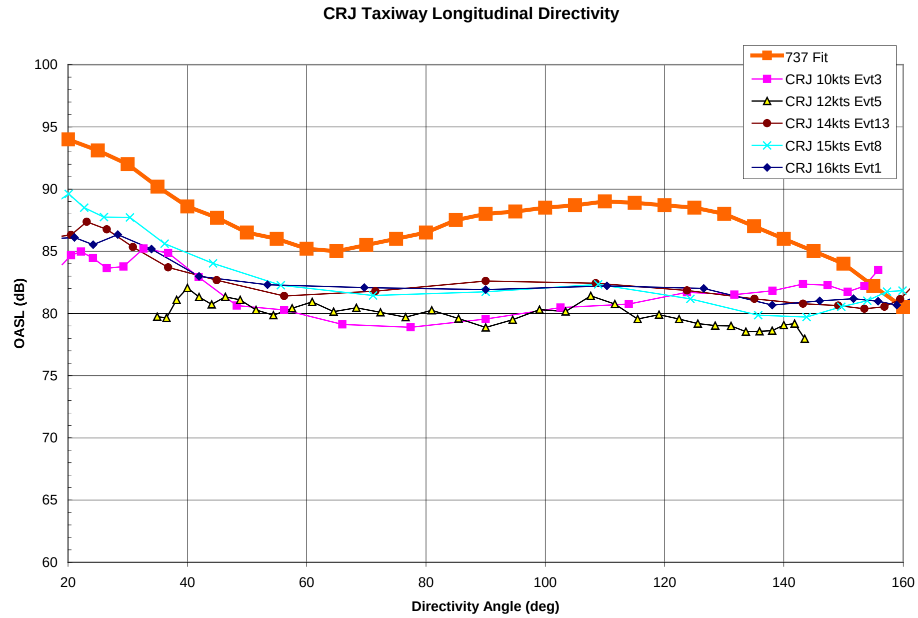

Figure 31. B737-700 normalized longitudinal directivity.

In summary, source directivity was identified in a range of measurement datasets. Although the levels of the directivity vary (likely due to differences in engine operating states) the shape of the directivity is similar suggesting that perhaps a nominal fleet-based directivity curve (as is currently implemented in INM for behind the start of takeoff roll) is plausible. Additionally, a collection of empirical taxi directivity data was presented for a wide variety of aircraft. There is a considerable amount of scatter in the normalized aircraft directivity assessments; however a wide variety of measurement techniques and atmospheric conditions were used for measurements. The most comprehensive and consistent measurement dataset for nominal taxi noise directivity and spectra is that obtained in Madrid. The documentation presents one longitudinal spectral directivity for each aircraft type in the form of sound power and does not address breakaway thrust.

3.3. Source Spectra

3.3.1. Taxiing Noise Levels and Spectra

A set of spectra, normalized to 70 dB at 1000 Hz, are compared in Figures 32, 33 and 34 for radials forward, abeam, and aft of the engine inlet. Measurement data obtained from airfield measurements conducted as a part of this study are labeled Event. Static engine test stand data for a similar thrust rated engine (Test + ICD) are also displayed along with the INM spectral classes for both approach (INM Arr) and departure (INM Dep). Additional data from Reference (*30*, *31*) is indicated (HMMH) as well as data from the Madrid measurements (Madrid) documented in Reference (*25*, *26*).

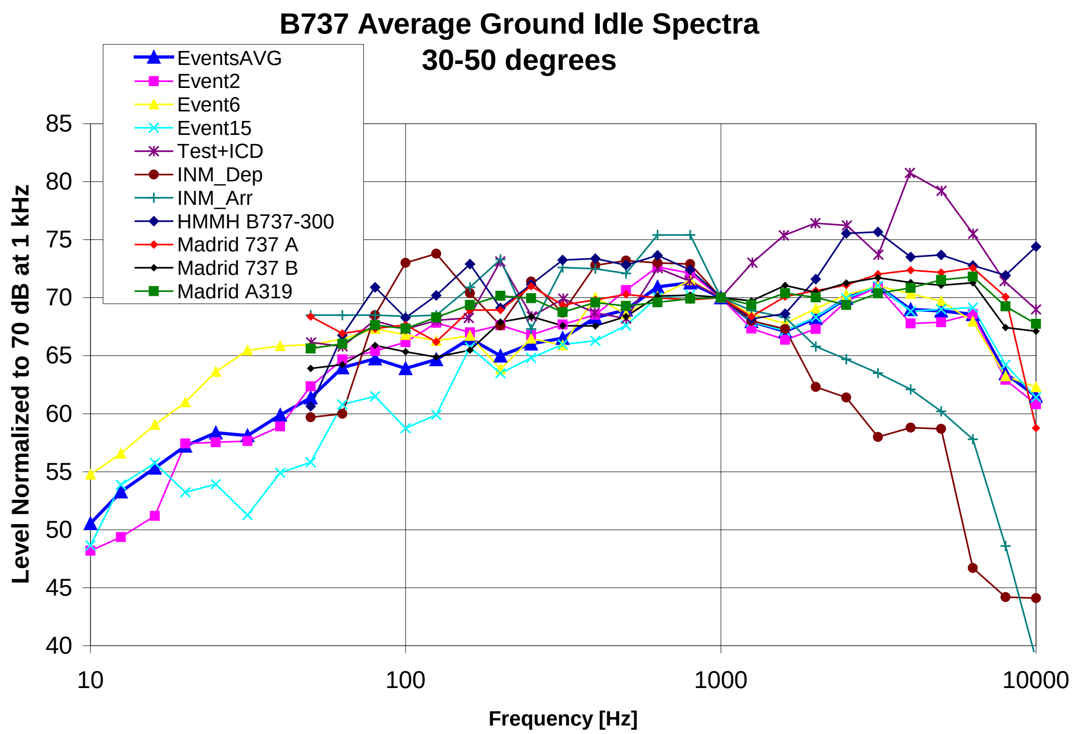

Figure 32. Normalized spectra – forward quadrant.

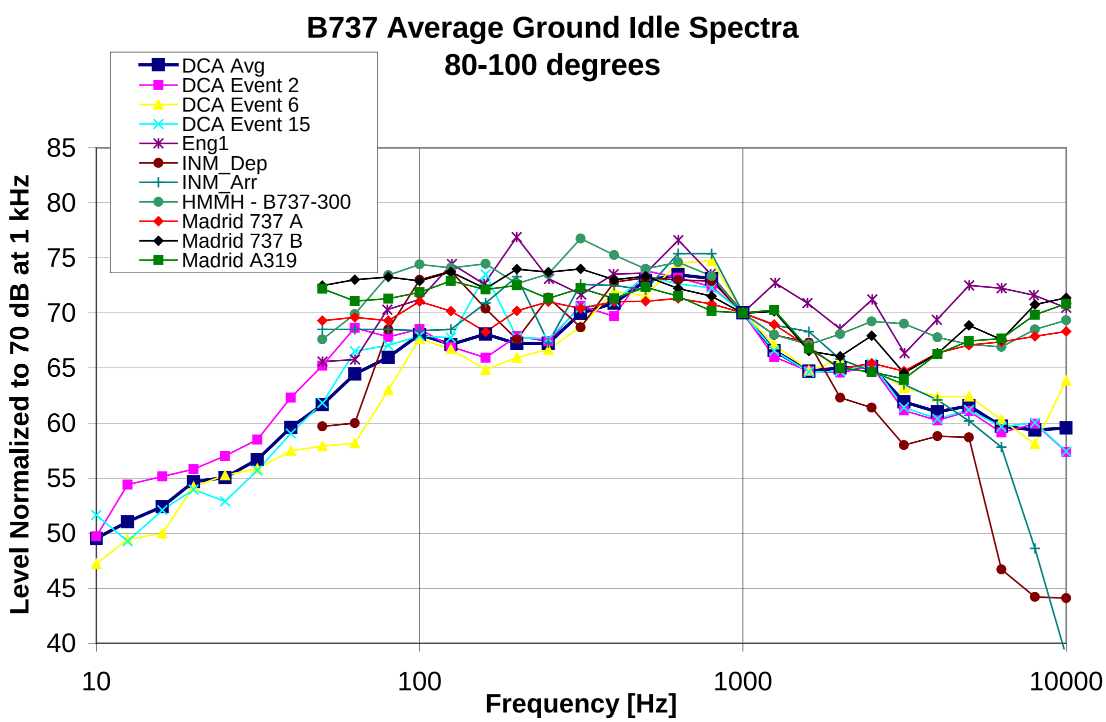

Figure 33. Normalized spectra – abeam.

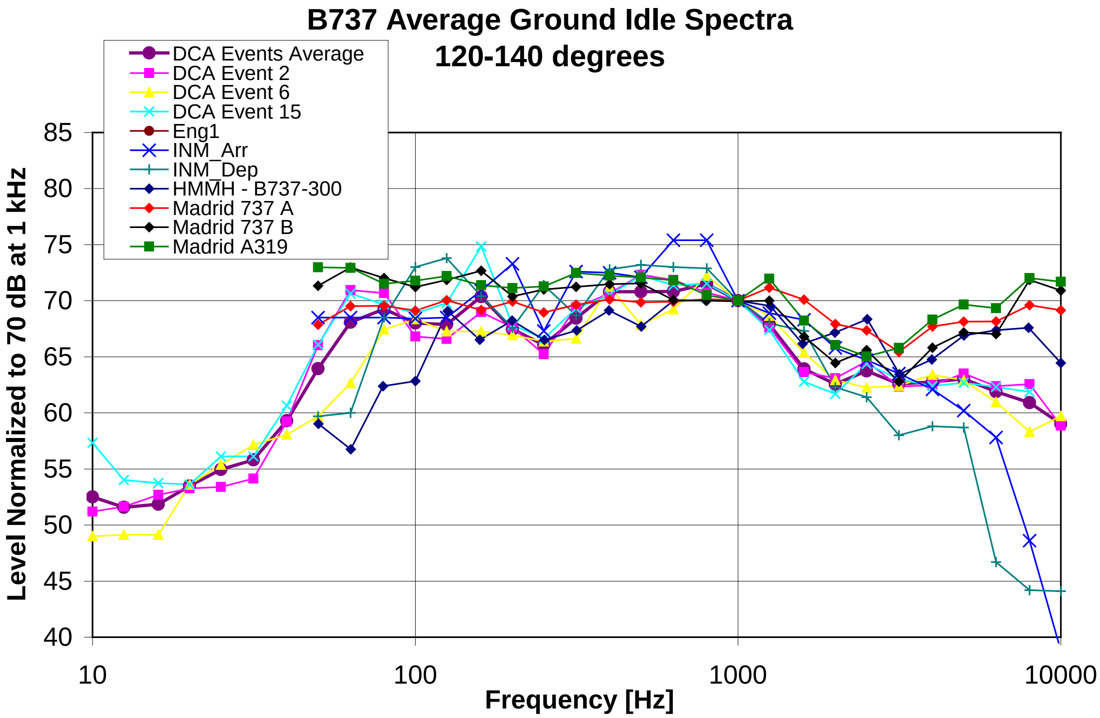

Figure 34. Normalized spectra – aft quadrant.

One important consideration of taxi way noise modeling is that of the aircraft spectra, and in particular the change in spectra with directivity angle. Given the geometric orientations of taxiways to community receptors, it is possible for certain regions to be repeatedly exposed to taxi operations at a narrow range of directivity angles relative to the source.

For measurements at the limits of the front and back directivity angle, the aircraft is at a considerably greater distance than point of nearest approach. When accounting for propagation (spherical spreading, absorption and ground effect) one can see that as an aircraft is approaching there is considerably more high frequency content. This is likely due the turbine whine and blade passage frequency emanating from the front of the engine. As the aircraft passes-by and moves away there is more low frequency content. This is likely due to the thunder and turbulent wake emitted from the aft of the engine. At all frequencies, there is a spike in the 63 and 160 Hz one-third octave band.

One can also conclude from the wide range of measurement data with spreads of over 10 dB at some frequencies as shown in Figures 29, 30 and 31, that there is considerable variability in noise emanating from an engine at taxi conditions.

3.3.2. The Impact of Spectral Class Selection

The effect of changing the spectral class of a departure noise ID to an approach spectral class can not be studied in INM directly, because there is no flexibility to change the spectral class assigned to an NPD curve, nor is there a feature to create user defined spectral classes. The run up duration analysis presented here therefore relies on a surrogate setup: utilizing the approach NPD versus the departure NPD both with different spectral classes. The primary impact of changing the spectral class drives the effect of atmospheric absorption over the propagation distances of interest. Appendices A and B in this report use local meteorological conditions in utilizing acoustic measurements for the creation of user defined NPD curves. For such cases it does matter significantly what spectral class is used to model the run up operations.

In summary, measured data was examined to assess differences between the published INM spectral classes and spectral directivity for low-thrust engine operations. A process was identified by which 3D spectral noise spheres can be created using limited taxi measurement data in conjunction with a simulation model to create NPD data for INM. Normalized spectral directivity data was shown from a multitude of taxi and static idle engine test stand measurement data. This difference in spectra from the INM spectral classes is primarily an increase in levels at higher frequencies oriented towards the front of the engine which could have an impact on A-weighted noise levels in nearby communities. The difference in the spectral content of existing INM flight operations spectral classes and measured taxi noise spectra is considerable suggesting that an additional taxi spectral class be implemented using similar aircraft spectral class groupings.

3.4. Source Noise Sensitivity at Low Power Settings

Within this section, a set of 3D noise spheres will be presented that were created using a combination of experimental data from a nominal taxi conditions and INM data such as Spectral Class and the NPD SEL (dBA). The spheres will be utilized later in a single event analysis in Chapter 4. The absolute level of the noise sphere will be determined by measurement data, but the sensitivity of the noise level with thrust will be based on an extrapolation of the noise sensitivity (dB/ lb Thrust) in the INM NPD curves.

A B737-700 taxi operation previously measured (Appendix B) was assigned a thrust of 1285 lbs, 5.25% based on the ICAO / CAEP paper (*18*) assessing idle taxi thrust settings. Longitudinal directivity was derived from empirical data from Wyle DCA measurements (Appendix A). The baseline sphere spectral class is that provided in INM for the CFM 56 engine. The baseline sphere source level was created based on the INM NPD and then adjusted to match the SEL (dBA) of the T.F. Green taxi measurement of a B737 (Appendix B). The INM NPD was matched by simulating a set of NPD level flight procedures in AAM and minimizing the SEL (dBA) differences for propagation distances under 4000 ft. Since the NPD curves include propagation as well as ground effects (for a nominal 4 ft high receiver) it was necessary to simulate these propagation. The easiest way to perform this calculation was by modeling a level over flight at 15 knots at the various distances in the NPD above a microphone placed 4 ft AGL.

This process of applying spectra, level and directivity in both directions completely defines a single noise sphere for the 1285 (5.25%) Thrust condition for a B737-700. The next step in the process is to make a ‘set’ of three dimensional spectral taxi noise spheres – each one representing a different engine thrust setting. Given a lack of noise level data for engines operating at different low thrust settings, the INM NPD curves were utilized (Figure 35) to obtain a simple variation in the SEL level with thrust. The delta-dB values as a function of 1000 lbs Thrust were computed based on the differential for 3000 Lbs Thrust Arrival NPD (the lowest thrust in the Arrival NPD curves) as well as for 6000 lbs Thrust Arrival NPD. For reference, the 10,000 Departure NPD (the lowest thrust in the Departure NPD curves) is also included in Figure 35.

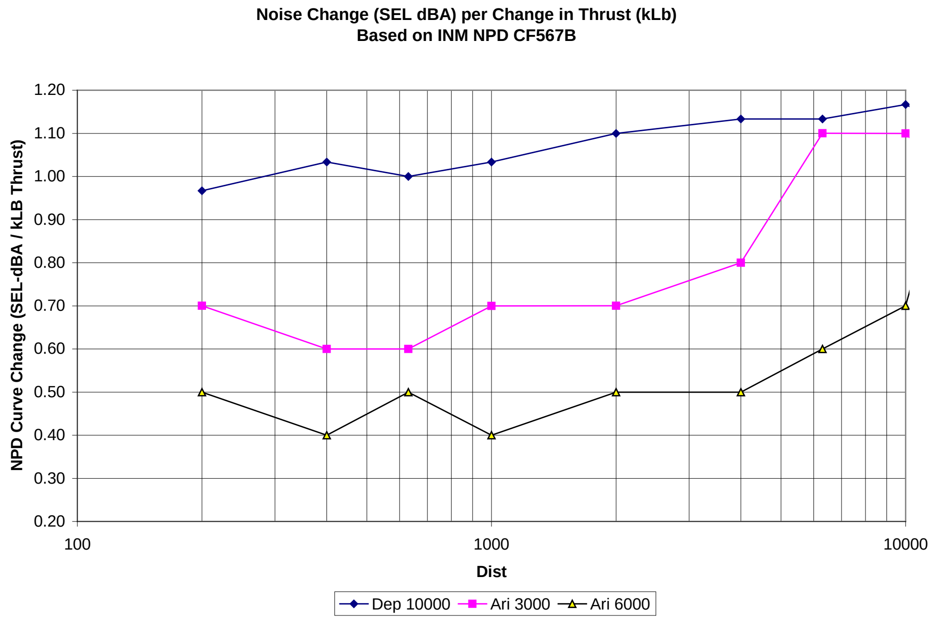

Figure 35. Noise-power relationship: INM NPD, delta-dB per 1000 lbs Δ-thrust.

The arrival NPDs were chosen because they include lower thrust settings. The rationale is that even though the NPDs include airframe / slats / gear / flap noise, the difference in noise between the 3000 and 4000 lbs thrust noise levels (for what is assumed to be roughly the same flight speed) will primarily come from changes in engine operating state. Based on the NPD curves a noise differential with thrust was estimated as 0.70 dB / klb. The average delta-dB / klb was applied to the spheres to scale them up and down to different thrust / noise levels. Six different thrust levels spheres were built and are itemized in Table 10.

TABLE 10 Noise Spheres for B737 at Various Thrust Settings

Run#	Thrust (lbs)	Thrust (%)	Delta-dB
005	480	2	-0.564
000	1285	5.25	0.0
001	1680	7%	0.277
002	2400	10%	0.781
003	3600	15%	1.621
004	4800	20%	2.461

Unfortunately, subsequent measurements conducted at Dulles International Airport (Appendix C) did not provide a suitable operational situation allowing us to directly measure noise at both taxi idle and at breakaway thrust conditions for a B737-700. However, Breakaway thrust measurements of a B757 and A320 increases of 4 and 7 dB for the breakaway thrust condition respectively.

In summary, analytical deductions suggested that changes in thrust could amount to instantaneous changes in taxi noise levels approaching 7dB. Practical application of typical durations of such breakaway thrust noise increases dilute the impact of the noise increases and lend credence to the short term suggestion that a "nominal" taxi thrust setting be implemented while additional research investigates in further detail the sensitivity of taxi and idle engine noise to changes in thrust.

3.5. Combining Spectra and Directivity into a Noise Sphere

With the spectra and directivity combined as described in Section 3.4, noise spheres for Run #5, 480 lbs thrust, were created and are shown in Figure 36 using different views and scales. The combination of lateral and longitudinal directivity affects the noise around the edge of the sphere. The noise in this location is what is creating the taxi noise in the community. When determining a suitable implementation for Taxi noise in INM and AEDT this difference in directivity (off the side versus directly under the aircraft) needs to be considered.

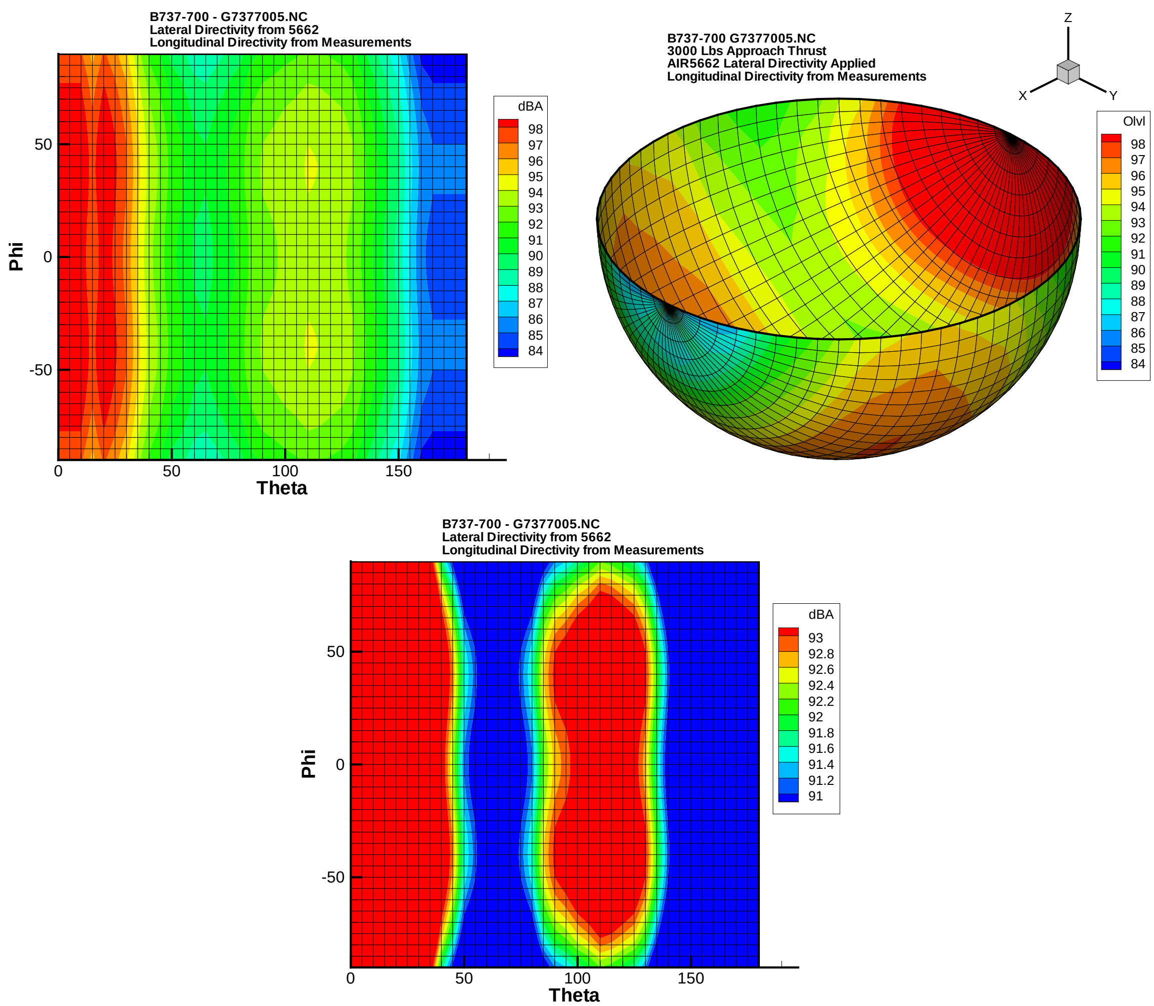

Figure 36. Multiple views of a 3D noise sphere for a B737 at taxi condition.

CHAPTER 4. OPERATIONAL MODELING

4.1. Single Event Analysis

4.1.1. Source Modeling (simulation comparisons using various fidelity spheres)

Analyses were performed using Wyle's acoustic simulation tools with 3D spectral sources for the various taxi throttle settings. The creation of these noise spheres was described in Chapter 3. One example, a comparison of the noise from constant speed taxi operations at different thrust settings, is shown here. An overlay of the various noise directivity contours is given in Figures 37 and 38. Shown are contours for six different thrust settings, from 480 lbs to 4800 lbs for a single taxi operation heading east at a speed of 15 knots over a distance of 2000 ft. The contours displayed are SEL values and indicate based on the assumed source sensitivity in the table above, the single event difference for this one particular element of a taxi operation. A contour comparison between the 480 and 4800 lbs setting, obtained by subtracting the SEL grids is provided in Figure 39.

Similar comparisons have been made for changes in speed, spectra and directivity (lateral and longitudinal). These elements serve as the building blocks of the sensitivity study from which increasingly complex combinations can be examined to determine what parameters are needed to be modeled for taxi noise assessments.

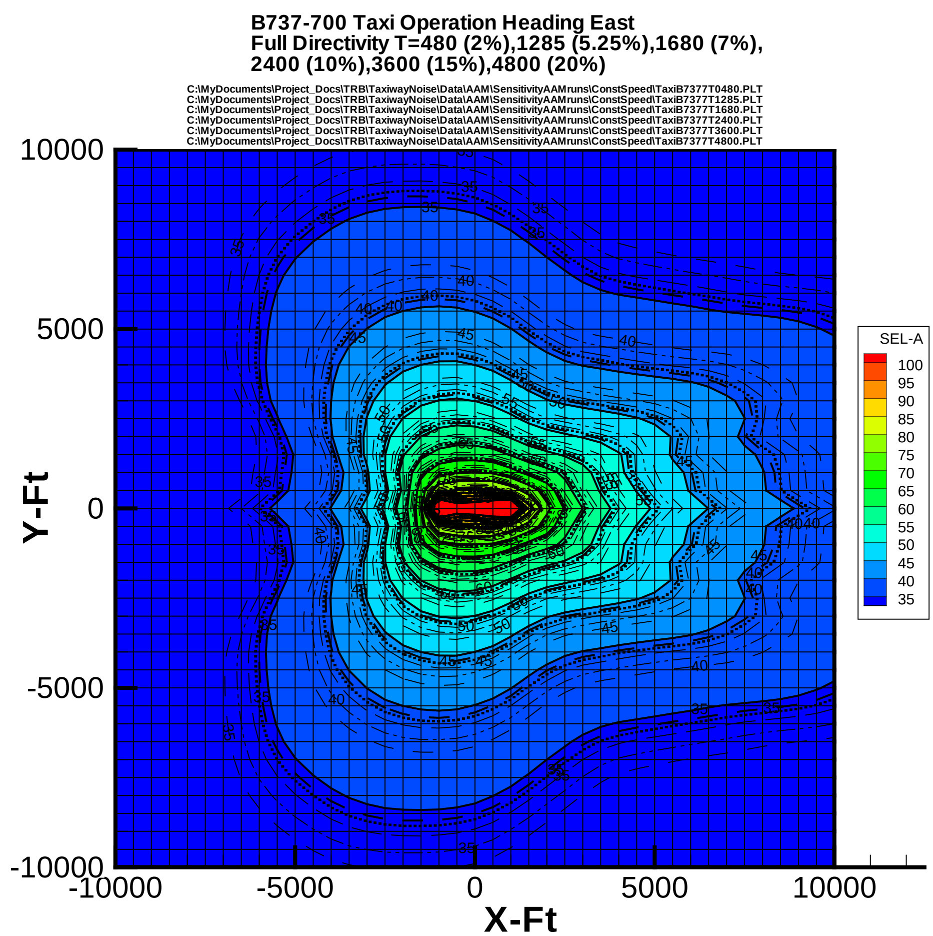

Figure 37. B737-700 with full directivity, thrust: 480 - 4800 lbs.

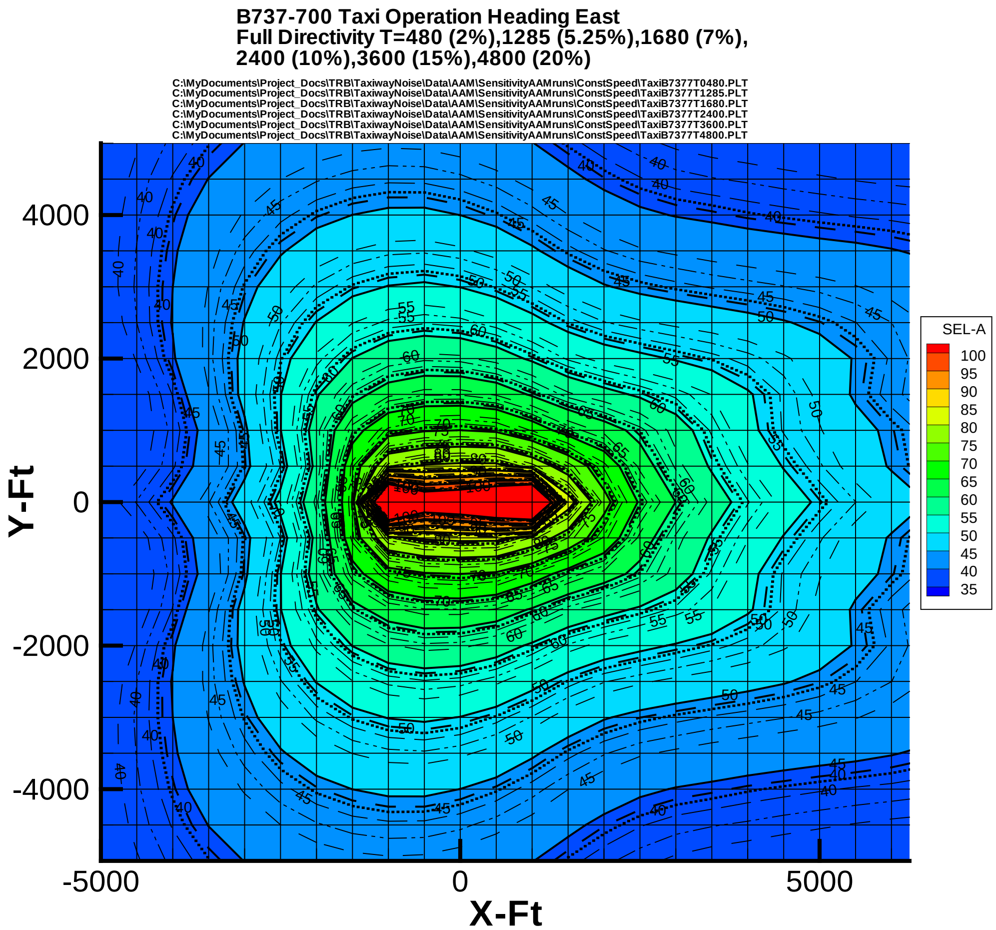

Figure 38. B737-700 with full directivity, thrust: 480 - 4800 lbs. – zoom.

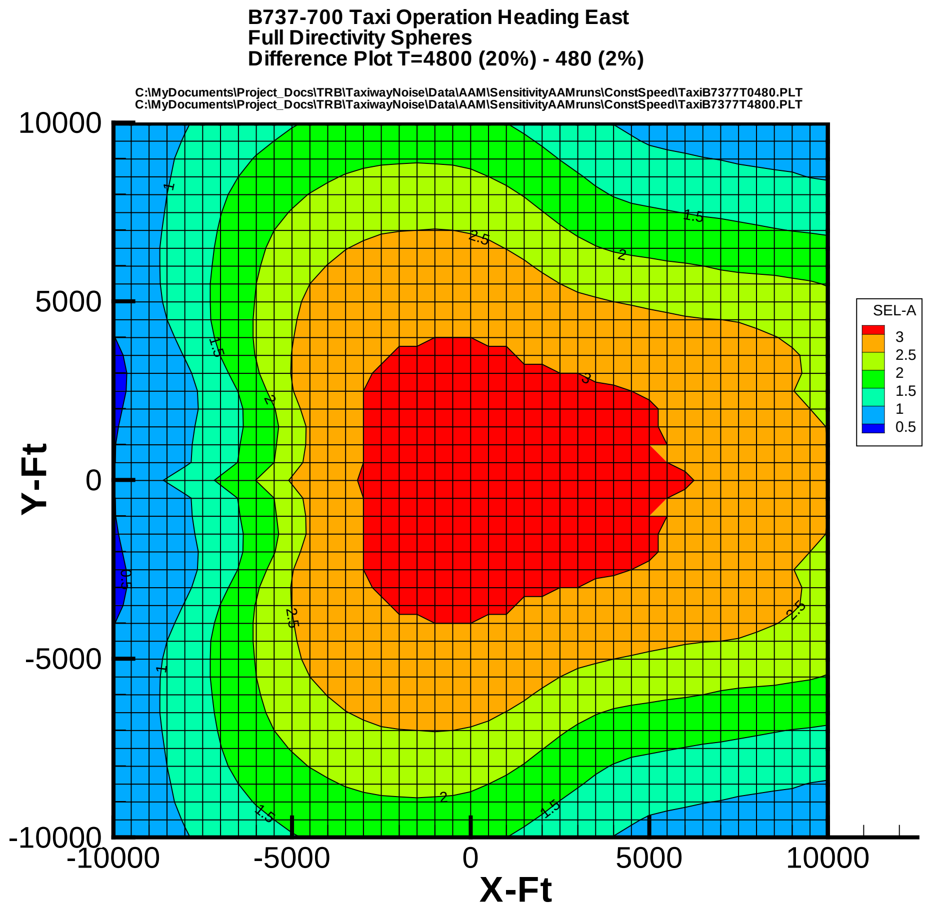

Figure 39. B737-700 difference plot: thrust: 4800 (20%) – 480 (2%) lbs.

An additional comparison provided here illustrates the need to obtain realistic throttle operation and corresponding noise data. This example illustrates the importance of getting the timing and duration of the events set properly. The total operation duration is 80 seconds. Of that only 3 seconds are spent at the bumped up throttle setting. The operation is a "Go-Stop-Bump-Go" 80 second operation, 20 second hold, 3 second throttle bump. The first operation moves at 15 knots using 1285 lbs thrust, bumps up to 3600 (15%) lbs. The second bumps up to 7200 (30%) lbs. The simulation trajectory is given in Figure 40.

T (sec)	X (feet)	Y (feet)	Z (ft AGL)	Speed (knots)	Yaw (degree)	Attack (degree)	Roll (degree)	Power	Thrust Angle (degree)	Cumulative Distance (feet)
0.000	-730.0	0.0	5.5	15.0	0.0	0.	0.	1285.	0.	0.
27.255	-40.0	0.0	5.5	15.0	0.0	0.	0.	1285.	0.	690.
30.324	-1.0	0.0	5.5	0.1	0.0	0.	0.	1285.	0.	729.
50.307	1.0	0.0	5.5	0.1	0.0	0.	0.	3600.	0.	731.
53.375	40.0	0.0	5.5	15.0	0.0	0.	0.	1285.	0.	770.
80.630	730.0	0.0	5.5	15.0	0.0	0.	0.	1285.	0.	1460.

Figure 40. Simulation trajectory

One can see from the SEL contour plot (Figure 41) and the difference (Figure 42), not a lot of difference from the 3 second throttle bump is discernable in the contour. This suggests that breakaway thrust applied over a short duration may not have a significant impact. However recall that this suggestion is based on the assumption that the difference in source noise characteristics is 0.70 dB / klb Thrust and the breakaway thrust value was 3600 lbs and was applied for 3 second duration. Differences over the computation range were generally of the order of 0.15 dBA within 5000 ft of the operation. The discretization and precision of the contour levels on the receiver mesh is responsible for the jagged contours in the difference plot (Figure 42).

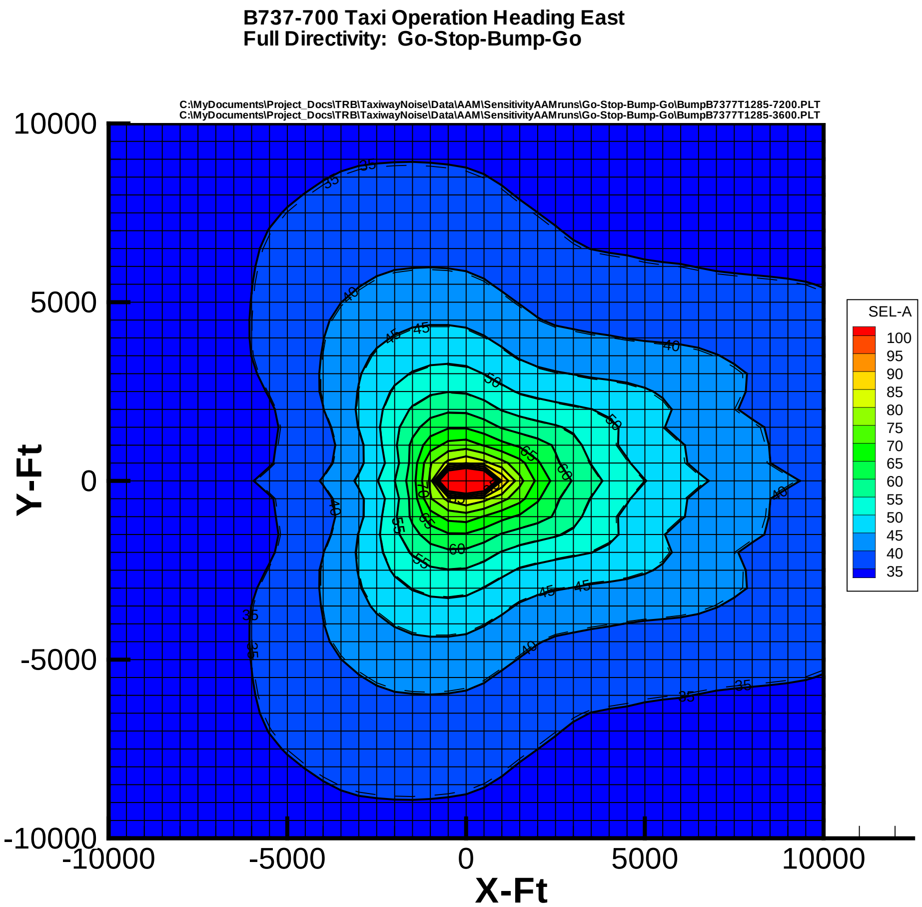

Figure 41. Overlay of both go-stop-bump-go operations.

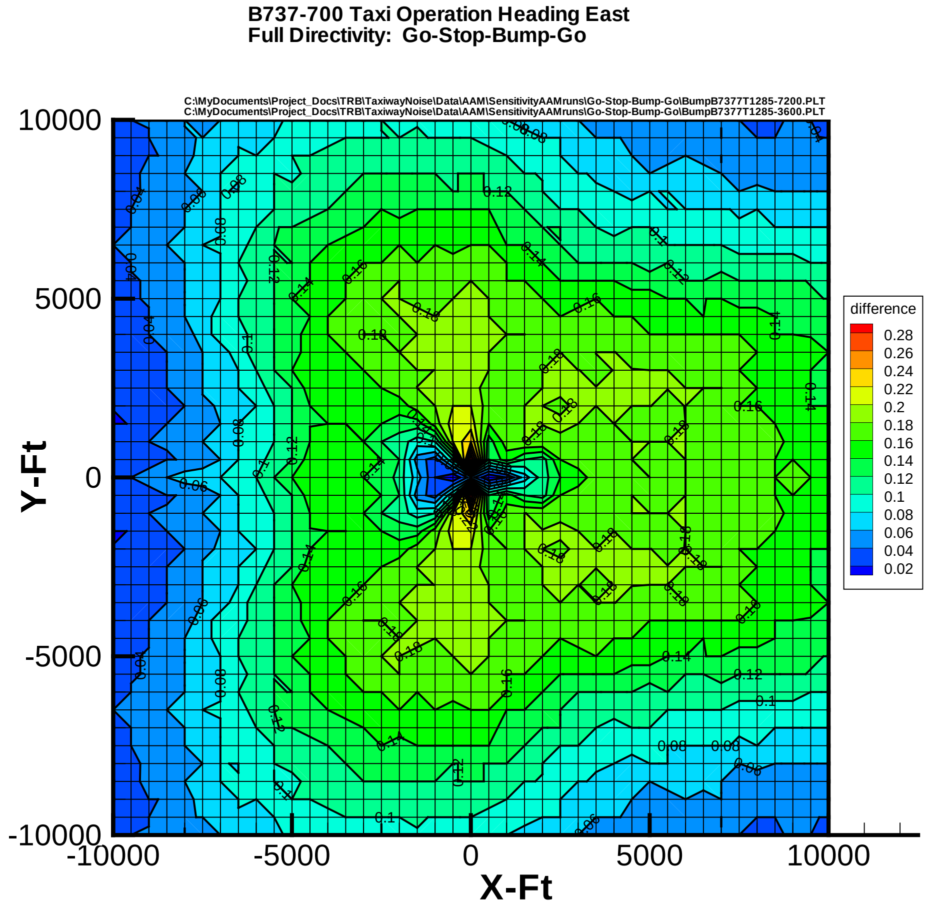

Figure 42. Difference: 7200 – 3600 bump thrust levels for go-stop-bump-go operations.

Analysis of the FDR dataset indicated that for some aircraft type, taxiing operations are performed with one or more engines shut down as much as 11 % of the time for moving taxi operations (Chapter 2, Table 2). While the 3D simulation model could analyze such asymmetric source directivity and incorporate such effects into the noise predictions, future research is needed to determine the source characteristics. One would need to either obtain empirical data simultaneously from both sides of the aircraft operating under asymmetric taxi engine conditions or exercise a shielding / diffraction model to account for the aircraft wing and fuselage shielding effects. An asymmetric source analysis was not performed during this study.

In summary, detailed simulation techniques were conducted with AAM using 3D spectral noise sources to assess the sensitivity of various source features on noise contours. AAM treats the lateral and longitudinal directivity as a source modeling input, not as propagation corrections as is the case within INM. Modeled changes in the source noise characteristics tended to become diluted for propagation distances over soft ground approaching 1 mile, (Fig 4-3 and Fig 4-6) supporting again the inclusion in the short term of a nominal taxi operating state, while leaving a higher fidelity source model as an item for longer term development.

4.2. Multiple Operations

In the ideal scenario, detailed ground operations will be modeled as individual tracks where the position and state of the aircraft is known as a function of time. Using INM's point to point tracks and user defined profiles to represent the movement of the aircraft as low altitude overflights in conjunction with stationary run up operations, represents the highest fidelity geometric modeling possible in INM. This section will begin with a high fidelity analysis of a realistic taxi scenario for a given day. Intermediate analyses spanning from high fidelity modeling to lumped time-in-mode assessments and the impacts of the modeling scenarios on the predicted taxi noise contours will be presented.

This analysis leverages a concurrent taxi assessment being performed for a major United States international airport. The acoustic predictions made with INM7 will be utilized as the framework for this sensitivity study assessing the geometric coverage of taxi aircraft movements. The standard INM7 code including the default NPD curves will be used. Since the intent of this section is to assess the applicability of different spatial modeling techniques, specific variations were not made to the acoustic source data within INM. As long as a consistent set of noise parameters are used across the entire sensitivity study, the impact on the output contours of the input modeling will depend purely on the selected input geometric fidelity. The full airport analysis presented here utilizes the following thrust values: Jets: 10% of Maximum Static Thrust; Props: 50% of maximum in appropriate units; Piper Cub: 1000 rpm.

4.2.1. Operational Modeling using INM7

INM7 fully supports the capability to include complex combinations of stationary and moving aircraft operations which can be applied to the prediction of taxi noise. Within INM7, a user can utilize multiple profile segments to model changes in aircraft speed and thrust such as when stopping and subsequently accelerating to cross over runways or intersecting taxi ways or to model aircraft holding queues, also holding queues and locations where aircraft accelerate to cross runways utilizing breakaway thrust can be modeled, provided of course one has the input taxi operational information available. Given what appears to be a wide choice of modeling options, we pose the following question:

"How much fidelity of motion must be modeled in order to properly predict the noise from aircraft taxi operations?"

This question will be explored by first examining a realistic dataset containing a full set of detailed taxi operations. Simplifications to the modeling of the location and orientation of the operations will be made, by assigning operations to a reduced number of taxi tracks, by combining run up operations and lumping them using varied orientations and locations. From this, insight can be obtained from the acoustic impact changes due to varying the fidelity of the taxi operations modeling.

The INM User's Guide (*1*) specifies a method for modeling taxi noise in INM, specifying that "a taxi path can be approximated by an over-flight track and a fixed-point over-flight profile." The specific INM analysis techniques employed in this Section are those based on the Federal Aviation Administration (FAA) accepted Noise Analysis Protocol Version 6 (*11*), for the Boston Logan Airport Noise Study (BLANS). The following steps which apply to each individual taxi operation:

- Step 1. Create an over-flight track consisting of the necessary number of segments to model straight segments, runway crossing points, and turns.
- Step 2. Create a corresponding fixed-point profile. Set the following parameters for each segment of the taxi profile:
  - Profile distance (the measured taxi track segment length).
  - Set altitude equal to engine height.
  - Set speed equal to average taxi speed along the segment.
  - Set thrust setting equal to the average taxi thrust along the segment.
  - Set operation mode to approach.
- Step 3. Create a taxi operation that combines the taxi track (step 1) with the taxi profile (step 2) and assign the proper numbers of daytime and nighttime operations.
- Step 4. Taxi track points will be added to represent runway intersections (where aircraft slow or wait to cross the runway). Low average speed and high average thrust will be used at track segments at these points represent acceleration across the runway.
- Step 5. For queue times longer than five minutes, a low-power run up operation will be defined in INM at the appropriate point and orientation on the taxiway.

4.2.2. Geometric Modeling Fidelity

A high fidelity analysis of a US International Airport was conducted using INM based on modeling specific gate to runway taxi tracks (Figure 43) as predicted by the Total Airspace and Airport Modeler (TAAM®) (*16*). This analysis considered 1205 individual taxi operations, spanning a fleet mix of 71 different aircraft for a typical busy day and included the impact of aircraft delay and queuing. Standard day and acoustically soft ground was considered without any acoustic considerations due to nearby bodies of water, terrain, buildings or other forms of shielding. In this segment of the report, *taxi noise only* contours are displayed down to the 55 dB DNL level in order to better illustrate the effect of taxi noise at a distance of several miles. The FAA policy is only to publish *airport noise* contours down to a level of 60 dB DNL.

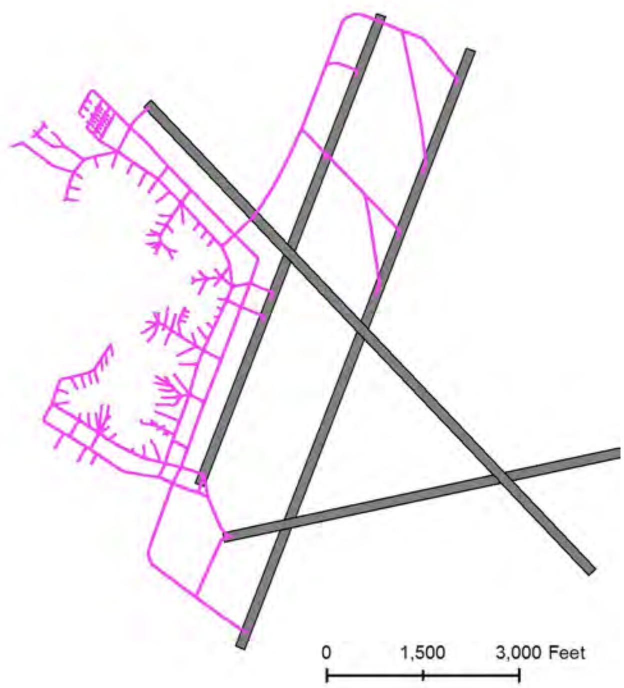

Figure 43. Complex taxi configuration with high-fidelity taxi movements.

Four high fidelity analyses, itemized below as #1 through #4, were conducted in INM. For these INM runs, detailed point to point tracks with user defined profiles were modeled and operations across the fleet mix were assigned.

1. High fidelity analysis – point to point tracks, user defined profiles, arrival NPDs for taxi, 5 min duration threshold run up assessment.
2. High fidelity analysis – point to point tracks, user defined profiles, departure NPDs for taxi, 5 min duration threshold run up assessment.
3. High fidelity analysis – point to point tracks, user defined profiles, departure NPDs for taxi, 1 min duration threshold run up assessment.
4. High fidelity analysis – point to point tracks, user defined profiles, departure NPDs for taxi, no run ups included.
5. High fidelity analysis, 1 min duration threshold run up operations only.

As shown in Section 4.3.4, run up operation data is consistent with departure NPDs in INM, therefore only departure NPDs will be utilized in this analysis. It is the differential in the DNL contours that is of importance, not the absolute value of the contour level. For reference, a comparison of the moving portion of the operations was made with arrival NPDS (#1) and with departure NPDs (#2) and are displayed in Figure 44. It is no surprise that selecting the departure-NPD operation type (solid line) are bigger than the arrival-NPD operation type (dashed line) due to the fact that the departure-NPD SEL curves are greater than the arrival-NPD SEL curves for the same thrust.

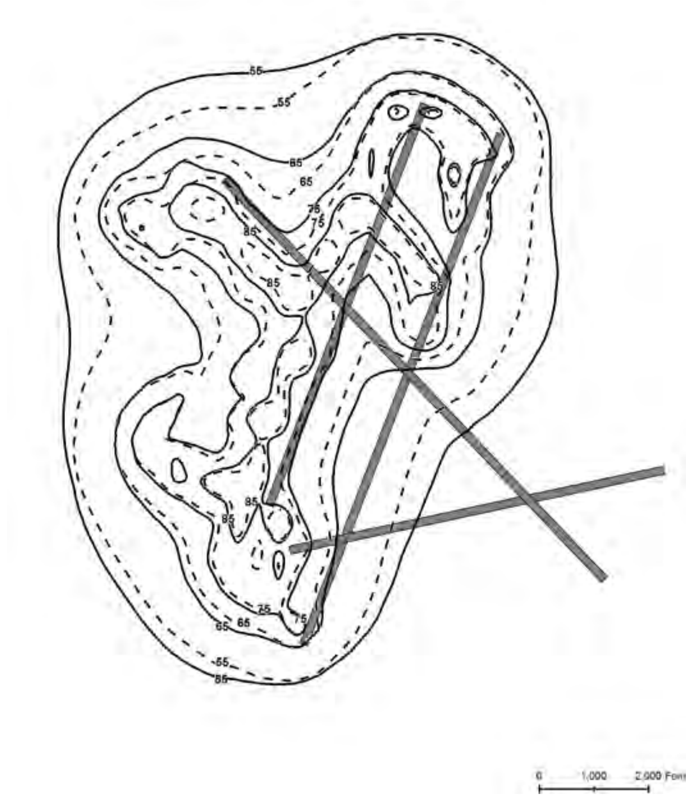

Figure 44. Arrival and departure NPD for moving taxi operations (#1-dashed vs. #2-solid).

Within this analysis any time an aircraft holds at a fixed position and exceeds a specified duration threshold, it can be modeled as a run up operation within INM as a static operation with the appropriate duration, location and heading. A comparison of a holding duration threshold of 1 and 5 minutes were considered (Figure 45). For this analysis departure-NPDs were used (solid lines: 1 minute threshold, dashed lines: 5 minute threshold). A total of 725 run up operations met the 1 minute holding threshold, whereas only 31 operations met the 5 minute holding threshold. The difference in the energy from these events can be considerable, as evidenced by the approximate 4 dB displacement of the south eastern portion of the 55 dB DNL contour. The importance of a holding threshold will be most important to the airport modeler in regions where queuing is most likely to occur.

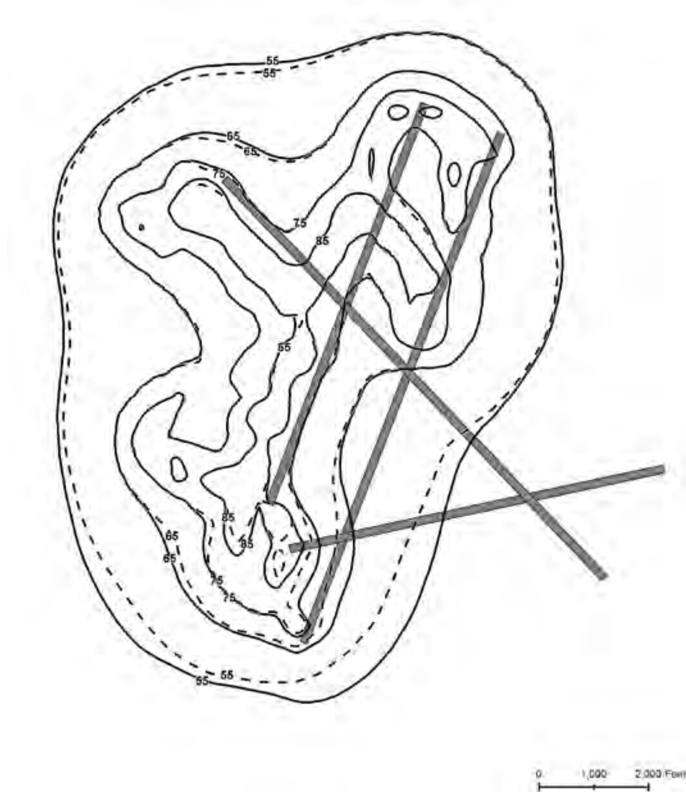

Figure 45. Holding duration threshold of 5 and 1 minutes, (#2-dashed and #3-solid).

4.2.2.1. Moving vs. Holding Modeling In order to visualize the relative importance of moving versus stationary operations, a buildup of the contours from the various modes of operations was created. Figure 46 shows a comparison of only the flight operations modeled as a departure-NPD operation type (dashed) and the run up operations using a 1 minute duration threshold (red) with the overall contour representing the sum of the moving and stationary operations (solid). It is apparent that the run up operations drive the bulge in the contour along the southern and northern edges of the DNL contour.

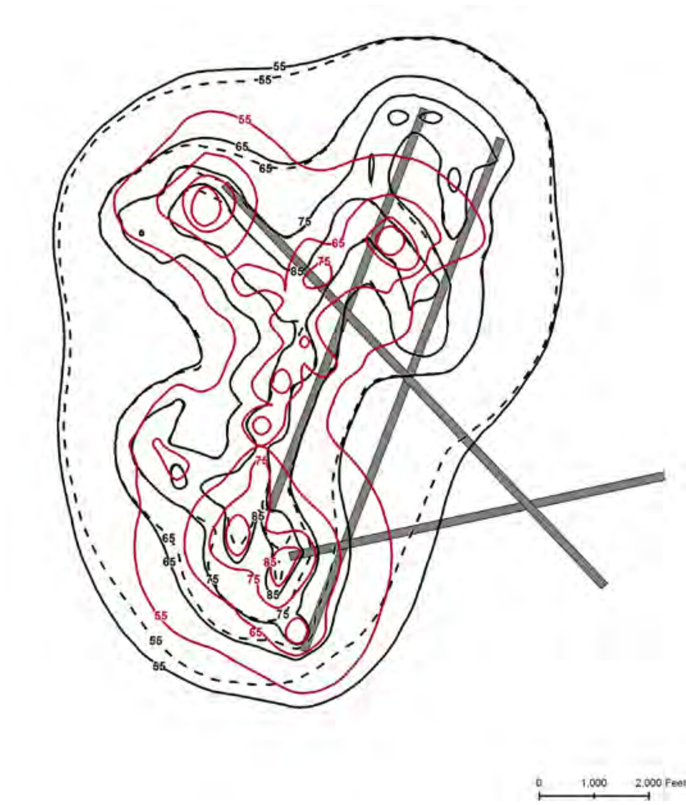

Figure 46. Contour build up #3-all (solid), #4-moving (dashed), #5-run ups (red).

4.2.2.2. Lumped Time in Mode Analysis One simplification of taxi modeling is to consider all the operations combined as a lumped time in mode. This style of modeling is currently employed in emissions inventory analyses as with EDMS (See Appendix D). Continuing with this example study, an assessment of the total time the aircraft spend on the ground was computed. On average independent of operation type the time spent on the ground for the entire taxi event (ramp to runway) was 374 seconds (6 minutes, 14 seconds). This does not include pushback or runway time.

An alternate technique would be to utilize the known queuing delays at the airport and simply lump the operations at one location. For this analysis all segments of the taxi, whether the aircraft is moving or stationary, will be computed by modeling the total duration as a run up operation.

Lumped Time in Mode Analysis: All operations at one location.

At one extreme, each run up could be modeled at the individual locations of the aircraft with the appropriate orientation. The other extreme is all operations lumped at one location. Both analysis techniques have the same total duration. The sensitivity of the contours to modeling scenario is shown in Figure 47 which displays the #5 run ups (red) with a 1 minute duration threshold, the full contour build up #3 (solid) with high-fidelity modeling and #6 Lumped Time in Mode (dashed). For convenience the location picked for this simplified analysis was the airport reference point. Had this been a 'real' study the modeler could improve the analysis by computing the geometric center of the taxi operations, or by taking guidance from runway usage statistics.

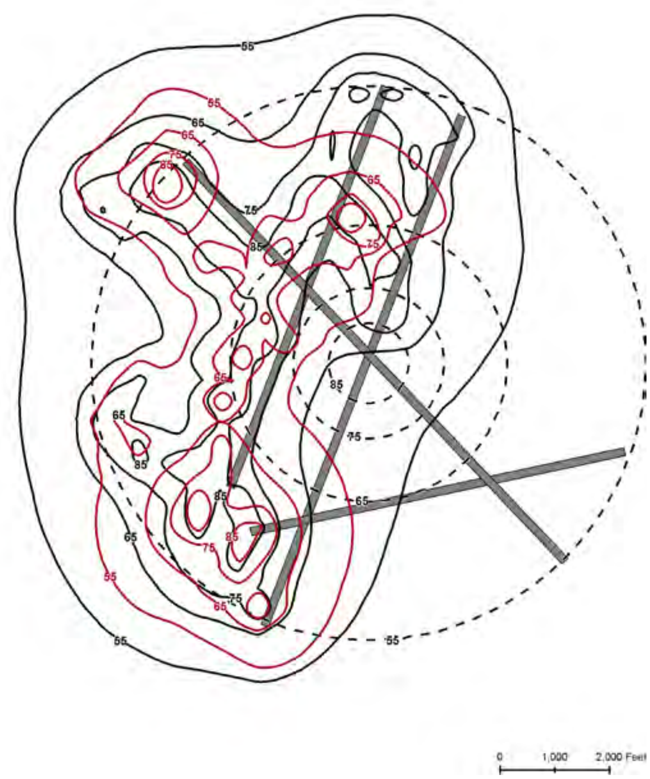

Figure 47. Contour build up #3-all (solid), #5-run ups (red), #6-lumped mode (dashed).

Clearly the impact of the geometric distribution (or lack thereof) of the time in mode operations can be seen. This suggests another simple improvement. Consider the primary holding locations at the airport. In this case there are three obvious holding locations driving the shape of the contours, one at the end of each of the primary runways. The high fidelity modeling including both one minute threshold stationary run up and moving operations was simplified to stationary operations at three locations, coincident with the end of the runway activity zones. The total duration of the operations remained constant as the modeling fidelity changed.

Lumped Time in Mode Analysis. All operations modeled at three run up locations.

Figure 48 compares the geometric level of modeling of the high fidelity combined operations (solid) with the simplified three locations lumped (red) time in mode operations. Since the purpose of this study is to assess the modeling sensitivity, no attempt was made to determine a broadly applicable modeling philosophy for selection of the three run up centroids. However, it was felt that at each location operations would be represented best by pointing the aircraft the 4 cardinal directions (East, West, North, South) because while taxiing, the aircraft will have potentially faced all directions during ground operations.

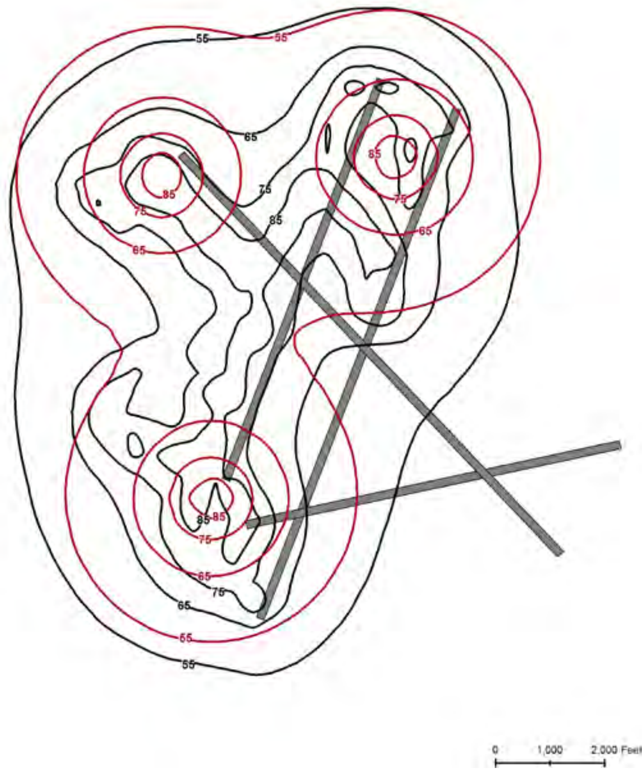

Figure 48. Run up operations: #3-high-fidelity all ops (black) and #7-lumped mode (red).

4.2.2.3. Nominal Taxi Track Modeling When considering the moving portion of the taxi operations, one can perform a high fidelity analysis (#4) or simplify the analysis by utilizing a fewer number of taxi tracks. In this case the overall taxi motions were assessed and six individual tracks were selected from the 1205 detailed tracks. The goal of the selection process was to cover the full extent of the spatial coverage over the airport grounds. Operations were then assigned to these 6 nominal taxi tracks randomly ensuring that the total number and type of aircraft represented in the study was preserved. Only the tracks were modified and assigned from the original detailed track to one of the 6 nominal tracks.

Low Fidelity Analysis. Nominal taxi tracks, user defined profiles, departure NPDs for taxi, no run ups included.

A side by side comparison of the high fidelity taxi tracks and the selected 6 nominal taxi tracks can be seen in Figure 49. Figure 50 provides a comparison of the community noise impact from the high fidelity tracks #4 (black) and the six nominal taxi tracks #8 (red).

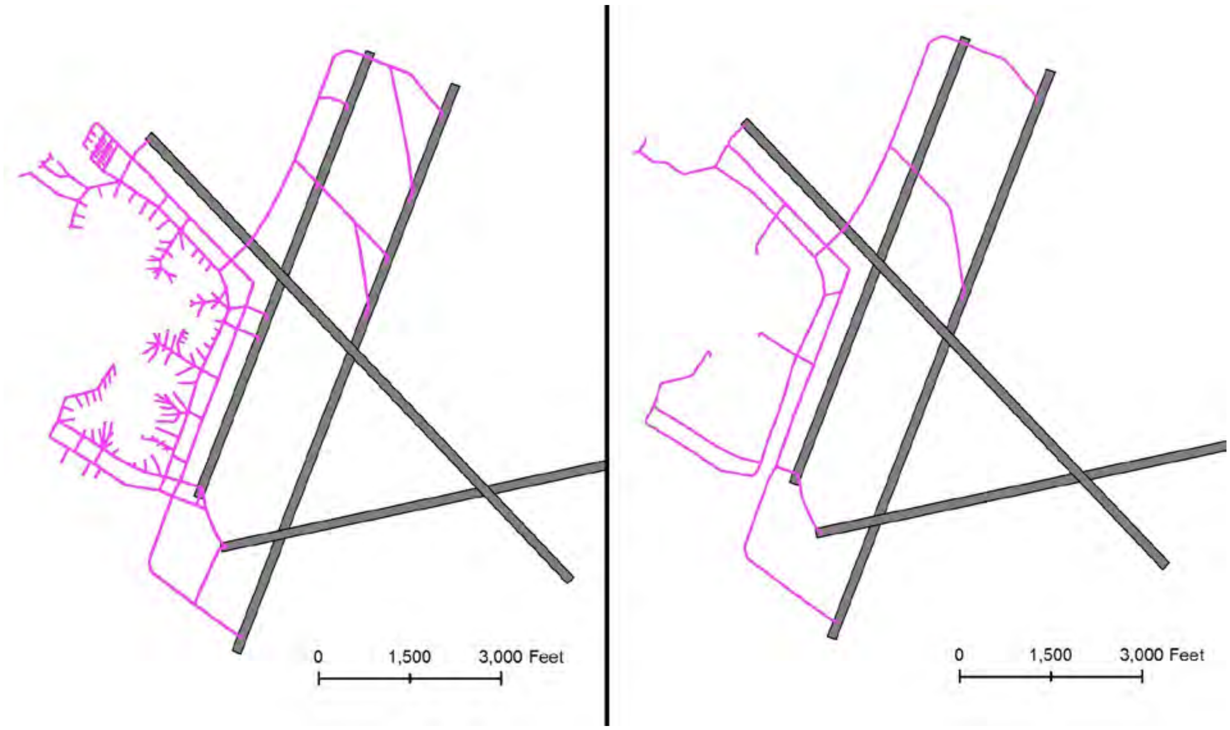

Figure 49. All taxi tracks and 6 nominal tracks.

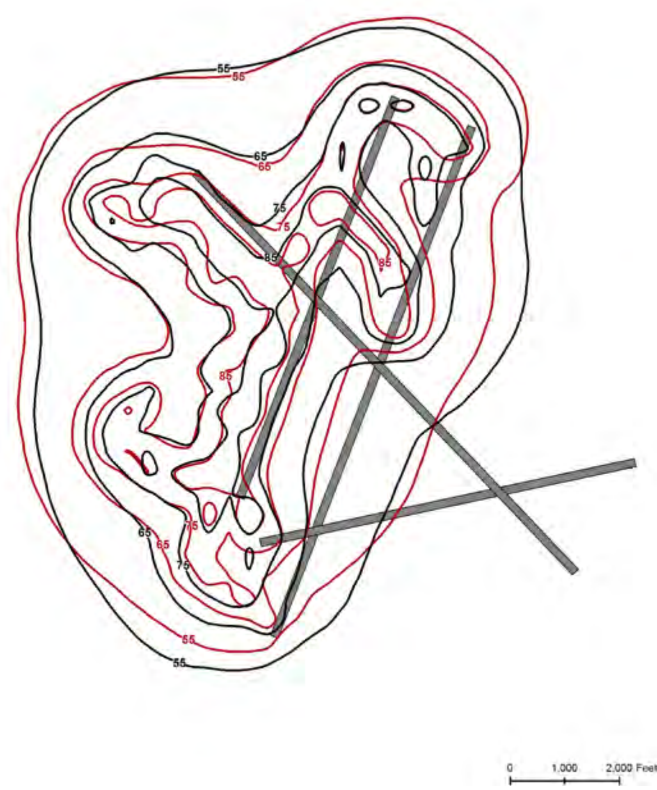

Figure 50. High fidelity tracks (#4-black) and nominal taxi tracks #8 (red).

Potential improvements to this modeling scenario would be to model the direction along the taxi ways tangent to the taxi heading, but modeling the run ups in the center of the taxi turning locations with all possible heading directions. This leads to the obvious parallels with detailed flight track analyses, namely the creation of backbone tracks based on statistical analysis, the assignment of operations to individual taxi segments (over flights in INM) and perhaps even the examination of ground radar data to obtain taxi movements.

In summary, one of the most surprising and unanticipated findings was the impact of the taxi geometry on the contours. It was very instructive to learn that a mere six taxi segments, selected to span the geographic area of interest, was comparable (within a few dB DNL) with the benchmark high-fidelity contours for an annual busy day at a major U.S. airport. This finding pointed strongly to the fact that the key element for taxi modeling (taxi operation geometric positioning) is already in INM, so a short term taxi modeling need can be met without requiring massive INM changes.

4.3. INM Modeling Considerations

In order to properly assess taxi modeling techniques targeting inclusion within the framework of INM 7, one must explore the capabilities of the current INM7 taxi operation modeling process. This section will explain and discuss the current recommended and accepted techniques for modeling taxi operations. In previous sections in this report, various INM modeling features have been used without detailed examination. The technical basis upon which INM has been built is described in Reference (*31*).

This Section will cover those elements in INM7 which impact the modeling of taxi noise. An in depth examination of the two sets of INM NPD data curves (approach and departure) will be made. The current INM extrapolation procedures for obtaining NPD data at lower thrust settings, typical of taxi operations, will be exercised. The impact of duration effects from static run up operations, the consistency between combining static and moving flight operations and alternative techniques using other modeling options currently available within INM will be examined. The use of flight profile altitudes in order to activate or deactivate specific propagation and source directivity features will be explored.

In the following examples a Boeing 737-700 aircraft was selected based on the availability of empirical data for taxi operations. Based on standard emissions ground idle recommendations (*14*), 7% thrust was used to model the taxi operations. For a Stage 4 operation with takeoff thrust at 24,000 lbs, this corresponds to an INM modeled thrust setting of 1680 lbs. Other sources of taxi thrust include recent ICAO / CAEP findings (*18*) indicating approximately a 5% idle thrust setting for the next generation 737s (-700, -800 and -900) and a slightly higher 5.5% - 6% setting for classic 737s (-200, -300, -400 and -500). For the purposes of the next few sections all INM modeling utilizes 1680 lbs for ground idle thrust for both stationary and moving taxi operations.

4.3.1. Duration and Noise Exposure from Static Run up Operations

Static run up operations and the associated duration equivalence between static and moving operations have already been employed in the high fidelity assessment in Section 4.2. The physical basis behind this equivalence will be explained. The effect of duration on the noise exposure metric (SEL) is straightforward. As provided in the INM Technical Manual, sound exposure is directly proportional to the run up duration time. In terms of sound exposure level, this may be represented by Equation 1.

$$SEL = 10 \log_{10}(t) + Level \qquad (1)$$

Here, “Level” is the adjusted maximum level of concern and “t” is the run up duration time in seconds. This fundamental relationship between exposure and duration is important in the modeling of taxi noise because INM can not model stationary aircraft, requiring instead the substitution of a run up operation for a taxiing aircraft in a stop and hold operation. The fundamental premise of the SEL NPD curves implies integrated noise from an infinite line segment. As a result, static operations occupying only a single point can not be computed from the SEL data. Rather, static operations require L_{max} source data, to which a duration adjustment applied, in order to obtain SEL contours. The consistency between SEL NPD and L_{max} NPD curves is therefore important, specifically when considering a single source at a constant thrust level which can either remain still or move merely by the release of the brakes. The impact of using the Approach or the Departure NPD curve becomes important when combining moving and static operations, or using a time assessment with one mode or the other to model taxi noise.

4.3.2. Selection of NPD Curves for a Moving Taxi Operation

The key item to be examined here is the multiplicity and consistency of data between the INM static run up data and the INM approach NPD and departure NPD data. The previous section detailed the duration relationship for stationary operations. For moving operations the time element has already been incorporated into the SEL values in the NPD curves. When modeling moving taxi operations, one treats the taxi segments as level over flights, at the altitude of the engines and flight speed of the taxiing aircraft. When modeling such an operation within INM, one may choose between arrival and departure NPD curves. The INM manual recommends using approach NPD curves, because they generally have data at lower thrust settings than the departure NPD curves, thereby requiring less data extrapolation. Two important facts must be considered: 1) the flight condition from which this data was obtained does matter and 2) consistency with static operations could be an issue depending on the modeling fidelity employed.

In exploring the impact of using a departure-NPD curve instead of an approach-NPD curve, it is important to note the fact that the INM GUI only allows run up operations to use Departure NPD curves and are modeled as ‘on the ground.’ No altitude variation is allowed for the run up pad. To show the difference of using a Departure NPD curve instead of an Approach NPD curve, a custom aircraft was created that had the same Departure NPD curves as the 737-700 Approach NPD curves. Figure 51 shows the contours from 100 sec duration of each aircraft for 1680 lbs thrust. The black line contour is a 737-700 (using the standard Departure NPD curves) and the red contour lines are from the custom 737-700 (using the standard Approach NPD curves). As can be seen the SEL levels from the custom 737-700 are less than those of the standard 737-700 farther from the aircraft and greater closer in.

Of interest is the fact that the 50 dB contours approximate one another. At higher contour levels the arrival NPD curve results in larger contours than the departure NPD curve. However at lower contour levels (further away from the run up operation) the reverse is true – the Departure NPD curve run up operation contours are larger than the arrival NPD curve run up contours. There is a consequence of which set of NPD curves are used to extrapolate down to typical taxi thrust settings, notably the result of two primary features: the available data levels and hence the extrapolation procedure, and also the difference in spectral classes and hence absorption rates for the two different sets of NPD curves.

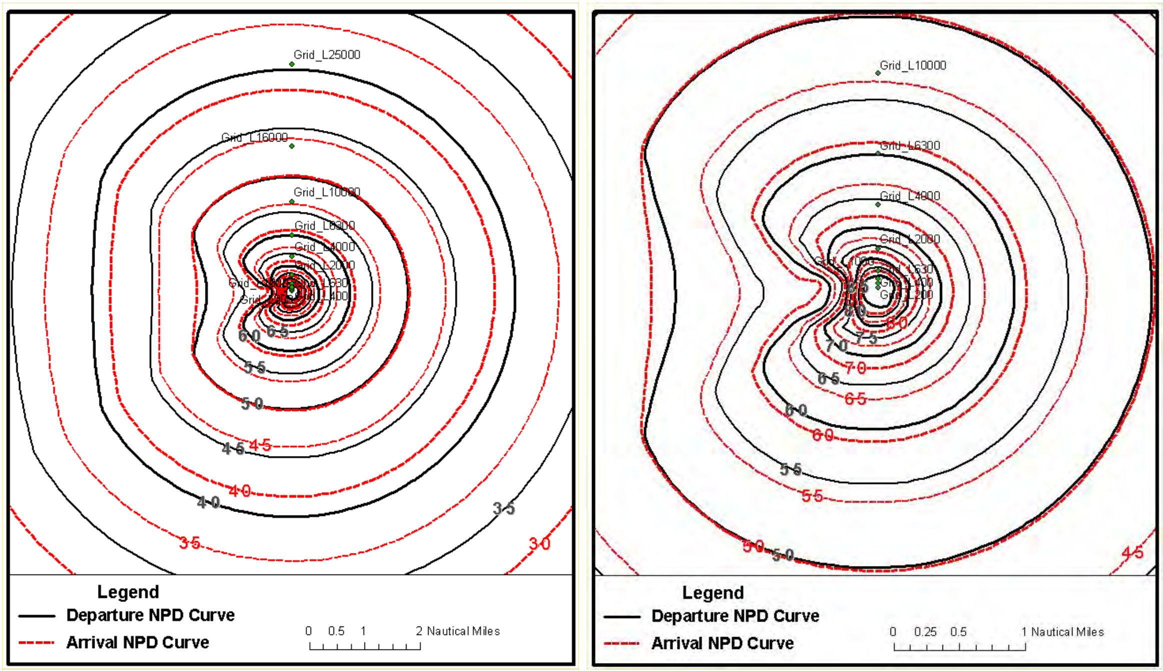

Figure 51. Run up SEL single event contours comparing departure NPD (black) vs. arrival NPD (red).

4.3.3. Combining Static and Moving Portions of Taxi Operations

Analyses were performed in order to investigate the effectiveness of the current taxi noise modeling technique - a combination of run up and near ground level over flight operations - as recommended in the INM 7.0 User Guide (*1*). Several elements come into play, including the source modeling, operational characterization and the importance of spatial distribution. This section will utilize a single event comprised of both static and moving portions, in order to investigate the impact of decisions the noise modeler must make. The effects of the combination of run ups and over flights near ground altitude and their relative spatial distribution will be considered from the perspective of the surrounding community. The community perspective is reflected in the contours by providing three levels of comparisons, over a large geographic area (~ 15 miles), an intermediate area (~8 miles) and finally a smaller area close to the airport property (~4 miles). A single recommendation for modeling technique can not be made; rather modeling decisions must consider the location of the communities of interest relative to the geographic scales of the modeling features.

Given a total taxi operation time and a percentage of time the plane is moving, what can be modeled? Consider the following case: a 737-700 taxiing down a one-half nautical mile straight taxiway. It has a total taxi time of 240 seconds (6 minutes): during 50% of the time the plane is moving, and during the remaining 50% of time, the vehicle is stationary. For this example an average taxi speed of 15 knots and 7% thrust (1680 pounds) is utilized. Within INM, a flight track representative of the moving portions of the taxi operation is defined, and locations at which static operations (treated as run ups) are defined. Both thrust level and speed are prescribed in the INM profile for the moving flight segments. A thrust level and run up duration are used to define static operations. An important exception is made here: in order to more closely compare run up versus over flight operations, the over flight will be modeled with the previously developed user defined SEL NPD extrapolated departure thrust settings in order to more closely match the Run up conditions. An alternative technique to enact a closer comparison between the operational types, would match the L_{Amax} level of the run up and over flight at some distance, it would also have introduced yet another sensitivity parameter, namely the distance at which the L_{Amax} predictions are matched, be them in the far, intermediate or close in community. This comparison based on L_{Amax} run up and Departure SEL NPD data will suffice to point out the major features and modeling implications for distributed operations.

Figure 52 a) shows a B737-700 run up modeled in a single location at 1680 pounds thrust with a duration of 120 seconds. Within the INM study three run up operations, each with a 40 second duration are modeled. This is the acoustical equivalent of a single 120 second event. The run up location is in the middle of the taxi segment.

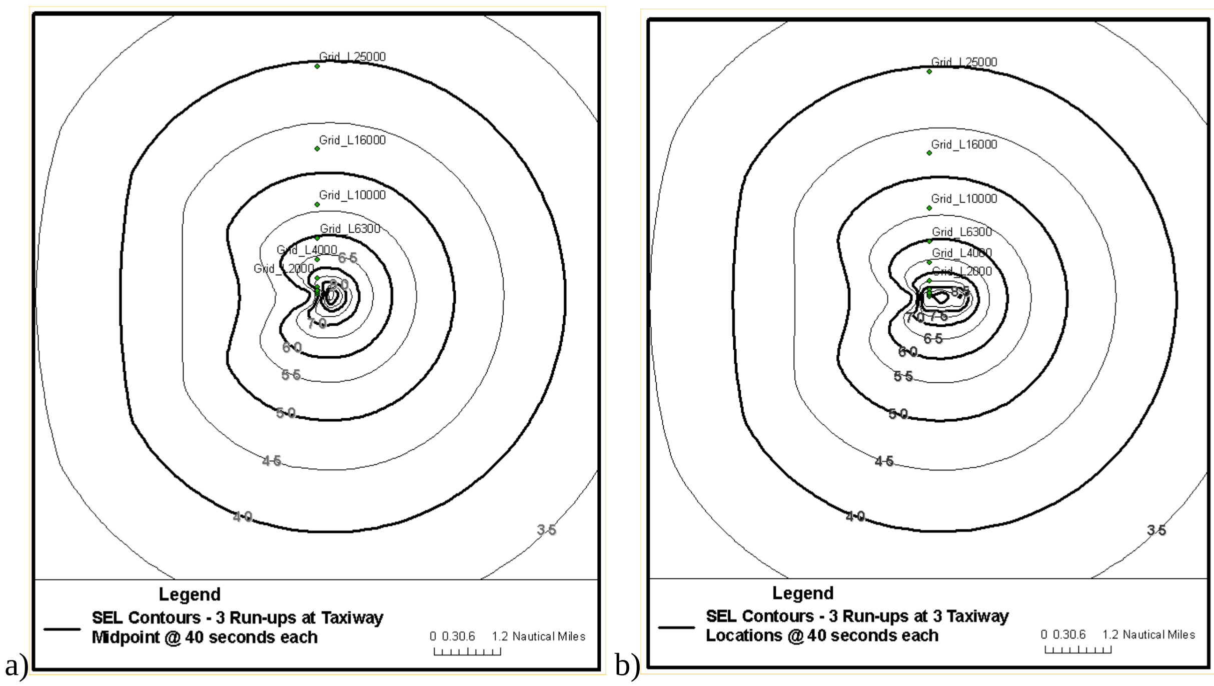

Figure 52. SEL run up operation a) center run up, b) west, center, east run up locations.

Figure 52 b) shows three run up locations modeled at the beginning, midpoint and end of the taxiway, each as a single operation with 40 second duration and 0.25 nm apart. A comparison of the single and triple location run up modeling effects is provided in Figure 53 over several regions of interest. If the community area of interest is over 5 nm away from the location of the run up operation, (Figure 53 a) modeling can likely be represented by a single run up location in lieu of three separate locations 0.25 nm apart. For community regions of interest at intermediate distances from the airport taxi operation (Figure 53 b) a judgment call must be made depending on the orientation of the community. For example if the point of interest are abeam the operations (north and south) contour differences are not as substantial and a single location with lumped operations might suffice. If the community area of interest is significantly closer to the airport, within a few nautical miles (Figure 53 c), then simplified equivalent duration modeling is not appropriate.

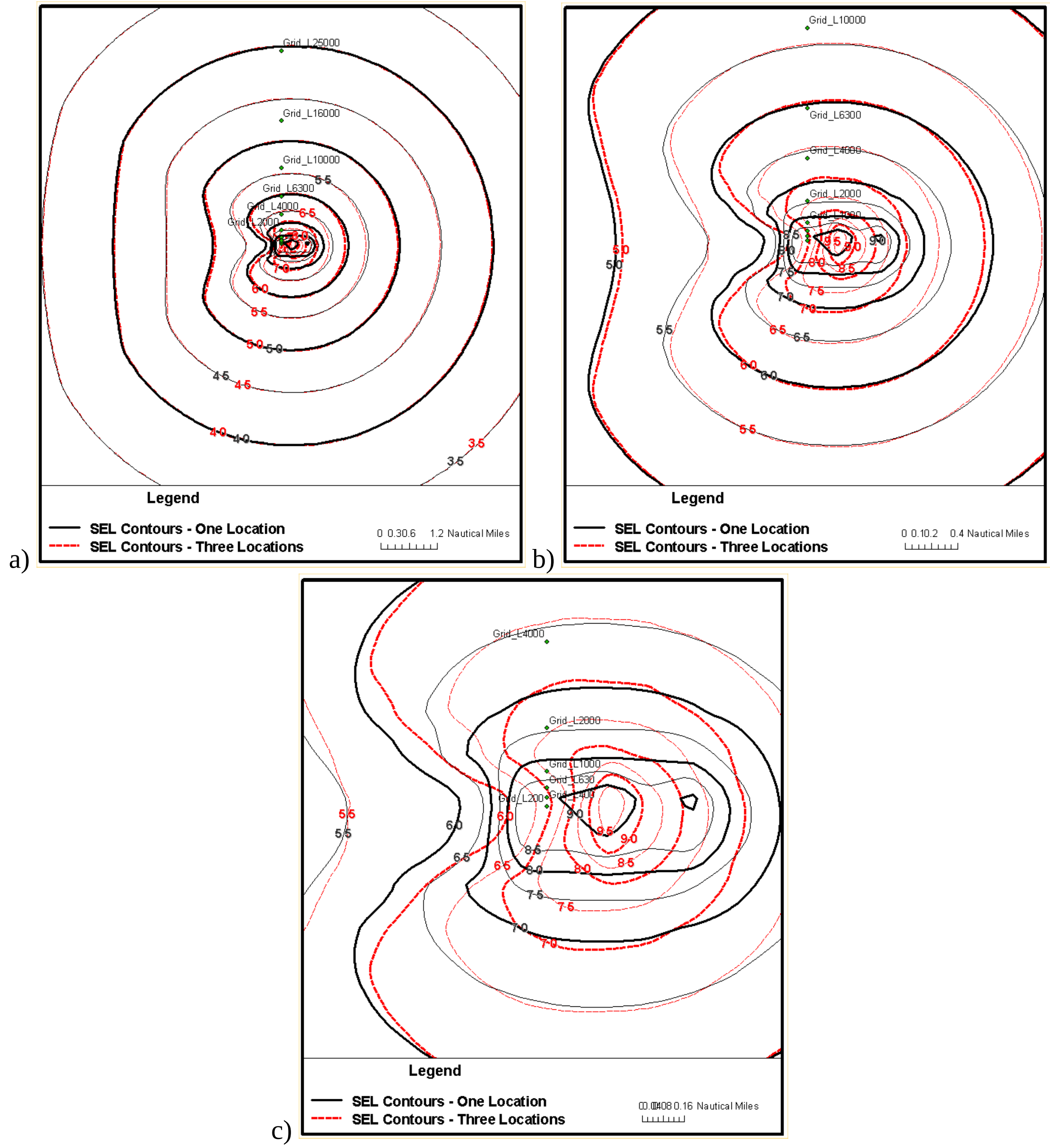

Figure 53. SEL run up contour, center only (black) and left+center+right (red) at different scales.

4.3.4. Comparison of INM7 Extrapolated NPD data with Taxi Measurement Data

Included here are the results from one sensitivity study, in which we compared INM7 predictions with measurement data. It is important to note that the actual engine operating state (% thrust) during the measurements was not known since flight data recorder information was not available during any of these measurements. Different thrust levels were modeled in INM in order to determine if a change in the modeled thrust would better match the measured taxi noise levels. If such a simple change in INM would bring predictions and measurements in alignment, it would be the simplest and least expensive way to model taxi noise in INM. Unfortunately, as will be shown in the remainder of this section, this simple thrust change in INM did not match measurement data.

In order to determine the sensitivity to thrust level in INM, a simple track was created to model a 737-700 aircraft during a single taxi operation. As suggested in the INM manual, a flight profile for the track was created with an altitude equal to aircraft's engine height. The speed was kept at a constant 15 knots for all profiles. The thrust of the profile was varied from 1 to 40% of the maximum static thrust, and the noise levels at detailed grid points were plotted. The standard INM extrapolation procedures were applied. The distances from the track to the grid points were the same as those used in the NPD curves plus an additional distance (235 ft) in order to mimic the location of noise measurements during taxi operations at Providence Rhode Island for ongoing activities at the T. F. Green State Airport (*33*). In order to better visualize the relationship between the different thrust settings, the difference level was calculated from the 7% thrust numbers. A comparison of the INM7 taxi predictions (lines) with the measurements (circles) is given in Figure 54 for several aircraft types, while Figure 55 focuses on the 737-700. The sensitivity to thrust setting of predicted taxi noise using default INM7 NPD data and extrapolation procedures is given in Figure 56.

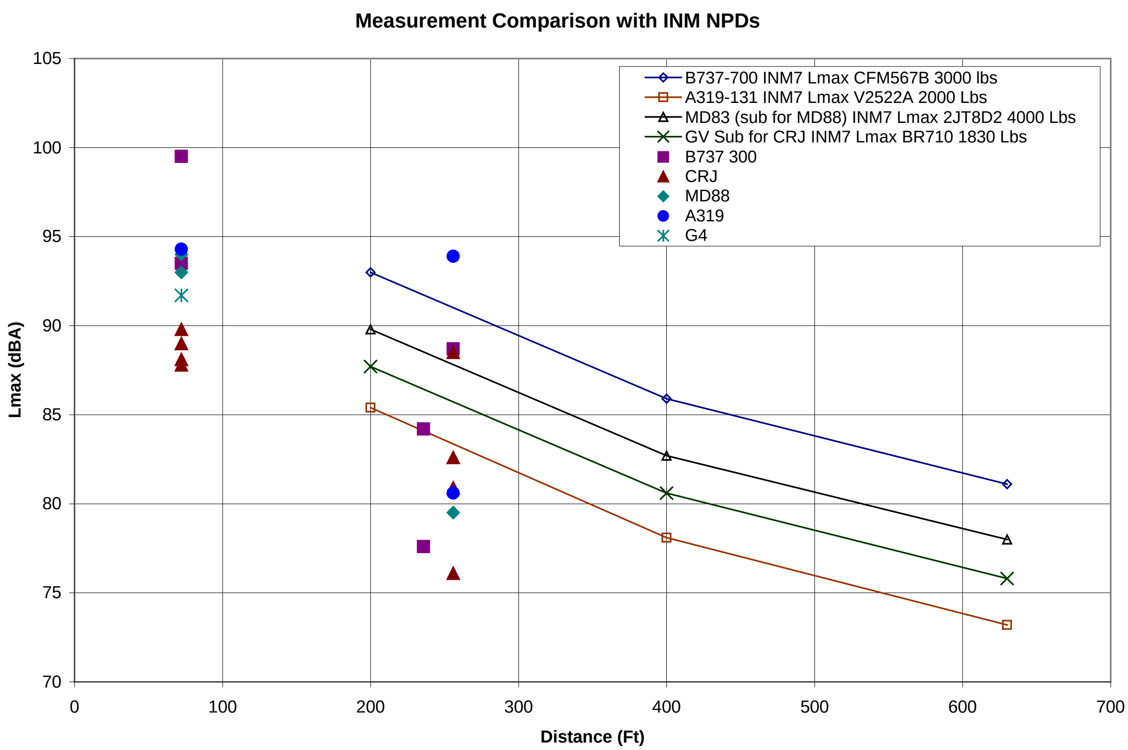

Figure 54. Taxi noise comparison for several aircraft types (INM7 and measurements).

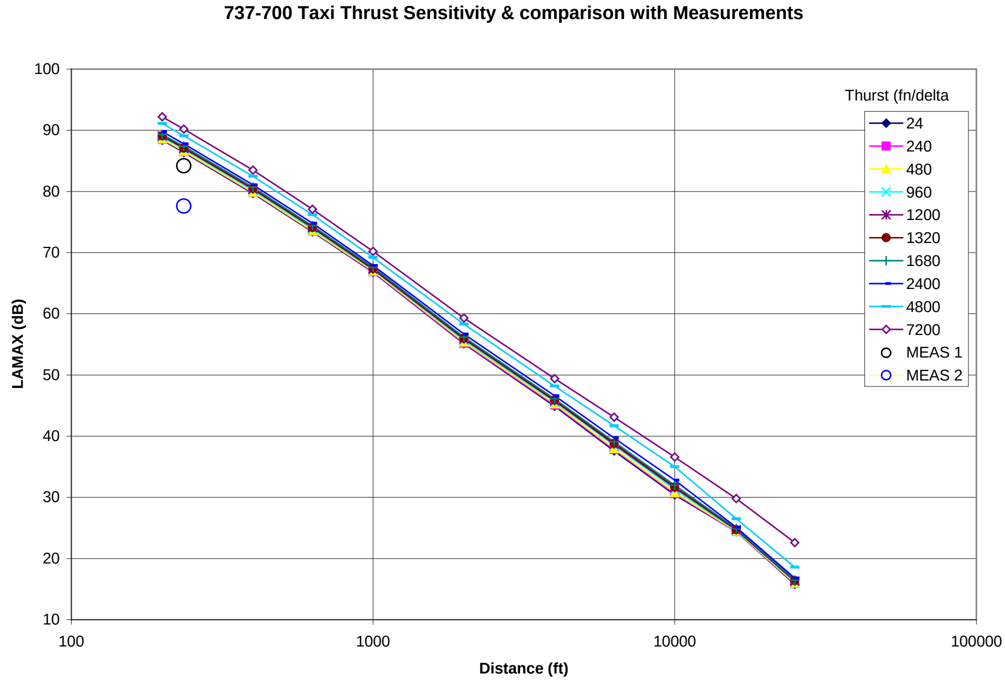

Figure 55. Taxi noise comparison for the B737-700 (INM7 and measurements).

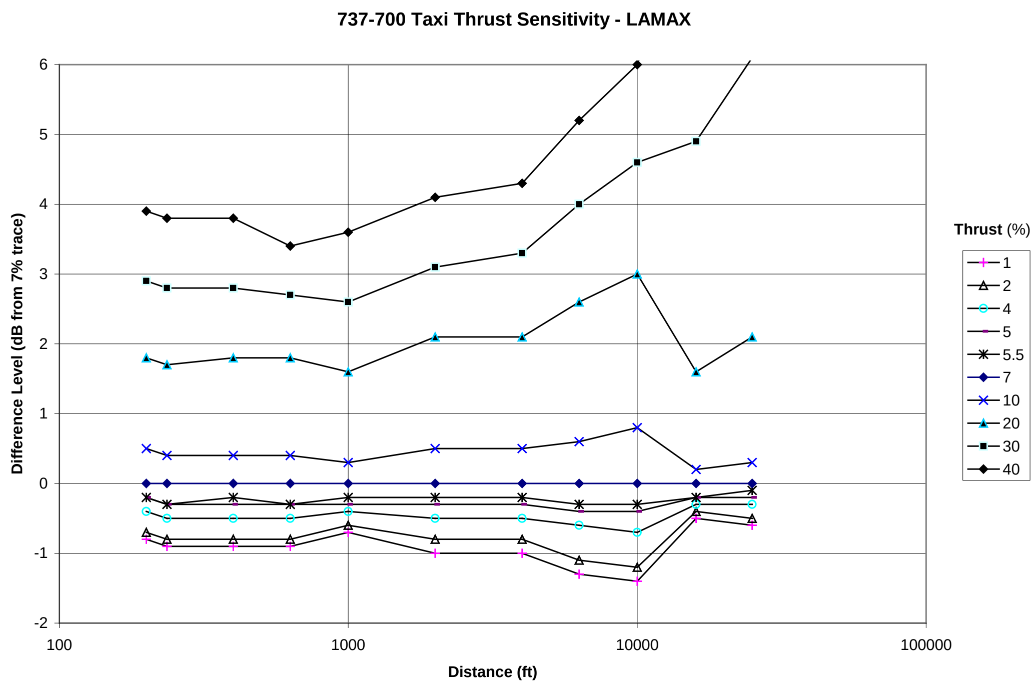

Figure 56. Difference between measurements and standard INM7 taxi noise predictions.

4.3.5. Specifying NPD Curves

Section 4.3.6 demonstrated that INM NPD data extrapolation to taxi / idle thrust settings did not agree particularly well with measurement data. The objective of this section is to determine whether customizing the INM NPD curves to match the measurement data would improve the quality of noise predictions. The data source for this analysis is two taxiing 737-700 aircraft events, measured at T.F. Green airport (Appendix B). The measurements were made 235 ft from the taxiway centerline. Both aircraft were traveling in the same direction. Their average taxi speed was 21 knots. The average SEL from the two operations was 90 dB. The meteorological conditions during the measurement were: Temperature 46 degrees Fahrenheit, barometer 30.17 in Hg and relative humidity 24%.

An INM7 study was created to mirror this scenario consisting of a 2 nm, straight-segment track oriented in the East / West direction. A 737-700 aircraft was added to the study together with a case and scenario. A user defined points profile was made for the aircraft using 3000 lb Approach thrust with speed 21 knots and altitude 5.5 ft (the composite engine height for this aircraft). A detailed grid was created 235' from the mid-point of the taxi segment. One flight operation was made that joined this profile and track.

To study the effect meteorological conditions, within the INM study the modify NPD curves feature was enabled. The effect of humidity on absorption is accounted for by using the spectral class to adjust the difference in absorption to the various distances which were pre-populated in the NPD curves (D: distance) for sea level standard day conditions. The measured data could have been corrected from the actual atmospheric conditions to sea level standard day, however we opted to instead engage the modify NPD curves option in INM thereby predicting INM results at the measurement atmospheric conditions.

The INM7 run for this operation predicted an SEL of 100.2 dB for the grid point for the case without modifying the NPD curves and an SEL of 98.2 dB with modifying the NPD curves. To obtain a corrected NPD curve for the custom aircraft, the 3000 lb approach levels were normalized to the measured levels by subtracting the difference between the predicted and measured SEL at 235'. This was done for both cases – with and without weather considered. The default approach-NPD curves at various power settings (indicated as 3000A, 4000A etc…) are compared with the corrected NPD curve (solid dots) and the corrected and modified NPD curve (plus symbol) in Figure 57.

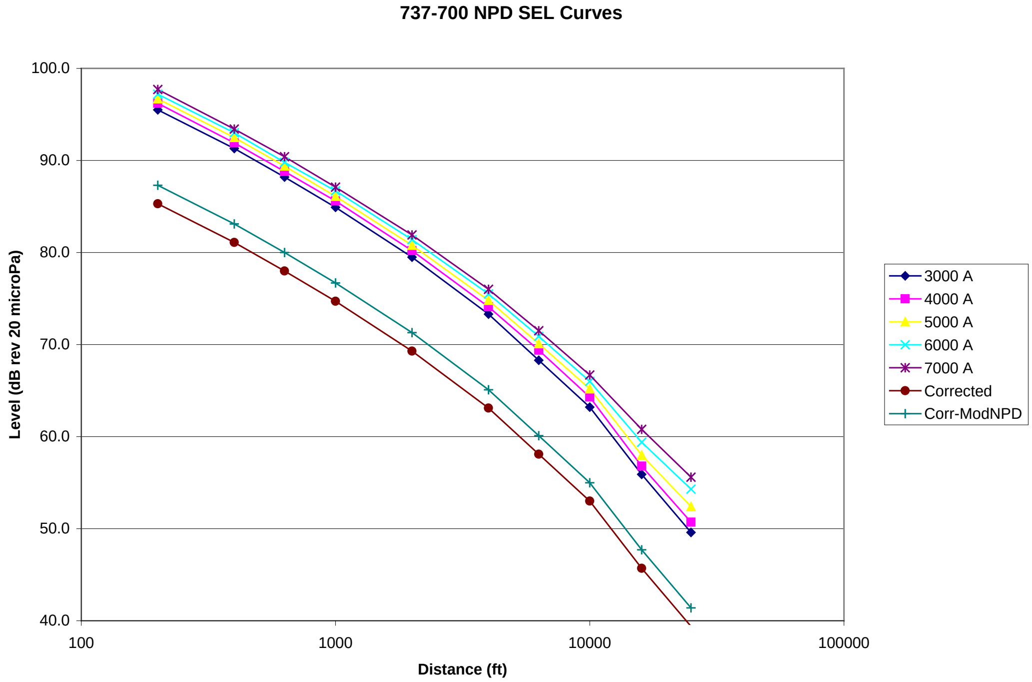

Figure 57. INM7 approach and user defined taxi NPD curves based on measurements.

Two user-defined aircraft were then added to the INM7 study using these custom noise IDs with the corrected data as the 3000 lb approach power condition. Since INM7 requires one to define in the custom NPD dataset for at least two power settings, a 4000 lb approach data NPD curve was added to the custom noise ID with identical corrections.

The custom aircraft were modeled as operations on as above. Both cases correctly predicted the measured SEL of 90 dB at 235'. The case for the corrected aircraft using the weather data to make the NPD curve had to be run checking the 'modify NPD curves' in the case study with the meteorological conditions noted above in order to match the 90 dB at 235'. The INM7 default spectral class, #203 for Approach, was used.

The difference in the SEL contour for the original 737-700 and these customized versions can be seen in Figure 58. The area is a 16 nm by 16 nm square. The dashed contour lines represent the corrected predictions for the aircraft made without modifying the NPD curves, the dotted contour lines represent the corrected predictions for the aircraft made with the 'modify NPD curves' option, and the solid lines represent the predictions from the original 737-700 aircraft modeled with 3000 lbs thrust and traveling 21 knots. As can be seen, the effect of the slightly higher amplitude NPD curve results in the contour area of the Corrected 737-700 expanding by a proportional amount.

The purpose of this simple exercise was to develop a process for obtaining a new INM NPD curve from a simple measurement data point, to create a user defined NPD curve within INM and successfully predict the measured noise value while correcting for atmospheric conditions using an INM spectral class. These objectives were accomplished, lending credence to one modeling concept whereby a new taxi-NPD class could be created in INM (in addition to approach-NPD and departure-NPD) and populated based on actual taxi noise measurement data.

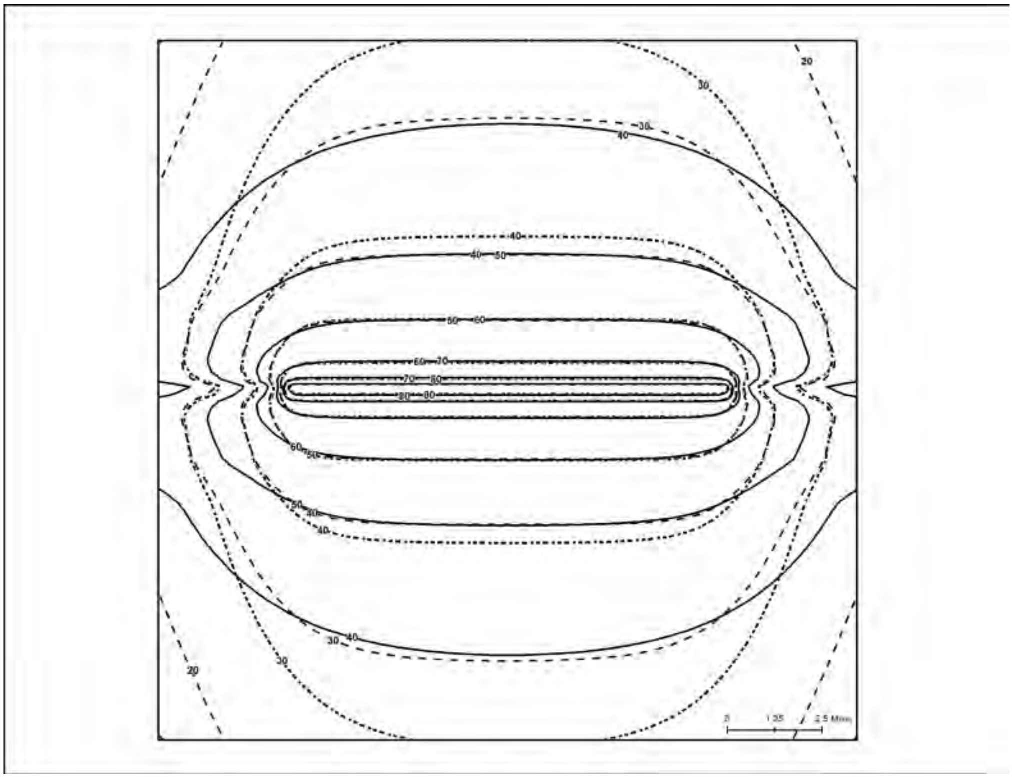

Figure 58. Contour comparison taxi operation: INM7, user defined, user defined + modified

4.3.6. Source Height Modeling and INM Directivity

The INM User's Guide specifies that for moving taxi operations the flight profile should specify the flight altitude as the average engine installation height. As long as the engine height is greater than zero, INM is prevented from applying longitudinal directivity (Ground-Based Directivity Adjustment - as is applied to the region behind the take off roll), to the propagation computations. Lateral directivity, as specified by SAE (*34*) is applied only when the aircraft is above 0 ft. height. In this section, the effects of the aircraft altitude defined in the user profile, are investigated.

The effect of varying the source height was explored using a single track operation. The taxi segment starts at the origin and heads 'East.' Two separate single event taxi operations were modeled, both using departure NPD curves at the same thrust setting, 1680 lbs. In one case the B737-700 aircraft was modeled at the composite engine height of 5.5 ft. In the second case, the aircraft was placed on the ground at 0 ft.

Figure 59 shows SEL predictions for a single 15 knot taxi operation traveling from west to east, modeled in INM as an over flight the half-nautical mile length of the taxiway with 1680 pounds departure thrust at an altitude of 5.5 ft AGL. A half nautical mile distance traveled at a speed of 15 knots will take 120 seconds to traverse. As can be seen in Figure 59, the 40 dB SEL contour nearly reaches the 25,000 ft grid point (corresponding to the largest distance in the INM NPD curves). The maximum width of this contour is only slightly less in extent than that of the 120 second single and combined static run up operations, as seen in Figures 51, 52 and 53. The pinched in aspect of the contour lines at the sides of the figure are an artifact of how INM applies a noise fraction to an infinitely long track segment to approximate the half mile segment modeled here. This example demonstrates INM's use of finite track segments and SEL NPD curves for predicting noise contours from moving operations. In this particular example the flight segment was modeled using a departure SEL NPD curve rather than an approach SEL NPD curve to more closely match the static run up computation presented above in Sections 4.3.2 and 4.3.3.

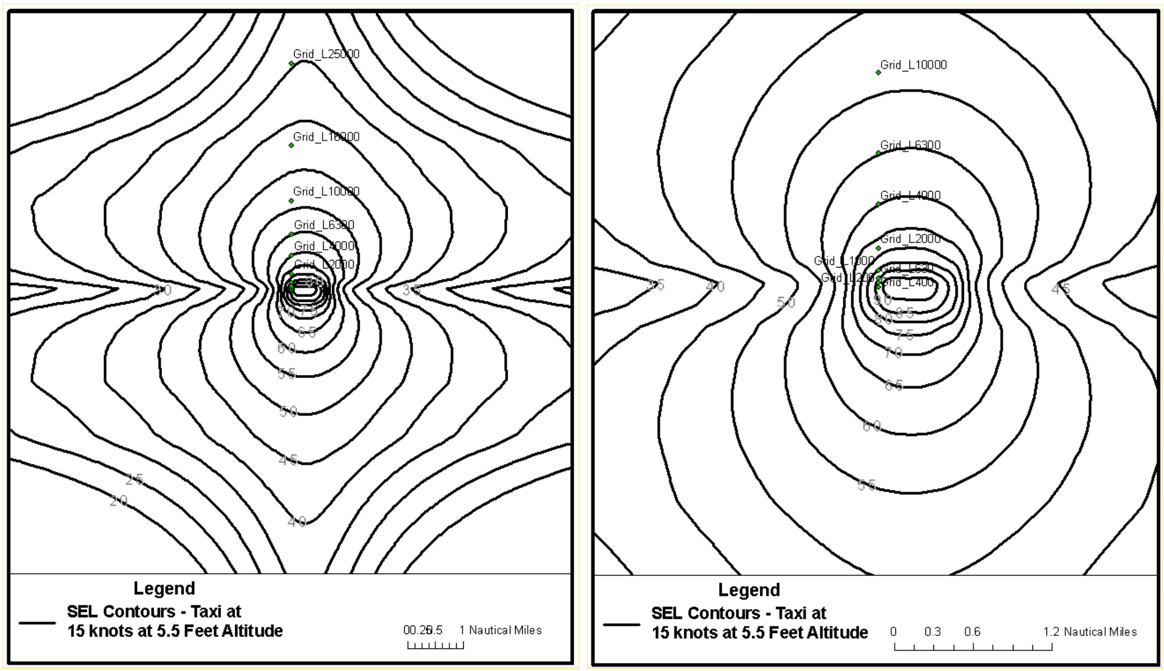

Figure 59. INM single segment moving taxi operation at 5.5 ft AGL.

An interesting effect, the filling in of the contour area behind the aircraft, can be seen when modeling the 15 knot taxi operation on the ground at 0. ft AGL (Figure 60). The taxi operation starts at the West side of the track and heads in the easterly direction. The contours are filled in based on the behind takeoff roll longitudinal directivity algorithms in INM. These algorithms are designed to more accurately portray departure operations, but are only enabled within INM by placing the aircraft profile at 0 ft. The East side of the figure still shows the effect of INM modeling a finite track segment. It should be noted that this track segment connected to another track segment, rather than treated as an isolated segment, the first segment would be 'filled in' by the subsequent track segment. This is related to the reasoning behind the noise fraction adjustment used by INM to account for finite length track segments; though how accurate this portrayal is for individual taxi segments especially at longer propagation distances with low grazing angles remains to be seen. Figure 61 displays INM contours for moving taxi operations at both 5.5 ft and 0 ft with one another. There is a significant impact on the noise contours due to INM applying the behind takeoff roll algorithm for taxi operations.

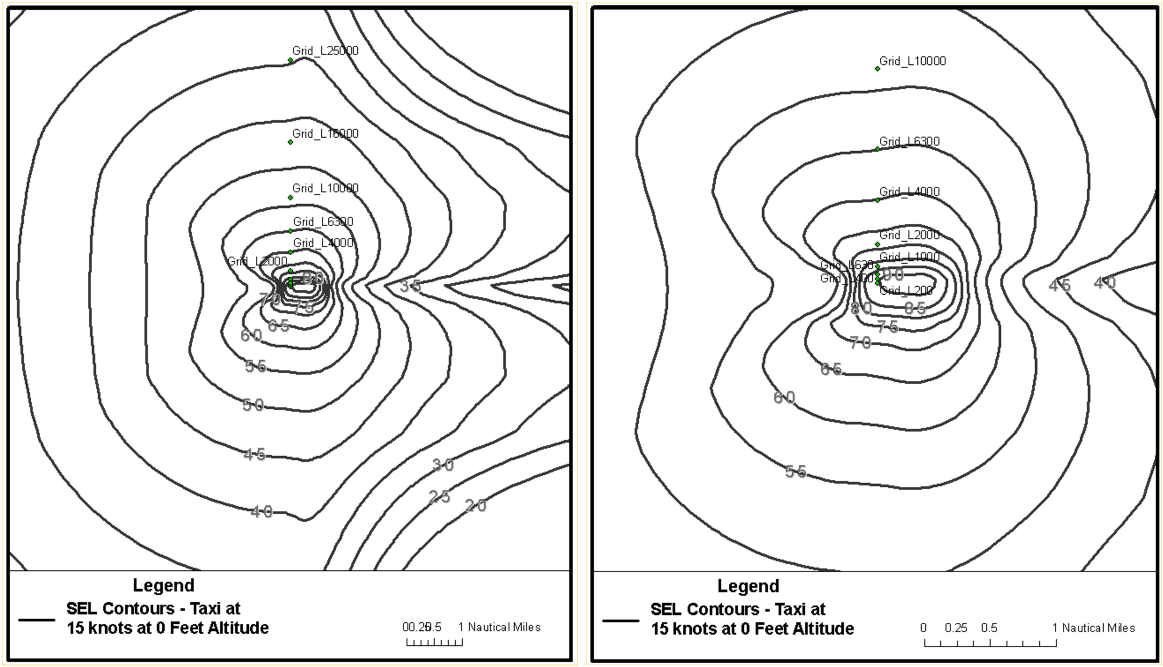

Figure 60. INM single segment moving taxi operation at 0 ft AGL.

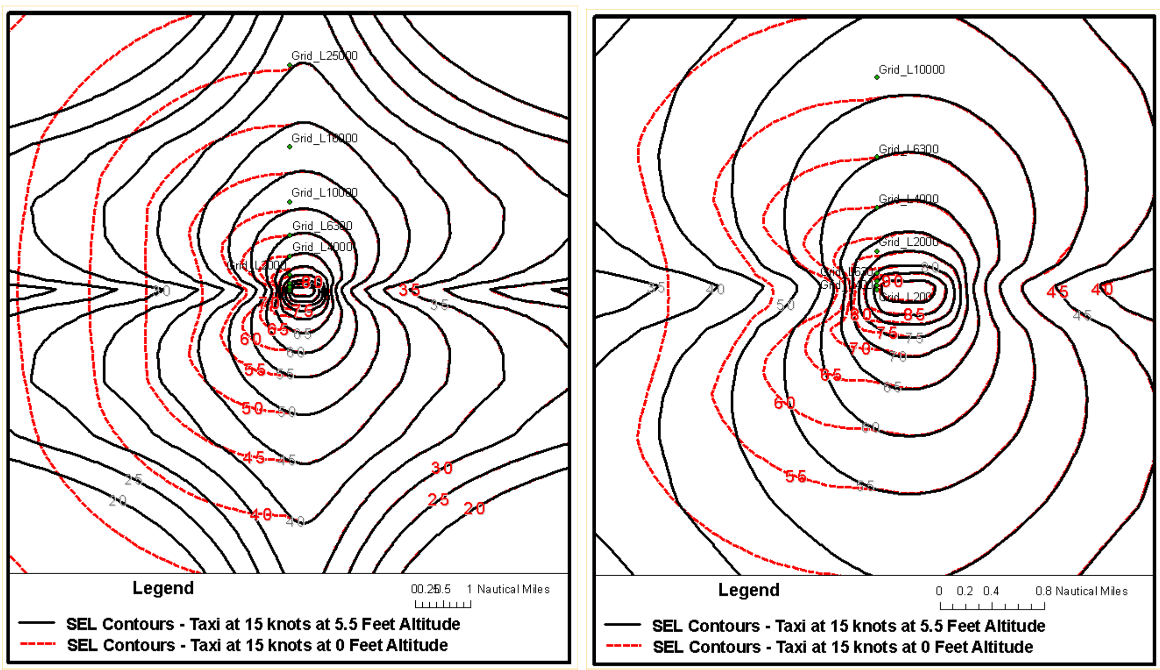

Figure 61. Comparison of INM Single Segment Moving Taxi Operations at 0 and 5.5 ft AGL

4.3.7. Effects of Taxi Speed

Of interest in the modeling of taxi noise is noting the fact that the speed assigned to a flight segment influences the exposure metric (SEL) as stated in the INM7 Technical Manual (Equation 2).

$$DURadj = 10 \log10(ASref/ASseg) \qquad (2)$$

Where ASref is 160 knots and ASseq is the speed of the aircraft on a track segment.

An increase in speed will decrease the SEL. Using a 2-nmi straight track a set of detailed grid points were made at distances perpendicular to the midpoint of the track. User-defined profiles were made for a 737-700 traveling at 5.5' altitude (the composite height of this aircraft's engines) at 1680 pounds thrust (7% of max static) using INM extrapolations of the approach operation NPD curves as recommended in the INM manual for speeds noted. As expected, for a doubling of speed doubled, the SEL decreased by 3 dB (Figure 62). This is important information in defining the relationship between when an aircraft is stationary and when it is moving.

Figure 62. INM7 effect of taxi speed on SEL.

4.3.8. Single Event Standard INM7 Modeling of Time in Mode Operations

It has been suggested that taxi operations can be more simply modeled using a "time in mode" approach, where operations are represented by an accumulation of time spent stationary and moving lumped together at key locations on the airfield. This example shows the dominance of the static operations over moving operations when employing the *current INM manual suggested modeling technique*: Approach-SEL for over flights and run up data for static operations. In this study, three different operations, each requiring 240 seconds, were considered and compared.

Figure 63 shows a composite of three different computations by INM, with each operation a duration of 240 seconds. The red contour indicates only the taxiway as an over flight – the same operation considered in the generation of Figure 59, and the blue contour is the over flight taxi operation and three static run ups at one location. The red contour lines result from modeling a single over flight of a 737-700 at 5.5 feet altitude with 1680 pounds of (departure) thrust traveling 7.5 knots on the taxiway. The time it would take an aircraft to travel the 0.5 nm length of a taxiway at 7.5 knots is 240 seconds. The dashed, green contour lines result from the summation of two operations in INM: an over flight of a 737-700 at 5.5 feet altitude with 1680 pounds of (departure) thrust traveling 15 knots on the same taxiway segment with a duration of 120 seconds and three static operations (as depicted in Figure 51). The three individual static run up operations are at the beginning, midpoint, and end of the taxiway for a total duration of 120 seconds. The solid blue contour lines result from modeling two operations in INM. One operation is the same over flight of the 737-700 at 5.5 feet altitude with 1680 pounds of (departure) thrust traveling 15 knots on the taxiway. The other operation is that depicted in Figure 52, a single run up at the midpoint of the taxiway of a 737-700 running with 1680 pounds thrust for a duration of 40 seconds with 3 operations assigned to it. As expected, these contours overlay those made from the 3 separate run up locations of equal durations.

One can see the dominance the static portion of the taxi operations have over the over moving portion of the taxi operations in most areas of the study. This is primarily due to the inconsistency between the approach-NPD curves and the L_{max} data for static run up operations. With the current range of available thrust settings and INM's extrapolation procedure, stationary operational noise (obtained from the run up L_{max} NPD curve) rather than the moving operational noise (obtained from the extrapolated approach-SEL NPD curve) dominates the contours. This example indicates that modeling of taxiway segments in INM may be represented as single run up operations at the midpoint of the segment with the caveat that the levels need to match those that actually represent a taxiing aircraft.

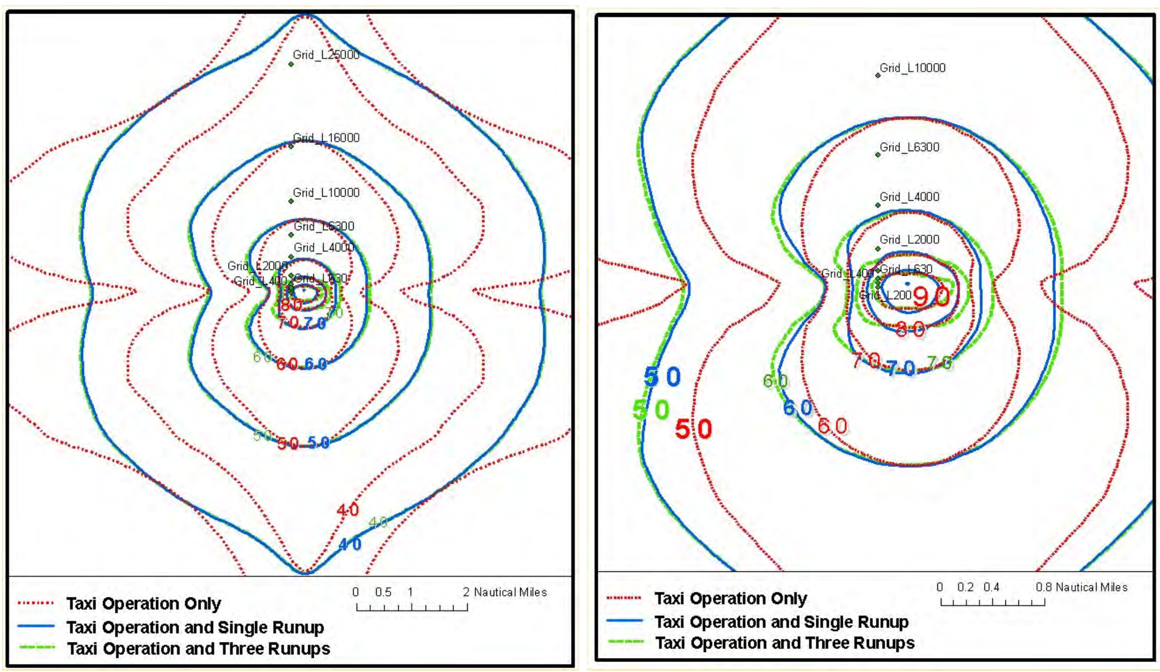

Figure 63. INM single event comparison from combined moving and stationary operations.

In summary, within INM and the current AEDT noise computational module, the distinction between source modeling and propagation modeling is not completely separated. It is important that there is consistency between the NPD data used for moving operations and the L_{max} data used for static operations. This consistency will permit taxi predictions from time in mode operational parameters if the geometric area of coverage is preserved. The impact of holding queues on the nearby community can be important for distances under one mile. Expansion of the taxi modeling capability within INM and in the future, AEDT will need to ensure consistency between propagation and source modeling effects and commonality between static and moving operations NPD source noise data.

CHAPTER 5. SUGGESTIONS

Considering the wide range of measured taxi noise and the spread of the source noise data presented thus far in this report, it would appear that the chief burden of improvements to current state of the art techniques for taxi noise modeling falls upon the creation of an adequate taxi noise source database for use in INM and AEDT.

The wide range of geometric operational modeling fidelity, a strong driver of the noise contours, can already be accommodated in INM, albeit some with significant user burdens. The finer details of the source noise modeling (spectra, lateral and longitudinal directivity and lateral attenuation) are present in INM, though not currently implemented in the most applicable manner for taxi noise.

The remainder of this chapter covers the principal elements involved in taxi modeling, gathering together the key points and suggestions of the sensitivity portion of the study.

5.1. Source and Propagation Modeling

5.1.1. INM NPD Data

A new taxi-NPD class should be created in addition to the existing approach-NPD and departure-NPD datasets. An interim extrapolation procedure for INM7 could be based on a simple dB / lbs Thrust correction as a short term patch to extrapolate existing NPD data down to taxi idle thrust conditions. This approach would require analysis of measurement noise data across a range of low thrust settings and engine types.

5.1.2. Thrust Settings for Taxi Operations

The thrust label in the NPD data is a label that points at the appropriate source SEL value. Taxi thrust is not a performance factor as it is in flight profile modeling. CAEP data (*18*) does not indicate a strong dependence of taxi thrust or breakaway thrust with aircraft takeoff gross weight, therefore one does not expect the noise from taxiing events to exhibit a strong dependence with aircraft takeoff gross weight either.

Breakaway thrust can be considered a secondary taxi engine and noise state. There is precious little flight data recorder data documenting breakaway thrust and detailed engine operating states, and even less capturing the noise from a breakaway thrust operation. We were not able to locate any data for which contains a synchronized time trace of the vehicle motion and engine operating state and acoustic measurement data. Limited measurements suggest that noise at the breakaway thrust condition for larger commercial aircraft is on the order of 3 - 7dB louder than idle thrust taxi settings. Simulation modeling shows some potentially important effects of breakaway thrust noise; however limited historical data on the frequency and duration of breakaway thrust use, combined with the limited acoustic data suggests further investigation is warranted.

5.1.3. Lateral and Longitudinal Directivity

Within INM the distinction between source modeling and propagation modeling is not completely distinct. Section 4.3.7 “Source Height Modeling and INM Directivity” considered the current INM process for applying lateral and longitudinal directivity to the taxi noise computations. Section 4.1 “Single Event Analysis” considered detailed simulation techniques with AAM using 3D spectral noise sources to assess the sensitivity of various source features on noise contours. AAM treats the lateral and longitudinal directivity as a source modeling input, not as propagation corrections as is the case within INM. Expansion of the taxi modeling capability within INM and in the future, AEDT will need to ensure consistency in propagation and source modeling effects between static and moving operations.

5.2. Trajectory/Airspace Modeling

Under some circumstances one may have access to detailed operational information documenting exact taxi paths, times spent holding at various locations and specific details of exact paths taken between terminals and runways, and an ambitious noise modeler might choose to undertake inclusion of such details in taxi noise predictions on the local community. Under these circumstances, (which admittedly will become more frequent when AEDT and EDMS become available), it is important that the future model for taxi noise feasibly permits the user to representing such aircraft motions by stringing together combinations of aircraft run up and over flight operations at altitudes near the ground. The effects of combining operations and their relative spatial distribution, as was examined in detail in Chapter 4, is important to preserve the multitude of potential modeling scenarios already implemented within the current INM7 architecture.

5.2.1. Terminal & Gate Modeling

Chapter 4 described changes in taxi noise contours from a series of operational and geometric modeling scenarios with decreasing complexity. These results indicate that the spatial coverage of the aircraft movements has the greatest impact on the contours. It is reasonable to simplify taxi tracks from a terminal area instead of individual gates if the tracks are selected appropriately.

5.2.2. Static Operations, Holding Queues and Breakaway Thrust Modeling

It is important that there is consistency between the NPD data used for moving operations and the L_{max} data used for static operations. This consistency will permit taxi predictions from time in mode operational parameters if the geometric area of coverage is preserved. The impact of holding queues on the nearby community can be important for distances under one mile. An initial assessment of the impact of breakaway thrust on contours from noise simulation using nominal taxi parameters was inconclusive due to the lack of noise sensitivity data at low thrust settings.

5.2.3. Moving Aircraft along Constant Speed Segments

One item which must be considered when making suggestions for taxi noise modeling is the scope of effort and the availability of the data required to perform the analysis. The high fidelity taxi noise assessment highlighted in Section 4 involves a significant amount of resources, from considering the overall annual operations, determining the average busy day, performing detailed queuing and delay assessments under a range of environmental conditions, modeling every individual taxi way at the airport, considering the distribution of airlines, gate assignments, equipment usage and determining individual aircraft taxi paths from gate to runway. Obviously the higher fidelity the available data, the more precise the taxi noise assessment will be. However in many cases such a study is unwarranted. The remaining sections in Chapter 5 will pull together the key findings of the sensitivity assessments presented in Chapters 1-4, and provide some guidelines and considerations for selecting the appropriate level of modeling.

5.2.4. Simplified Time in Mode Modeling

When computing taxi noise contours, the application of simplified emissions parameters for time in mode modeling is not recommended. The acoustic impact will depend on the difference between the actual and modeled times in mode. FAA databases are available to obtain taxi times from historical operations. As seen in the noise contours presented in Chapter 4 combining various techniques for moving and stationary operations and considering the duration computation, the taxi noise contour sizes are related to taxi operational duration. Of course for those airports where flight operations dominate the overall noise contours, the impact of the taxi portions can be significantly diluted.

5.3. Taxi Noise Modeling Implications on INM Data Requirements

5.3.1. NPD Data

The thrust settings used in taxiing are well below the high thrust settings used for takeoff, but can be comparable to the thrust settings used for approach and landing. Taxi and idle operating state noise data is not included in the standard Noise-Power-Distance (NPD) curves employed in INM7. The noise levels defined for approach are associated with much higher airspeeds, and include the contribution from airframe noise–a noise source not associated with taxiing operations. It is questionable that the lower thrust approach condition NPD data present in INM is applicable to taxi noise modeling. Comparisons with measurements indicate an over prediction of noise by INM when using the standard NPD curves. Extrapolating the curves down to these low thrust levels appears to be a simple solution, but the current extrapolation procedures employed in INM do not yield results that agree with measurement data.

This report presented a multitude of acoustic measurement acoustic test data for low-thrust taxi conditions obtained from various sources, supplemented with noise data measured specifically for this study. A wide variety of aircraft types have been measured internationally using several different measurement techniques and analytical methodologies for assessing engine source characteristics. Differences in the measured SEL values for taxiing aircraft varied considerably.

5.3.2. Spectral Classes

Measured data was examined and assess differences between the published INM spectral classes and spectral directivity for low-thrust engine operations. Chapter 3 documented one process by which limited taxi measurement data could be applied to 3D spectral noise spheres and then simulated trajectories could be used to analytically build NPD data for INM. Normalized spectral directivity data was shown from a multitude of taxi and static idle engine test stand measurement data. This difference in spectra from the INM spectral classes is primarily an increase in levels at higher frequencies oriented towards the front of the engine which could have an impact on nearby communities.

5.3.3. Directivity Considerations

A collection of empirical taxi directivity data has been presented for a wide variety of aircraft. There is a considerable amount of scatter in the normalized aircraft directivity assessments; however a wide variety of measurement techniques and atmospheric conditions were used for measurements. The most comprehensive and consistent measurement dataset for nominal taxi noise directivity and spectra is that obtained in Madrid, however the documentation presents one longitudinal spectral directivity for each aircraft type in the form of sound power and does not addresses breakaway thrust.

5.3.4. Aircraft Performance/Operational Thrust Data

Data assessing the operating state of aircraft engines during taxi operations was presented as was acoustic data for idle taxi and breakaway thrust noise events. It is suggested that in the long term, additional measurements be made for taxi operations where synchronized noise and engine operating parameters can be obtained. This data will be required to determine the noise sensitivity at low thrust settings and allow a realistic evaluation of breakaway thrust impact.

CHAPTER 6. INM TAXI NOISE IMPLEMENTATION

INM 7 contains the backbone necessary to define detailed taxi aircraft movements and compute noise from taxi operations; however several modifications are necessary to affect a proper solution. These modifications fall into two areas: Operational and Acoustic. One important consideration for taxi noise which has not been a focus in INM (other than to a limited degree for run up operations) is the element of time. Taxi noise contours are directly impacted by the amount of time spent performing taxi operations (taxiing and holding). The treatment of the time element in INM is a common thread in many of the proposed features.

Within INM, analysis of taxi operations should be treated much as any other analysis and the user given the flexibility to organize studies, scenarios and cases. There are some extensions to the GUI that will need to be made to accommodate taxi analyses as proposed in this report. These are also described in the following sections.

For each of the specific modifications, an importance assessment of low, medium or high has been made. An appraisal of the difficulty of implementation in INM has also been provided with the ranking of easy, moderate and difficult. A ranking of easy is reserved for those features which likely only require a simple flag status check and enabling of a specific algorithm for taxi situations. The difficult implementation ranking is expected to require major changes both to the database, current internal storage arrays, and will likely impact data screens in the GUI. With each taxi noise feature discussion, an indication of a rough order of magnitude level of effort and costs (based on an average $150/hr burdened labor rate) as well as any other required modifications has been provided.

6.1. Taxi Operations

In INM, operational trajectories are created in the compute module, by combining ground tracks with flight profiles. In keeping with this structure, the most suitable method of input for taxi motion is via ground tracks and point-to-point profiles. Procedure step algorithms for determining aircraft altitude, speed and thrust based on aircraft performance data as defined in SAE-AIR-1845 are not applicable to taxi operations.

6.1.1. Taxi Tracks

User creation of taxi tracks should be consistent with the existing P-tracks feature in INM. Helicopter taxi tracks are not extended using a 100 nmi straight segment on the last defined track, and taxi tracks should be treated similarly. Track dispersion for taxi tracks should not be enabled as it is not a realistic scenario.

The Add Track menu (Figure 64) already displays the Taxi track type; however taxi tracks need not be associated with a runway or helipad as they can be used to model tracks to and from run up or maintenance facilities.

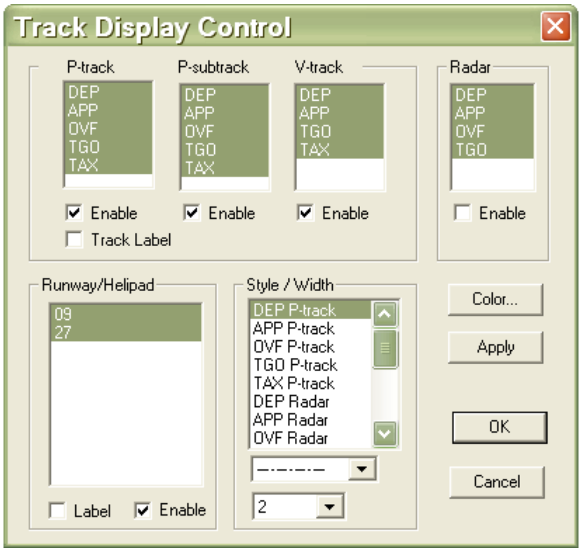

Figure 64. Track display control screen.

Taxi Tracks

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
High	Easy	80	12k	None

6.1.2. Taxi Profiles

Taxi profiles should be structured in such a way as to permit the user to string together segments modeling changes in speed and thrust. For taxi operations, the aircraft altitude does not change; therefore, it is important to add the height of engines above the ground to the aircraft-specific data used for taxi profiles.

For analyses requiring only low fidelity computations or backwards compatibility with previous studies, a simple two point profile with constant speed and thrust as is currently recommended in the INM manual can be used. As was demonstrated in the sensitivity study, the existing INM track and profile modeling techniques combined with static run up operations can be used to model detailed taxi motions.

To reduce the input burden on users performing higher fidelity modeling, it would be beneficial to include the ability to define specific taxi profiles with multiple segments including stationary holds and stationary regions where breakaway thrust is applied. The operations can then be split internally into stationary and moving segments (transparent to the user), and the noise computed in the same manner as currently exists in INM. The benefit to the user of defining and linking holding queues to specific taxi profiles is that it would significantly reduce the amount of external record keeping.

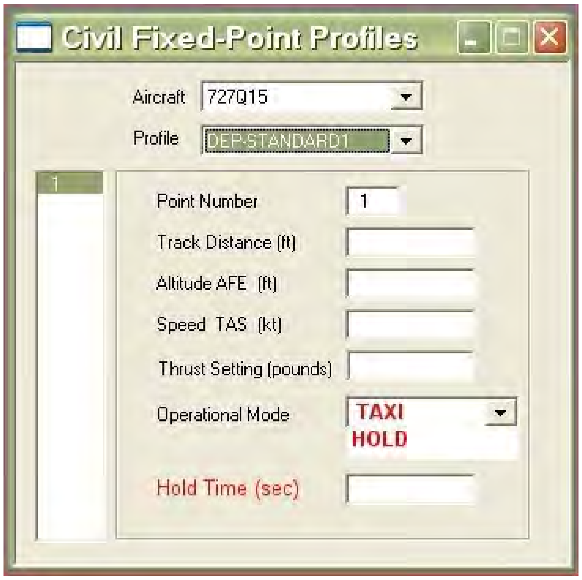

Figure 65. Fixed point profile form.

Taxi and Hold Profiles Implementation

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
Medium	Moderate	160	24k	Aircraft Engine Height Dataset

Aircraft Engine Height Dataset - Assimilation from Public Data Sources

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
Medium	Moderate	60	9k	Taxi and Hold Profiles GUI

6.1.3. Thrust Settings for Taxi Operations

The thrust in the NPD data is a label that points to the appropriate source SEL or L_{max} data. There is scatter in existing empirical taxi noise data. Current taxi modeling guidelines for emissions analyses suggest a nominal value of 7% thrust, however this is a subject of debate. INM currently requires the user to specify a suitable thrust setting, but this feature is only required if the current NPD structure (see Section 6.1.1) is retained. If the recommendation to create a ND database (with no acoustic thrust sensitivity) is implemented in INM, then this feature is not needed.

Breakaway thrust is used by some aircraft types more often than others and reflects a higher taxi engine and noise state. Limited measurements conducted as part of the sensitivity study suggest that noise levels at the breakaway thrust condition for larger commercial aircraft are on the order of 3-7dB higher than idle thrust taxi settings, and last for approximately 10 seconds. Nominal taxi thrusts, speeds, breakaway thrust settings and duration can be implemented in INM as standard taxi profile steps with the flexibility to build more complex user defined taxi profiles.

Default INM Assignment of Taxi Thrust Settings

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
Low	Easy	40	6k	None

6.2. Acoustic Algorithms

Within INM the distinction between source modeling and propagation modeling is not completely obvious. Expansion of the taxi modeling capability within INM, and in the future AEDT, will need to ensure consistency in propagation and source modeling effects between static and moving operations.

6.2.1. Source Spectra

Differences in spectral content between flight and taxi noise suggests that a new taxi-NPD class be created in addition to the existing approach-NPD and departure-NPD datasets. Taxi noise spectra often contain higher frequency content noise due to engine ingestion of a ground vortex. These differences in spectral content can cause an under prediction of taxi noise in communities located at shorter propagation distances from the taxi operations.

INM Spectral Class data is located in the system subdirectory SYS_DATA and contained in an encrypted compressed binary format file SPECTRA.BIN. At present INM contains 34 Approach and 34 Departure spectral classes. The most logical extension would be to create 34 taxi spectral classes. Each of these new taxi spectral class data should be based on nominal empirical taxi spectra for the same aircraft types representing each class. The process used for determining the nominal spectra (i.e. fleet mix weighted average) should mirror the process that was used to develop the approach and departure spectra already in INM.

With the addition of a new Taxi Spectral Class the Civil and Military Noise Identifiers interface will need to be expanded to point to the appropriate Taxi Spectral Class (Figure 66).

Figure 66. Noise identifiers screen.

Taxi Spectral Class – GUI & Database Updates for INM 7

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
Medium	Difficult	40	6k	Taxi Spectral Class Dataset Taxi Spectral Class Acoustics

Taxi Spectral Class – Dataset Development

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
Medium	Difficult	80	12k	Taxi Spectral Class Dataset Taxi Spectral Class Acoustics

Taxi Spectral Class – Acoustic Implementation in INM 7 Computational Module

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
Medium	Difficult	80	12k	Taxi Spectral Class GUI & Database Taxi Spectral Class Dataset

6.2.2. Taxi-NPD Data

Implementation of a taxi-NPD database for INM will require preparation of measurement noise data across a range of aircraft and engine types, and will require either adoption of an existing comprehensive taxi noise database or additional acoustic measurements. In the short term we suggest adoption of the taxi noise data contained in reference (*26*). This data will need to be processed for each aircraft type from the current form (spectral directivity sound power) to a taxi spectral class for use in INM. This activity is referred to as Taxi NPD Database Development. Additional aircraft types found in the INM database, but not contained in reference (*26*) (primarily regional jet aircraft, turbo props and general aviation) will also need to be measured under nominal taxi conditions.

The new NPD data will need to be displayed in the NPD Data screen (Figure 67). It is proposed that T be used to indicate the Taxi-NPD type. The existing capability in INM to copy/edit/paste records should be supported for taxi NPDs as well.

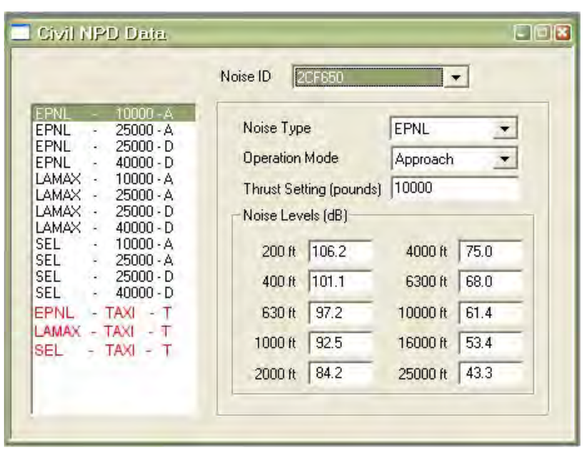

Figure 67. NPD data screen.

Taxi NPD - Database Development

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
High	Difficult	160	24k	Taxi NPD – Acoustics Taxi NPD Data – GUI

Taxi NPD - Database Development, Augmentation with Measurements

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
High	Difficult	300	60k*	Taxi NPD – Acoustics Taxi NPD Data – GUI

* Costs for Measurements include labor and other elements.

Taxi NPD - Acoustic Implementation in INM

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
High	Difficult	40	6k	Taxi NPD - Database Taxi NPD – GUI

Taxi NPD – GUI Implementation in INM

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
High	Difficult	40	6k	Taxi NPD - Database Taxi NPD - Acoustics

6.2.3. Taxi Longitudinal Ground-Based Directivity

INM presently includes the capability for applying a Ground-Based Directivity Adjustment resulting from the normalized noise pattern defined by a 360-degree area in the horizontal plane around a noise source. This directivity adjustment does not include any changes in front of the vehicle, only behind the aircraft. In INM, measurement-based directivity is accounted for in run up operations and flight operations (such as behind the takeoff roll) when the altitude is exactly 0 ft AGL. If the height of the segment is above 0 ft AGL then this directivity adjustment is not applied. INM should be modified that Ground-Based Directivity is applied for all taxi operations.

The current Ground-Based Directivity Adjustment should be extended for taxi operations such that it represents a nominal taxi directivity shape, including the increase in noise ahead of the aircraft as was shown in the sensitivity study report. Three possible concepts for taxi directivity are:

a) A single taxi directivity pattern applied to all aircraft.

b) *Suggested:* A simplified taxi directivity class pattern which considers different groups of aircraft. i.e. jet versus propeller aircraft and wing versus tail mounted jet types.

c) A directivity pattern that is different for each specific aircraft type.

It is our suggestion that option b) be implemented in INM; however, this will also require the incorporation of a database which assigns an aircraft directivity class to each aircraft directivity class. This option is consistent with recent research (*35*) on directivity behind the start of takeoff roll. It is suggested that directivity patterns for taxi and behind the start of takeoff roll be based on classes of aircraft. In the event that this is not feasible in the short-term, a description of option a) which is consistent with the current INM7 single directivity adjustment is also provided. One existing measurement dataset has been identified (*25*, *26*) which contains full spectral directivity for a wide variety of aircraft types and could be adopted as option c) however, considerable scatter between this and other empirical data has been observed.

Database Development – Required for Option a) Single

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
Low	Moderate	80	12k	GUI (a) & Physics (a) Implementation in INM

Database Development – Required for Options b) Class or c) by aircraft type

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
Low	Moderate	160	24k	GUI (b or c) & Physics (b or c) Implementation in INM

Taxi Longitudinal Directivity Physics in INM – Option a) Single taxi directivity pattern

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
Low	Moderate	40	6k	Single Directivity Curve

Taxi Longitudinal Directivity Physics in INM – b) Directivity patterns for aircraft classes

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
High	Moderate	120	18k	Directivity Database & GUI

Taxi Longitudinal Directivity GUI in INM – Option b) Directivity patterns for aircraft classes

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
High	Moderate	20	3k	Directivity Database & Physics

Taxi Longitudinal Directivity Physics in INM – c) Aircraft specific directivity patterns

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
Medium	Difficult	120	18k	Directivity Database & GUI

Taxi Longitudinal Directivity GUI in INM – Option c) Aircraft specific directivity patterns

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
Medium	Moderate	40	6k	Directivity Database & Physics

6.2.4. Ground-Based Directivity Smoothing at Larger Distances

For all moving flight operations in INM the directivity adjustment is modified by a smoothing equation (*1*), computed as a function of slant range from the observer location to start of takeoff, and is activated for distances greater than 2500 feet. This smoothing accounts for the effects of variations in the heading of the aircraft. The smoothing serves to make the noise source look more circular at very large distances, while at closer distances the details of the directivity pattern are preserved. This directivity adjustment should be used for all operations, where taxi directivity is applied, for both stationary and moving segments.

Ground Based Directivity Smoothing at Larger Distances

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
High	Easy	20	3k	None

6.2.5. Engine Installation Effects (Lateral Directivity)

Within INM 7 there is a component of the lateral attenuation adjustment of SAE-AIR-5662 (*34*) that takes into account the directivity of the sound from an aircraft as a function of engine/aircraft type (jet, prop, helicopter), engine mounting location (fuselage or wing), and depression angle. A graphical illustration of this is reproduced from reference (*1*) in Figure 68. This is structured such that the difference in directivity for engine fuselage and wing mounted locations has a 0 dB difference directly under the aircraft, and a 3 dB difference in the plane of the wing of the aircraft. When computing taxi noise this engine installation effect should be disabled and the values in the taxi-NPD database should be representative of measurement sites roughly in the plane of the wing, and not below the aircraft.

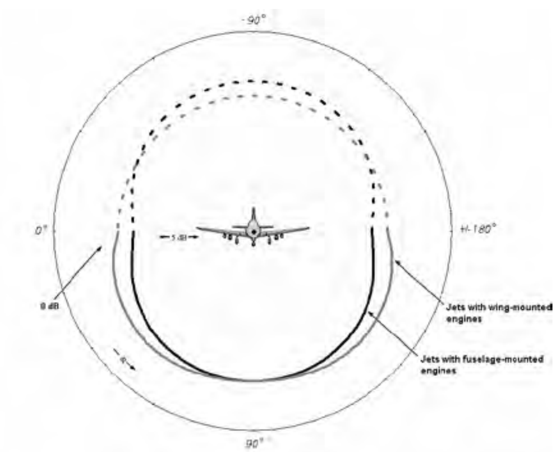

Figure 68. Lateral source directivity from SAE-AIR-5662.

Lateral Source Directivity

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
High	Easy	20	3k	Taxi NPD Dataset

6.2.6. Noise Fraction Adjustment for Taxi Segments

The INM taxi-NPD data represents the noise exposure level associated with a taxi path of infinite length. However, the aircraft taxi path is described by a set of finite-length segments, each contributing varying amounts of exposure to the overall noise metric computed at an observer. The noise fraction algorithm, which is used exclusively for computation of the exposure-based metrics and indirectly for computation of the time-above metrics, computes the fraction of noise exposure associated with a finite-length flight path segment. This fraction of noise exposure is computed relative to the noise associated with a flight path of infinite length. It is based upon a fourth-power, 90-degree dipole model of sound radiation. Because taxi noise sources are not very well represented with 90-degree dipoles, this noise fraction adjustment is not recommended for use with the taxi noise module.

The Noise Fraction Adjustment for Behind the Start of Takeoff Roll ensures consistency between the 90-degree adjustment (to the side of the aircraft) and that at 180-degrees (behind the vehicle). As illustrated with INM contours in the sensitivity study, it serves to 'fill in' what would otherwise yield a significant reduction in noise directly behind the vehicle. For taxi noise computed from flight segments this Noise Fraction Adjustment should be reflected towards the front of the vehicle as well as behind and applied for taxi segments.

Noise Fraction Adjustments for Taxi

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
High	Low	0	0k	Included with Ground-Based Directivity Smoothing at Larger Distances in 6.2.4

CHAPTER 7. AEDT IMPLEMENTATION CONCEPT

The core concept behind AEDT is that of modularity. Many of the computational modules were replicated (to varying degrees) in multiple legacy software algorithms and were integral to their respective applications. Under the new AEDT architecture, these core components are being decoupled and integrated to create a common set of modules that can be leveraged to create new tools. A primary feature of the AEDT approach is the ability to quickly and seamlessly add new modules by simply adding them to the suite of tools and exposing their interface for developers to use.

The AEDT taxiway noise module concept presented here draws upon capabilities that are suggested to be added to INM Version 7 (Step 1) and capabilities already existing in EDMS Version 5 and slated for implementation in AEDT. The Step 2 AEDT implementation concept and has been structured in a manner compatible with the current AEDT system design (*36*).

7.1. EDMS Description

EDMS (*3*) is a combined emissions and dispersion model for assessing air quality at airports, was developed by the Federal Aviation Administration (FAA) in cooperation with the United States Air Force (USAF). The model is used to produce an inventory of emissions generated by sources on and around the airport or air base, and to calculate pollutant concentrations in these environments. Within EDMS, taxiway emissions are modeled for on-ground, non-runway operations of aircraft.

The simplest way to generate an emissions inventory and obtain a coarse estimate of the total annual emissions is to use the ICAO/EPA default times in mode along with the default operational profiles, and the annual average weather from the EDMS airports database. Doing so only considers the total number of operations for the entire year without regard to when they occurred

If a more precise modeling of the aircraft taxi times using the Sequencing module is desired (required if dispersion is to be performed), then the user must define the airport gates, taxiways, runways, taxi paths (how the taxiways and runways are used) and configurations (weather dependent runway usage).

7.2. Airport Description

EDMS contains modules that allow the user (when needed for sequence modeling) to define in detail an airport's taxiway layout, outbound pathways for every gate - runway pair and inbound pathways for every runway exit - gate pair. The airport layout of EDMS defines the physical "fixed" infrastructure components of the airport, while the airside network components include the runways, gates and taxiways, which are optional for performing an emissions inventory. This information will be needed by the taxi module.

Airport Description

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
High	Easy*	0	0	None

* Already a planned part of AEDT

7.2.1. Taxi Tracks

EDMS allows users to identify one taxi path for each departure gate-runway pair and each arrival runway-exit-gate pair. Inbound taxiway paths are defined for each runway exit to allow aircraft of different sizes to be assigned the first possible runway exit and to automatically determine the pathway to be followed based on an aircraft's gate and runway assignments and flight profile. Each departure is assigned a unique taxi path when the appropriate gate-runway pair is identified and similarly, each arrival operation is assigned a unique taxi path when the appropriate runway-exit-gate pair is identified. For computing taxi noise the inputs, operational assignments and taxi paths should be made accessible to the taxi noise module in AEDT.

Taxi Tracks

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
High	Easy*	0	0k	None

* Already a planned part of AEDT

7.2.2. Taxi Profiles

At present information about the aircraft engine height is not a part of the AEDT Fleet Database. If a feature to automatically populate the aircraft engine height is to be implemented in AEDT this will need to be added to the AEDT Fleet database. If this data is already gathered as part of an INM implementation effort, the task will not need to be repeated and the engine height data only added to the AEDT database.

Taxi and Hold Profiles Implementation

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
Medium	Moderate	160	24k	Aircraft Engine Height Dataset

Aircraft Engine Height Dataset - Assimilation from Public Data Sources

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
Medium	Moderate	60	9k	Taxi and Hold Profiles GUI

7.2.3. Gates

A gate is a physical point of arrival and departure for an aircraft, and is defined as a polygon. The location of the gate can affect the overall annual emissions inventory by changing the distance (and hence the taxi time) needing to be traversed between the gate and the runway. Within EDMS taxi paths are only required to have some overlap with the gate. If a taxiway is supposed to connect to a gate (or runway or intersect with another taxiway), then the taxiway must be constructed such that it has some overlap with the connecting gate (runway, or taxiway). There are three approaches for handling taxi operations directly to the gates. The suggested EDMS implementation is option b.

This approach does not require any EDMS modification. The current day EDMS (5.x), permits one to model aircraft operations in higher level of detail by defining a taxiway or taxi path to each aircraft parking position. In this way, a gate is represented by a point, and the total number of gates, taxiways and taxi paths will be (significantly) increased.

To extend a taxi path to a point inside the gate polygon to account for a portion of a taxi path that aircraft traverses within a gate area, all aircraft would traverse the same path to get into or exit the gate. This approach requires a slight modification of EDMS.

To define a network of paths within each gate. Each aircraft traverses a path (within the gate area) assigned in a (pseudo) random manner. This approach would require much larger implementation effort.

The Check Taxipaths feature in EDMS performs a check of whether the taxiways used in the taxi paths have proper linkages. Since the aircraft position at the gate is not specifically defined in EDMS a mechanism for defining the aircraft resting location will be needed. This could be determined without significant user input by utilizing the connecting taxi path and creating a geometric extension into the gate polygon area, considering the known aircraft lengths and procedures; however, this would require the creation of an aircraft database of geometric parameters which is information that is readily available for the range of aircraft types in INM. The interface should display this location graphically within the GUI so that the user can verify that the taxi path extension and gate polygon area are properly defined or apply any necessary changes (Figure 69).

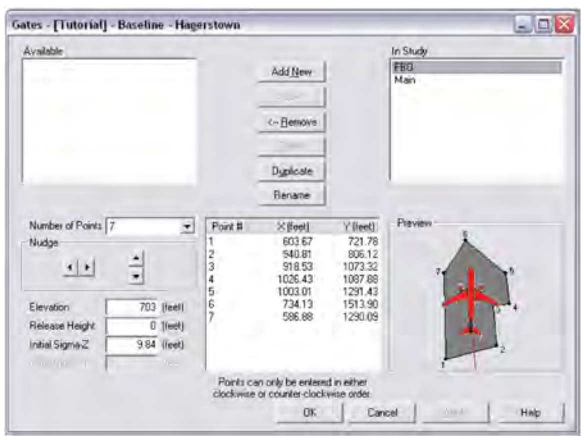

Figure 69. Taxi path extension into the gate polygon area.

Gate Polygon Geometry and Assignments

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
High	Easy*	0	0k	None

* Already a planned part of AEDT

Taxi Path Extension into the Gate Polygon Area

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
Medium	Medium	80	12k	Aircraft Geometry Database

7.2.4. Terminal Area

Terminal Areas are neither defined nor used in EDMS, however they serve a useful function in the prediction of taxi noise when using lower fidelity inputs. The terminal area may be defined as a polygon (similar to the gate area) and used when specifying operations, namely by connecting terminals to runways rather than specific gates. A GUI input similar to the gate definition (Figure 69) may be utilized in conjunction with the current EDMS gate geometric extension to define track ends. A feature such as this would most likely be implemented for airports where known aircraft and airline types utilize predominantly specific terminals thereby relieving the user of modeling specific gate usage.

Terminal Area Geometry and Assignments in GUI

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
Low	Medium	40	6k	None

7.2.5. Taxi Speed

Speed is the taxi speed of an unimpeded aircraft on that segment of the taxiway and in EDMS it is entered by the user. This parameter, input as part of the Taxiways screen (Figure 70) should be shared with the taxi noise module in AEDT. In the event that multiple speeds are needed for different analyses, the ability to easily copy and edit taxiways, as well has define multiple taxiways whose only difference is speed, should be permitted.

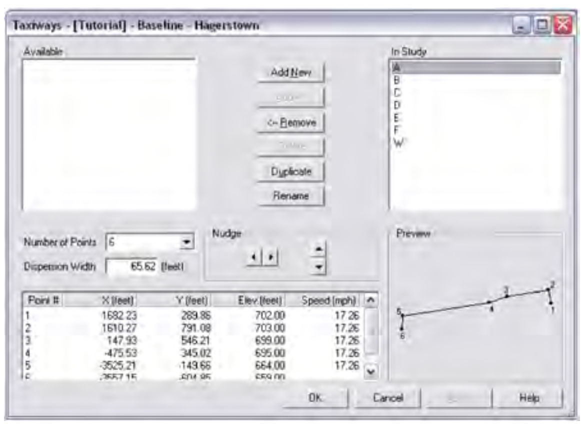

Figure 70. Taxiway input in EDMS.

Taxi Speed

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
Medium	Easy*	0	0k	None

* Already a planned part of AEDT

7.2.6. Buildings

The Buildings window of EDMS enables the user to specify the identification and location of each building at the airport. In dispersion analyses, buildings affect the emitted point source plumes, and therefore can have a significant impact on concentrations. In taxi acoustic analysis, buildings can provide a significant shielding effect primarily via blockage of line of sight. The acoustic module in INM 7 has the capability to utilize Maekawa's shielding to determine the building attenuation and will therefore be able to take advantage of the building geometry which has been defined for dispersion modeling. Within AEDT this building information (location and height) should be shared with the Taxi Noise Module.

Building Definitions

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
Low	Easy*	0	0k	None

* Already a planned part of AEDT

Acoustic Impact of Building Definitions

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
Medium	Medium			Acoustic Module Implementation

7.3. Operations

7.3.1. Times in Mode

"Times in mode" refers to the amount of time an aircraft spends in different portions of a landing-takeoff cycle (LTO). In EDMS an LTO cycle is divided into six phases: approach, taxi-in, startup, taxi-out, takeoff and climb-out. Within EDMS Version 5.1, the landing roll portion of the approach segment is incorporated into the taxi-in time. For computation of taxi noise based on times in mode data, the taxi-in time in EDMS needs to be differentiated into separate landing roll and taxi-in segments. Landing roll noise is computed as part of the flight contribution whereas taxi-in noise is considered part of the taxi operation.

There are two options for determining the times in mode for the aircraft being modeled: *Performance Based* and *ICAO/USEPA Default*. Performance based modeling uses the specific airframe and engine characteristics along with weather data to model each flight dynamically. ICAO/USEPA defaults are standardized values read from a table.

Taxi times generated from either form of modeling should be made available to the taxi module. As was suggested in the sensitivity study under some circumstances it could be appropriate to simply distribute the times in multiple distinct locations by taking guidance from runway and taxiway usage statistics.

Times in Mode

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
Medium	Easy*			None

* Already a planned part of AEDT

7.3.2. Taxi Time Modeling

EDMS contains two options for determining taxi times: *User-specified taxi times* for each *aircraft and Delay and Sequence Modeling*. For user-specified taxi times, the user can define defaults for taxi-in and taxi-out times that apply to each aircraft added to the study. These taxi times can then be changed for each aircraft if necessary. Delay and Sequence modeling takes into account the aircraft operational schedule demands, active runway configurations, and delays associated with airport capacity to model the ground movement of the aircraft and determine specific taxi times for each aircraft operation. Taxi times generated from either form of modeling should be made available to the taxi module.

Delay and Sequence Modeling Results

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
High	Easy*			None

* Already a planned part of AEDT

7.3.3. Aircraft Schedule Options

User defined schedule files containing scheduled pushback and landing times can be used by EDMS as the basis for sequence modeling. If no schedule file is available, EDMS can generate a "pseudo-schedule" from the annual operations and operational profiles, and use that as the basis for sequence modeling when that is selected.

This sequence data can be used within the noise module to make day, evening and night time assignments to operations for computation of acoustic metrics.

Aircraft Schedules

Importance	Difficulty	ROM Effort (Hrs)	ROM Cost ($)	Other Required Features
High	Easy*			None

* Already a planned part of AEDT

7.4. Acoustic Computation

As stated in the introductory sections, Step 2 implementation details have been structured with the understanding that those features cited for Step 1 have been made available. With regards to the Aircraft Acoustics Module no additional AEDT features will be needed to permit taxi noise computation. The primary changes will be those necessary to access and utilize the aforementioned input data from EDMS and other AEDT modules.

7.5. Thrust-Noise Sensitivity

The sensitivity study made some assumptions to link together acoustic and operating state data, and projected reasonable acoustic changes with changes in thrust. Given a lack of concurrent acoustic and FDR data, this assessment was performed for one very common aircraft engine type (CFM56 series) for which we had isolated acoustic (B737) and isolated FDR (A319, A320, A321) data. For this engine series, based on an approximate 0.70 dB/klb thrust, one would expect for a thrust change from 5 to 15% to result in less than +/- 1dB (or a total spread of about 2dB) for a single operation. While this acoustic change in source level is not very large, there could be situations at certain airports where such changes could accumulate over repeated operations and cause a localized bulge in the taxi noise contours. Taxi operations occurring frequently in a specific location with regular operational increases in thrust (i.e., in a holding taxi queue leading up to a specific runway during periods with flight delays) might therefore require a higher fidelity modeling of thrust-noise sensitivity. In regions where the community is in close proximity to the holding queues or if there is demonstrated community concern, such higher fidelity thrust-noise modeling could be warranted.

The short term approach suggested here addresses only a ‘nominal’ taxi condition and makes no allowance for changes in noise with changes in thrust. This is due in part to the lack of concurrent measurement and operating state (FDR) data and the expectation that a reduced number airport noise studies will require such high fidelity modeling. The “Comprehensive Long Term Solution” to this situation suggests that further measurements be conducted in order to obtain this thrust-noise data experimentally. In order to utilize such data, further changes will need to be made to AEDT in order to provide the capability to model thrust-noise sensitivity for taxi operations. The ROM level of effort and cost to conduct these acoustic measurements and AEDT thrust-noise sensitivity programming changes are not included in this report.

CHAPTER 8. THE PATH FORWARD

The objective of this taxi noise scoping project was to determine the best way to model airport noise from aircraft taxi operations and to create a plan for implementation of a taxi noise prediction capability into INM in the short term and AEDT in the longer term. While the scoping study suggestions were developed for both INM and AEDT, we suggest short term implementation in INM, so that an improved taxi modeling capability may be provided to the noise modeling community sooner rather than later.

Sections 6 and 7 itemized the various computational, GUI and database elements which will need to be implemented in INM and/or AEDT, to provide a taxi noise modeling capability. A composite summary of the suggested and minimum required features are presented in Table 11. Data gathering and database development need be performed only once. Because of the two completely different programming language platforms of INM and AEDT, computational algorithm development for AEDT following development of computational algorithms for INM, result in only a 25% savings in the level of programming effort.

The projected ROM cost for implementing a taxi noise capability in INM alone is $220k, in INM + AEDT is $310k and in AEDT only is $240k. Included in these estimates is the approximate $130k cost for development of the various aircraft and acoustic taxi databases.

TABLE 11 Summary Level of Effort for INM, INM+AEDT and AEDT

Recommended INM Implementation	**Comput-ational**	**GUI**	**Database Prep.**	**ROM Effort (Hrs)**	**ROM Cost ($)**	**Section**
Taxi Tracks	X	X		80	$12k	2.1.1
Taxi and Hold Profiles	X	X		160	$24k	2.1.2
Aircraft Engine Height Dataset			X	60	$9k	2.1.2
Spectral Class		X		40	$6k	2.2.1
Spectral Class - Reference 6			X	80	$12k	2.2.1
Spectral Class - Add'l Measurements			X	300	$60k	2.2.1
Spectral Class	X			80	$12k	2.2.1
NPD by Aircraft Type			X	160	$24k	2.2.2
NPD by Aircraft Type	X			40	$6k	2.2.2
NPD by Aircraft Type		X		40	$6k	2.2.2
Longitudinal Directivity - by AC Class			X	160	$24k	2.2.3
Longitudinal Directivity - by AC Class	X			120	$18k	2.2.3
Longitudinal Directivity - by AC Class		X		20	$3k	2.2.3
Directivity Smoothing at Large Dist.	X			20	$3k	2.2.4
Lateral Directivity	X			20	$3k	2.2.5
Totals				**1380**	**$222k**	

AEDT Implementation Building upon INM Implementation	**Comput-ational**	**GUI**	**Database Prep.**	**ROM Effort (Hrs)**	**ROM Cost ($)**	**Section**
Taxi and Hold Profiles	X	X		160	$24k	3.2.2
Spectral Class		X		40	$6k	2.2.1
Spectral Class	X			60	$9k	2.2.1
NPD by Aircraft Type	X			30	$5k	2.2.2
NPD by Aircraft Type		X		40	$6k	2.2.2
Longitudinal Directivity - by AC Class	X			90	$14k	2.2.3
Longitudinal Directivity - by AC Class		X		20	$3k	2.2.3
Directivity Smoothing at Large Dist.	X			15	$2k	2.2.4
Lateral Directivity	X			15	$2k	2.2.5
Gate Polygon Taxi Extension in EDMS	X	X		80	$12k	3.2.3
Terminal Area		X		40	$6k	3.2.4
Totals				**590**	**$89k**	

AEDT Implementation In Isolation	**Comput-ational**	**GUI**	**Database Prep.**	**ROM Effort (Hrs)**	**ROM Cost ($)**	**Section**
Taxi Tracks	X	X		80	$12k	2.1.1
Taxi and Hold Profiles	X	X		160	$24k	2.1.2
Aircraft Engine Height Dataset			X	60	$9k	2.1.2
Spectral Class - Reference 6			X	80	$12k	2.2.1
Spectral Class - Add'l Measurements			X	300	$60k	2.2.1
Spectral Class		X		40	$6k	2.2.1
Spectral Class	X			80	$12k	2.2.1
NPD by Aircraft Type			X	160	$24k	2.2.2
NPD by Aircraft Type	X			40	$6k	2.2.2
NPD by Aircraft Type		X		40	$6k	2.2.2
Longitudinal Directivity - by AC Class			X	160	$24k	2.2.3
Longitudinal Directivity - by AC Class	X			120	$18k	2.2.3
Longitudinal Directivity - by AC Class		X		20	$3k	2.2.3
Directivity Smoothing at Large Dist.	X			20	$3k	2.2.4
Lateral Directivity	X			20	$3k	2.2.5
Gate Polygon Taxi Extension in EDMS	X	X		80	$12k	3.2.3
Terminal Area		X		40	$6k	3.2.4
Totals				**1500**	**$240k**	

REFERENCES

1. Boeker, E.R., et al., "Integrated Noise Model (INM) Version 7.0 Technical Manual", FAA-AEE-08-01, Jan 2008.
2. Aviation Environmental Design Tool (AEDT) System Architecture, Document #AEDT-AD-01, Section 3.7.1, June 2008.
3. Emissions and Dispersion Modeling System (EDMS) User's Manual, FAA-AEE-07-01 (Rev. 5), September 2008.
4. Continental Airlines; R. Zimmerman personal interview with Pilot, Atlanta, GA, 4 October, 2007.
5. Delta Airlines, R. Zimmerman, personal interview with Pilot, Atlanta, GA, 4 October, 2007.
6. Air Wisconsin (US Airways Express); R. Zimmerman, personal interview with Pilot, New York, NY, 7 October 2007.
7. Scannell Citation, LLC, J. Page e-mail communication with T. A. Lanham, Chief Pilot and Mechanic, June, 2008.
8. Federal Aviation Administration; R. Zimmerman, personal interview with Air Traffic Control Specialist, Teterboro, NJ, June 2008.
9. Wells, A., Young, S.; Airport Planning & Management (5th edition), McGraw-Hill, New York, 2004.
10. U.S. Department of Transportation, Federal Aviation Administration, Order JO 7110.65S, *Air Traffic Control*, February 14, 2008.
11. "Boston Logan Airport Noise Study Noise Analysis Protocol Version 6.0", December 2007.
12. Environmental Data Report, Boston-Logan International Airport, EOEA #3247, September 2007.
13. FAA Aviation System Performance Metrics (ASPM) online database for 2006 (http://aspm.faa.gov/).
14. International Civil Aviation Organization (ICAO). "Environmental Protection, Annex 16, Volume 2, Aircraft Engine Emissions." Second Edition. July 1993.
15. Federal Aviation Administration (FAA). "Emissions and Dispersion Modeling System (EDMS), Version 5.0.2." Airport Taxi data (APT_TAXI.dbf) from EDMS system database. EDMS User Manual, FAA-AEE-07-01. June 29, 2007.
16. TAAM® Total Airspace and Airport Modeller, by Jeppesen subsidiary of The Boeing Company, http://www.jeppesen.com/documents/aviation/government/TAAM-ebrochure.pdf, 2008.

17. Cimorelli, A.J., Perry, S.G., Venkatram, A., Weil, J.C., Paine, R.J., Wilson, R.B., Lee, R.F., Peters, W.D., Brode R.W., Paumier, J.O., AERMOD: Description of Model Formulation. Prepared for Office of Air Quality Planning and Standards Emissions Monitoring and Analysis Division Research Triangle Park, North Carolina 2004. (EPA-454/R-03-004).

18. “Results from a Number of Surveys of Power Settings Used During Normal Taxi Operations”, Alternative Emissions Methodology Task Group, CAEP7-WG3-AEMTG-WP7-08, May 2006.

19. Brooke, A.S, Caves, R.E, Jenkinson, L.R , Methodology for Assessing Fuel Use and Emissions of Aircraft Ground Operations, TT 95 R 05, Loughborough University of Technology, December 1995.

20. Dawes, Jane, Results from LHR AOC Carrier survey (unpublished data) BAA, September 2005.

21. Gerencer, Christine, Survey of operational practises that result in improved fuel efficiency and potential emissions reduction benefits – Overview of survey results, WG 2-TG 4-IP, AA/IATA, June 2005.

22. Downing, M., et al., “The Effect of Bodies of Water on Aircraft Noise Propagation”, Wyle Research Report WR 04-17, August 2004.

23. Bradley, K.A., et al., "Aircraft Engine Run Up Noise Study at Milwaukee’s General Mitchell International Airport”, Wyle Research Report WR 00-08, June 2000.

24. “Methods of Controlling Distortion of Inlet Airflow During Static Acoustical Tests of Turbofan Engines and Fan Rigs,” SAE AIR 1935, Reaffirmed 2007-11.

25. Asensio, C. et al., “Estimation of Directivity and Sound Power Levels Emitted by Aircrafts During Taxiing, for Outdoor Noise Prediction Purpose”, Applied Acoustics 68 (2007) 1263-1279.

26. “Determinacion De La Potencia Acustica Emitida Por Aeronaves En Operaciones De Tierra”, Grupo de Investigacion en Instrumentacion y Acustica Aplicada (I2A2), Cod. Informe: P000104LEA0005F02rev2, May 2004.

27. Page, J.A., et al., “Advanced Acoustic Model Technical Reference And User Manual", Wyle Report WR 08-12, May 2009.

28. Society of Automotive Engineers, Committee A-21, Aircraft Noise, “Standard Values of Atmospheric Absorption as a Function of Temperature and Humidity” SAE ARP 866a, 15 March 1975.

29. “American National Standard Method for Calculation of the Absorption of Sound by the Atmosphere,” ANSI S1.26 (R2004).

30. “Logan International Airport Additional Taxiway Evaluation Report Per FAA August 2, 2002 Record of Decision”, HMMH Report No. 300280.001, May 2006.

31. Menge, C., et al., “Attachment B: Noise Analysis of Taxi Queuing Alternatives for Taxiway November at Logan International Airport”, HMMH Report No 300280.003, May 2006.

32. Society of Automotive Engineers, Committee A-21, Aircraft Noise, Procedure for the Computation of Airplane Noise in the Vicinity of Airports, Aerospace Information Report No. 1845, Warrendale, PA, March 1986.

33. Stusnik, E., et al., “A Technical Assessment of the First Phase of the T.F. Green State Airport Residential Noise Mitigation Program”, Wyle Research Report WR 92-19, November, 1992.

34. Society of Automotive Engineers, Committee A-21, Aircraft Noise, Method for Predicting Lateral Attenuation of Airplane Noise, Aerospace Information Report No. 5662, Warrendale, PA: Society of Automotive Engineers, Inc., April 2006.

35. “Start of Takeoff Roll Directivity in INM Research”, Dulles Measurement Data and Analysis Summary presented to the A-21 Aircraft Noise Committee, Cambridge Mass, October 2007.

36. AEDT Interface Control Document, Aircraft Performance Module, Version 2.7.1, Doc #AEDT-ICD-01, September 2008.

Appendix A: Reagan Washington National Airport (DCA) Taxi Noise Measurements

A.1. DCA Taxi Noise Measurement Setup

Aircraft taxiway noise was measured at Ronald Reagan National Airport (DCA) on June 30, and July 3, 2008. Sound level meters and a video system were deployed in order to obtain noise levels, aircraft speed, and positional information. Accessible measurement locations were selected in conjunction with airport operations personnel based on the prevailing weather conditions and active runway configuration. Both measurement locations are shown as red diamonds on the airport diagram of DCA in Figure A-1. Measurements conducted on June 30 and July 3, 2008 were at locations M1and M2, respectively. Measurements on June 30 only recorded aircraft pass-by after arrival on Runway 19 while taxiing to the terminal. Measurements on July 3 recorded idle noise of single and multiple aircraft at the holding pad prior to departure on Runway 19.

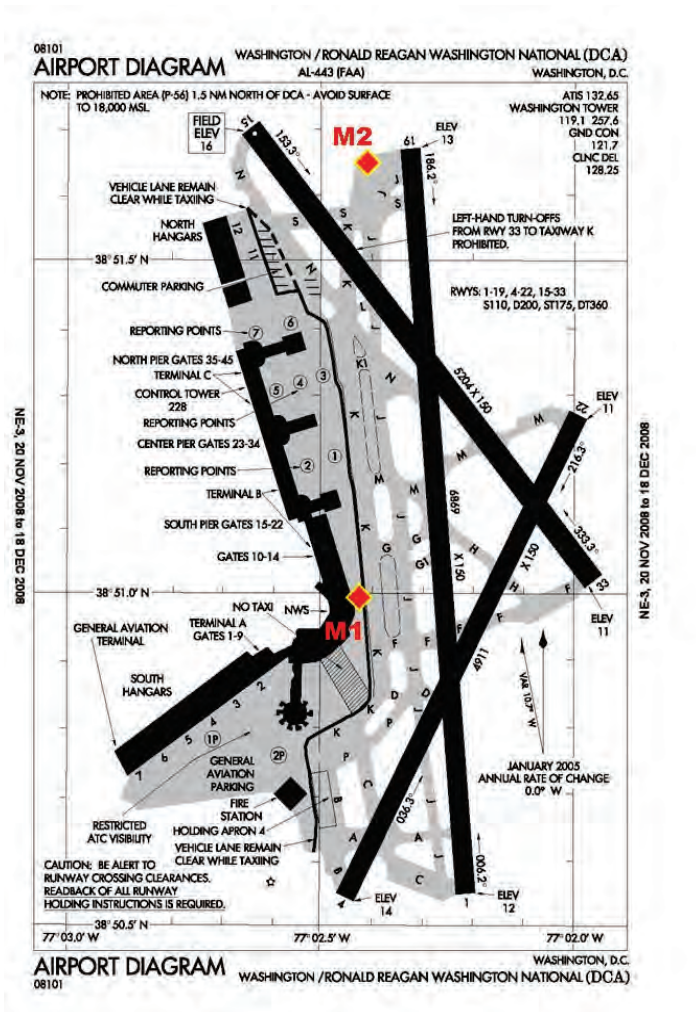

Figure A-1. Washington / Ronald Reagan Washington National (DCA) Airport

The June 30 measurement location was adjacent to the two primary taxiways J and K adjacent to runway 19 (Figure A-1). The measurement site was situated approximately 72 feet (22 meters) from the point of closest approach to an operation using Taxiway K and approximately 256 feet (78 meters) from the point of closest approach to Taxiway J (Figure A-2). The taxiway centerlines can be seen in Figure A-3 highlighted in bold yellow. Two Larson Davis 831 sound level meters (SLM) were placed at positions Kilo-Fox 1 and Kilo-Fox 2 shown in Figures A-3. The SLM at Kilo-Fox 1 was placed 1.3 m (4.5 ft) above the ground and SLM at Kilo-Foxtrot 2 was placed to 1.4 m (4.8 ft) above the ground. The SLMs were programmed to collect A, C, and Un-weighted levels and 1/3 octave 1-second time histories. A photograph showing the equipment orientation to the taxiway is given in Figure A-4.

Figure A-2. Measurement setup at DCA on 30 June 2007

Figure A-3. Close Up Schematic of Taxiway Pass-by Measurement at DCA on 30 June 2008

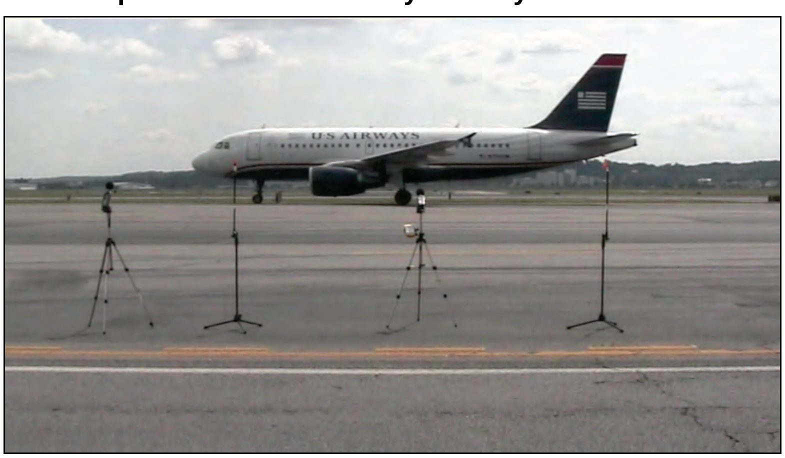

Figure A-4. Camera View of Taxiway Pass-by at DCA on 30 June 2008

Meteorological data was obtained from the DCA weather hourly report for the duration of the measurements. The weather data is shown in Table A-1.

Table A-1. Meteorological Conditions

30 June 2008		
Temperature	82	ºF
Relative humidity	51	percent
Atmospheric pressure	1009.7	mbars
3 July 2008		
Temperature	87	ºF
Relative humidity	40	percent
Atmospheric pressure	1016.4	mbars

Vertical marker posts were placed on either side of the SLM at distance of 6.5 feet. A video camera was placed 40 feet behind the SLM such that the distance to both vertical markers was equidistant. Rangefinders were used to verify distance from SLM to engine. Speed was estimated by elapsed time for aircraft to pass from right vertical marker to left marker. Traverse distance was determined by focal angle and geometry of camera, marker locations, and distance to engine. By this method the aircraft was assumed to be traveling at constant speed. Observations support the constant speed assumption.

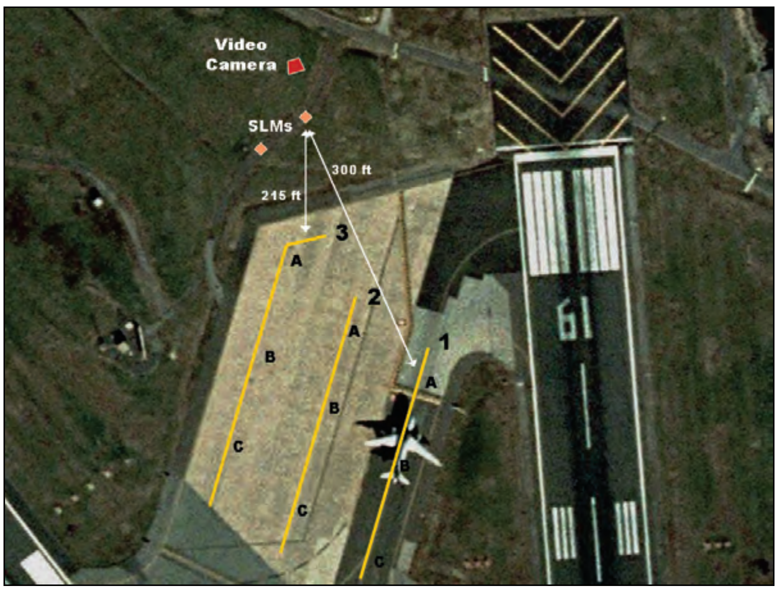

Figure A-5. Schematic of Taxiway Idle Measurement at DCA on 3 July 2008

Figure A-6. Camera View of Taxiway Idle at DCA on 3 July 2008

Measurements were made on 3 July 2008 to measure taxiway and holding block idle and acceleration noise. Larson Davis 831 sound level meters, vertical markers and video camera system were set-up in similar configuration to the earlier measurements. It was observed that aircraft would line-up along centerlines arbitrarily named 1, 2 and 3 at holding block J at the beginning of runway 19, as shown in Figure A-5. The aircraft would queue-up in the holding block and hold at positions A, B, and C along the centerlines. During the measurements 1 to 5 aircraft were observed in the holding block at any given time. There were a few brief periods where no aircraft were in the holding block, which provided an ambient noise level measurement.

A.2. DCA Taxi Noise Field Measurements

On June 30 and July 3, 2008, Wyle measured the taxiway noise of 47 and 35 aircraft operations, respectively, ranging from regional jets to 737-700s. Figures A-7 and A-8 contain the field note log sheets from the June 30 measurements, while Figure A-9 through A-11 contain the field note log sheets from the July 3 measurements.

Title : Taxiway Measurements
Name & Date : DRobinson & CKarner
Job Number : 30 Jun 2008
Location : Reagan National Airport (DCA)
Source :

A = arrival
D = departure
R = road traffic

RangeFinder distances from camera position.

PXI: (I / II) Cards : ____ File Name : ________ Chans : ___@______(samp/sec)(AC/DC)

	ID	Code	Time	Deploy 1000 Comments
Tape 1	KiloFox		10 :13 : 33	CARJ 675BR Delta
		E135/E145	10 :17 : 25	Emb E135 N718AE AA
		A319	10 :19 :	N511NK Spirit
		B737	10 :20 : 31	N943AN AA, plane landing in bkgrnd
		A319	10 :21 : 42	N742PS USAir take-off 64 & just after
		~~B717~~	10 : :	
		E145	10 :26 : 21	N279SK USAir Chris & Mike at meter
		CARJ 200	10 :29 : 18	N410AW USAir Chris at SLM
		737-300	10 :35 : 55	N518AU USAir tate off @ 10:36:18
		CARS	10 :37 : 12	N 402AW USAir (AW = Air wisconsin)
		B737300	10 :40 : 58	N342UA United take off just prior
		MD80?	10 :46 :	N909DE Delta truck drive by, take off
			: :	Deploy 1001 SLM LHS
		CRJ7	10 :49 :	N709PS USAir landing
		A319	10 :50 : 20	N705UW USAir *truck hauk horn
		CRJ200	10 :53 : 29	C-FEJA AirCanada take off 10:53:22
		CRJ7 or 9	10 :55 : 29	N582CA Delta A10:55:31, R
		MD88	10 :56 : 40	N994DL Delta
	E175	~~B717?~~	10 :58 : 29	N113HQ USAir
		A319	11 :01 : 25	N750UW USAir D 11:01:58
		CRJ200	11 :07 : 25	N456ZW USAir R 11:07:29
		B717	11 :08 : 01	N908ME Midwest turning away
Tape 2		CRJ200	11 :12 : 54	N8718E Northwest
		A319	11 :14 : 27	N359NB NWA 34m
		E135	11 :15 : 09	N700LE AA 91m
		CRJ200	11 :16 : 46	N447AW USAir 90m R 11:16:40
		A320	11 : 18:	~~diesel~~ diesal truck idle in bkgrnd

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Figure A-7. Field note log sheet for 30 June 2008 (part 1/2)

Title : Taxiway Measurement

Name & Date : DRobinson & CKarner

Job Number : 30 Jun 2008

Location : DCA

Source :

SLM 1000 stop 12:09:10 Taxiway.001
SLM 1001 stop 12:10:10 Taxiway.001

PXI: (I / II) Cards : ____ File Name : ______ Chans : ___@_____(samp/sec)(AC/DC)

ID	Code	Time	Comments
KiloFox	CRJ100	11 :20 :22	N595SW Delta 90m Δ 11:20:27 scare gun diesel idle
	B737-700	11 :23: 44	N16703 Continental 34m scare guns A 11:24:00
	E135	11 :24 :53	N735TS AA 34m R 11:25:10?
	CRJ200	11 :26: 22	N458AW USAir 90m A 11:26:33
	MD80	11 :27: 53	N916DE Delta 34m A 11:28: 22
		: :	11:40:23 124 m ~~A 11:29:58~~
	E	11 :30 :46	N813MA US Air 90 helo, R, Δ 11:31:02
	A319	11 :31 :50	N769US USAir
	CRJ	11 :32 :23	N251PS USAir
	B717	11 :32 :5?	N924ME Midwest A 11:32:47 R
		11 :34 :53	N130HQ USAir 90m A 11:34:58
	CRJ	11 :35 :19	N423AW USAir 90m Δ 11:35:46
	B737-400	11 :37 :36	N379UA United Δ 11:37:57
	G4	11 :40: 31	01 USCG 34m A 11:40:38 R
	CRJ200	11 :42:43	N430AW USAir 90m
	A320 ?	11 :45: 20	N330NB NWA 90m Δ 11:45:15 R 11:45:33
	E175	11 :45:47	N109HQ USAir 90m
	A319	11 :53:07	N766US USAir 90m Δ 11:53: R 11:53:34
	MD80	11 :55:42	N7506 AA 90m A 11:55:37
	B737-700	11 :56: 25	N348AT AirTran 90m
	E135	11 :56 :50	N725AE AmEagle 90m R
	E135	12 :00 :01	N703MR AmEagle 90m
	E145	12 :01 : 35	N816AE AmEagle cutting at angle
		: :	idle at ~~~37m~~ ramp engine 12:02:40 53m
		: :	A 12:03:30 rev 12:07:00 slow roll
	B737-800	12 :03 :56	N941AN AA
		: :	

diesel idle

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Figure A-8. Field note log sheet for 30 June 2008 (part 2/2)

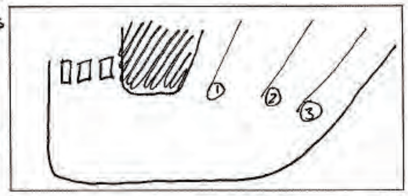
Title : Taxiway Idle Noise Measurements

Name & Date : D Robinson & B Robinette

Job Number : 3 Jul 08

Location : Reagan National Airport (DCA)

Source :



PXI: (I / II) Cards : _____ File Name : ________ Chans : ____ @ ______ (samp/sec)(AC/DC)

ID	Code	Time	Comments
	~~A319~~	11 :14 :20	Start notes
	A319	11 :14 :	N770UW USAir 6? m (3) near corner
		11 :15 :47	A
		11 :16 :10	N923ME Midwest 105m roll far
		11 :18 :00?	N14972 Continental 93m (2) slow roll
		: :	↑ parked behind N770UW for as long as we meas
	E145	11 :19 :40	N830AY NWA 96m (1) short roll
	E145	11 :20 :25	N562RP Delta (1) short roll
→		: :	N439AW USAir (1)
		11 :22 :18	N951AA AA (3) park behind N770UW
		11 :23 :00	Arr
	B737-800	11 :23 :45	→ roll thru (2) → 19
	E145	11 :25 :20	?? AA roll thru (2) → 19
	CRJ900	11 :25 :50	N601LR Delta 84m
		11 :27 :48	Arr USAir
→	CRJ200	11 :28 :16	N439AW (1) → 19 parked for long time
	MD80	11 :28 :52	N420AA AA (1) → 19 short 92m
	B737-300	11 :30 :00	N334UA United (3) behind N770UW 128m
		11 :31 :40	→ (2)
		11 :32 :37	Arr USAir
		11 :32 :56	→ 19
	A319	11 :33 :20	N722US USAir (2) 108m
	B717	11 :33 :57	N910ME Midwest (1) 172m
		11 :34 :50	N461AW USAir (3) behind N770UW
		11 :35 :07	Arr
	B717	11 :35 :45	→ roll 19
	CRJ200	11 :36 :23	N461AW → (2) 100m

11 : 37 : 00 Arr

11 : 37 : 10 → roll to 19

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Figure A-9. Field note log sheet for 3 July 2008 (part 1/3)

Title : Taxiway Idle Noise Measurements
Name & Date : DRobinson + BRobinette
Job Number : 3 Jul 08
Location : Reagan National Airport (DCA)
Source :
PXI: (I / II) Cards : ____ File Name : ______ Chans : ____ @ ______ (samp/sec)(AC/DC)

ID	Code	Time	Comments
	MD88	11 :38:10	N916DE Delta ~~USAir~~ ③ behind N770UW
		11 :38:27	Arr Continental
		11 :39:57	Arr
		11 :40:05	N770UW USAir ①→ 19
		11 :40:26	70m → ③ first
		: " :	USAir ③ 120 m
		: " :	N293SK USAir ①
		11 :41:28	Arr NWA
		11 :42:01	N293SK → roll 19
		: :	(2 at ①)
		: :	Arr USAir
	CRJ200	11 :43:19	C-GKGC AirCanada ① 159
	A	: " :	USAir ~~NWA~~ ①
		: :	(4 tot 2@① 2@③)
		11 :44:32	Arr AA
		11 :45:40	Arr Airtran
		11 :45:47	→ roll 19
		11 :46:16	→ return to terminal
	A319	11 :46:58	N345NB NWA ① 154 m
		11 :47:17	Arr
	MD88	11 :47:25	N916DE Delta ① roll to 19
		11 :48:46	*lone aircraft NWA ①
		11 :49:06	Arr AA
	E135	11 :50:28	N735TS AA ①
		11 :50:48	Arr
		11 :51:20	roll to 19
	737-700	11 :51:58	N296AT Airtran ① 156m
		11 52 42	→ roll to 19

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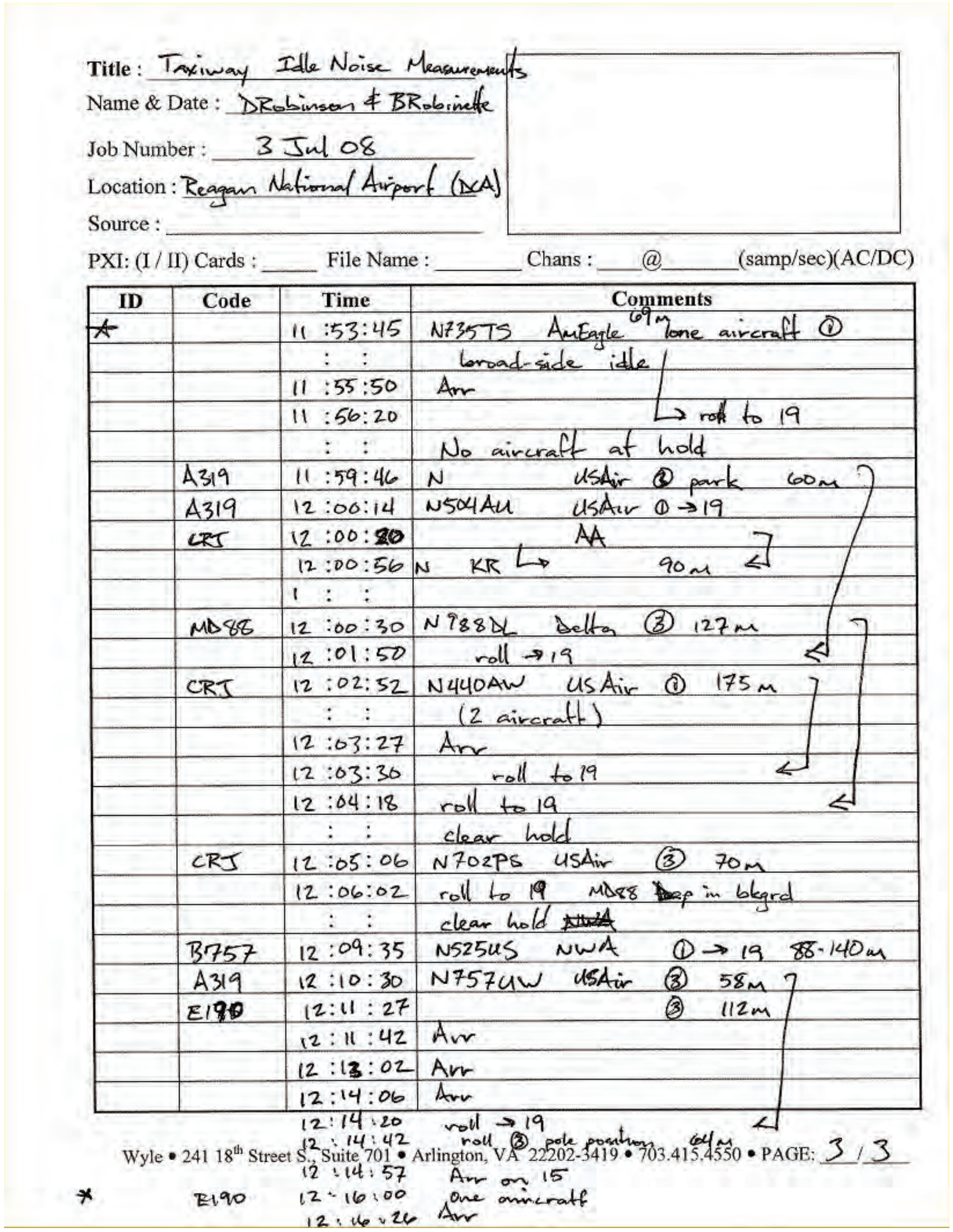
Figure A-10. Field note log sheet for 3 July 2008 (part 2/3)



Title : Taxiway Idle Noise Measurements

Name & Date : DRobinson & BRobinette

Job Number : 3 Jul 08

Location : Reagan National Airport (DCA)

Source :

PXI: (I / II) Cards : ____ File Name : ________ Chans : ____ @ ______ (samp/sec)(AC/DC)

ID	Code	Time	Comments
*		11 :53:45	N735TS AmEagle 69m lone aircraft ①
		: :	broad-side idle
		11 :55:50	Arr
		11 :56:20	→ roll to 19
		: :	No aircraft at hold
	A319	11 :59:46	N USAir ② park 60m
	A319	12 :00:14	N504AU USAir ① → 19
	CRJ	12 :00:30	AA
		12 :00:56	N KR → 90m
		: :	
	MD88	12 :00:30	N988DL Delta ③ 127m
		12 :01:50	roll → 19
	CRJ	12 :02:52	N440AW US Air ① 175m
		: :	(2 aircraft)
		12 :03:27	Arr
		12 :03:36	roll to 19
		12 :04:18	roll to 19
		: :	clear hold
	CRJ	12 :05:06	N702PS USAir ③ 70m
		12 :06:02	roll to 19 MD88 dep in bkgrd
		: :	clear hold
	B757	12 :09:35	N525US NWA ① → 19 88-140m
	A319	12 :10:30	N757UW USAir ③ 58m
	E190	12:11 :27	③ 112m
		12 :11 :42	Arr
		12 :13:02	Arr
		12 :14:06	Arr
		12 :14 :20	roll → 19
		12 : 14 : 42	roll ③ pole position 64m
		12 : 14 : 57	Arr on 15
*	E190	12 : 16 : 00	One aircraft
		12 : 16 : 26	Arr

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Figure A-11. Field note log sheet for 3 July 2008 (part 3/3)

A.3. DCA Measurement Analysis

A total of 47 taxiway pass-by events were measured on 30 June 2008. From that dataset 20 were found to be free of extraneous noise such as arriving or departing operations. All events were arrivals taxiing from the runway to the terminal. The 20 events are listed in Table A-2.

Table A-2. Measured Taxiway Pass-by Events at DCA on 30 June 2008

Event Number	Tail Number	Aircraft Type	Engine	Max Rated Thrust (lb)	SEL (dB)
1	N675BR	CRJ	CF34-3B1	9220	98.3
2	N943AN	B737-800	CFM56	26300	104.0
3	N279SK	E145	AE 3007A1P	7580	87.5
4	N410AW	CRJ 200	CF34	9220	99.2
5	N518AU	CRJ	CF34	9220	87.9
6	N342UA	B737-300	CFM56	19500	106.8
7	N909DE	MD88	JT8D	21700	103.8
8	C-FEJA	CRJ 200	CF34	9220	99.0
9	N582CA	CRJ	CF34-8C5	14500	96.2
10	N994DL	MD88	JT8D	21700	91.5
11	N750UW	A319	CFM56	22700	91.0
12	N908ME	B717-200	BR 700	17000	100.1
13	N871BE	CRJ 200	CF34	9220	98.4
14	N359NB	A319	CFM56	22700	104.2
15	N16703	B737-700	CFM56	22700	102.4
16	N735TS	E135	AE 3007A	7580	102.0
17	N458AW	CRJ 200	CF34	9220	91.9
18	N916DE	MD88	JT8D	21700	105.1
19	N379UA	B737-300	CFM56	19500	97.6
20	N430AW	CRJ 200	CF34	9220	90.0

A method was devised to obtain free-field spectral directivity data for each of these events at a reference distance of 150 ft. Using video images and scaling, the ground track of each event was estimated at times corresponding to the third-octave band time histories. An omni-directional source was run in a Wyle aircraft noise simulation model to calculate the effects of spherical spreading, absorption, and the ground for each instance in the ground track. This ray-tracing analysis used the same atmospheric conditions as during measurements, allowing these elements to be removed from the noise measurement data. The next step in the analysis was to apply spherical divergence and atmospheric attenuation based on standard atmospheric conditions to the data in order to obtain reference directivity data at the desired radius.

In Figures A-12 through A-14 the corrected longitudinal directivity is plotted by aircraft types; B737 and A319s, MD88s, and CRJs, respectively. In Figure A-12 the A319 event is included with the B737 events because they both have the same CFM56 series engine. The overall sound pressure level (OASL) is plotted versus directivity angle. Events at the 72 feet distance span a wider range of directivity angles than the 256 feet distance. The angle increases rapidly when the aircraft is near to the SLM (90º) and changes slowly when the aircraft is at the extent angles.

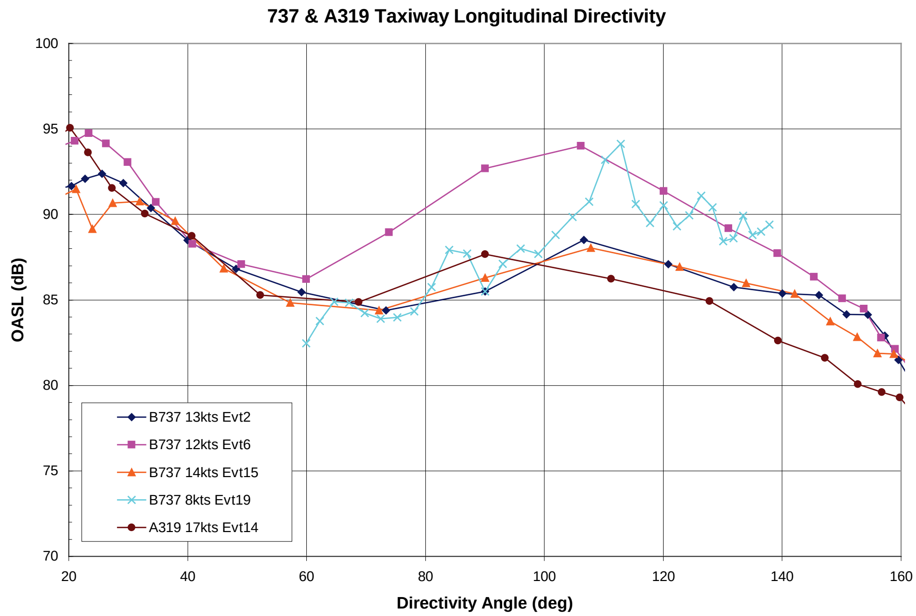

Figure A-12. Longitudinal Directivity of B737 and A319 Events

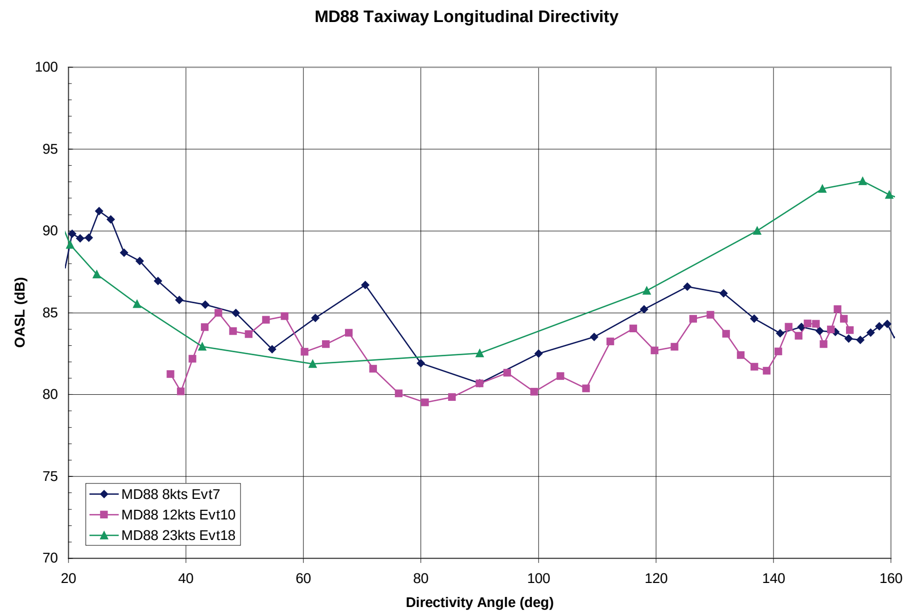

Figure A-13. Longitudinal Directivity of MD88 Events

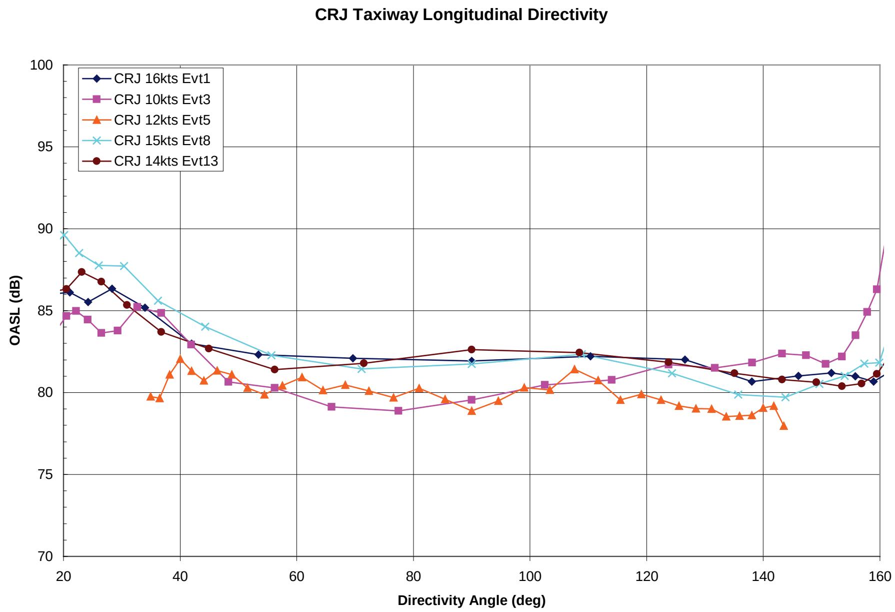

Figure A-14. Longitudinal Directivity of C/RJ Events

One of the primary considerations of taxi way noise modeling is that of the aircraft spectra, and in particular the change in spectra with directivity angle. Given the geometric orientations of taxiways to community receptors, it is possible for certain regions to be repeatedly exposed to taxi operations at a narrow range of directivity angles relative to the source.

Aircraft measurements at the limits of the front and back directivity angle, the aircraft is at a considerably greater distance than point of nearest approach. When accounting for propagation (spherical spreading, absorption and ground effect) one can see that as an aircraft is approaching there is considerably more high frequency content. This is likely due the turbine whine and blade passage frequency emanating from the front of the engine. As the aircraft passes-by and moves away there is more low frequency content. This is likely due to the thunder and turbulent wake emitted from the aft of the engine.

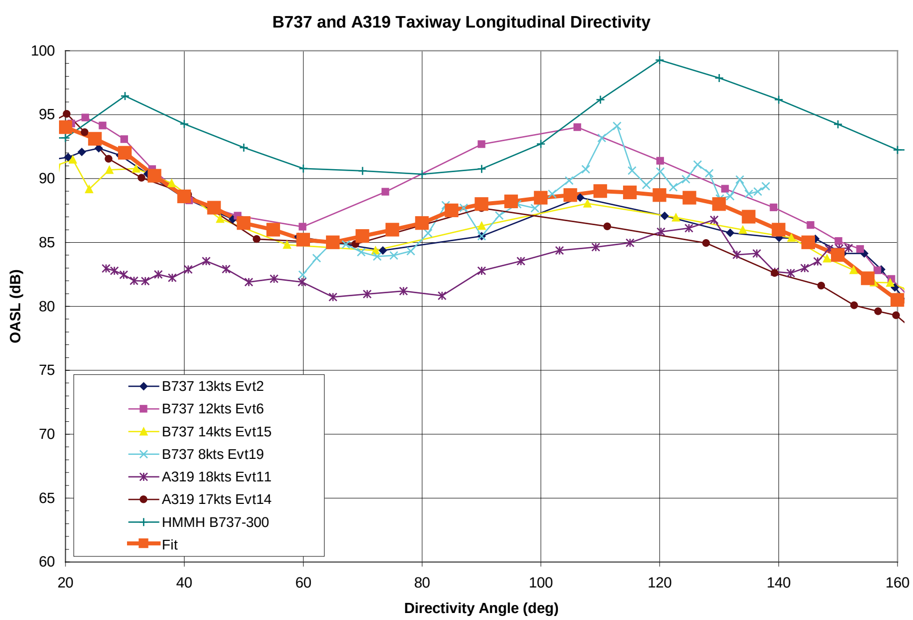

Figure A-15. Comparison of B737 and A319 Events

A curve fit was determined as representative of measured B737 taxiway longitudinal directivity, shown as an orange curve in Figure A-15. This representative 737 directivity profile is used for the detailed single event simulation studies presented in the main report in Chapter 4.

A total of 35 taxiway idle events were measured on 3 July 2008. From that dataset 16 were found to be free of extraneous noise such as arriving or departing operations. Several different combinations and aircraft configurations were measured. The 16 events are listed in Table A-3.

Table A-3. Measured Taxiway Idle and Acceleration Events at DCA on 3 July 2008

Event	# AC in Hold	Description: Lane # & AC Type	Start	Stop	SEL	Leq
1	2	3A - A319, 3B - E145	11:14:00	11:15:55	103.1	83.8
2	3	1A - CRJ200, 3A - A319, 3B - B737-800	11:22:15	11:22:50	98.4	83.1
3	3	3A - A319, 3B - B737-300, 3C - A319	11:30:35	11:31:25	100.6	83.1
4	2	2A - A319-112, 3A - A319-112	11:32:55	11:33:25	100.9	85.4
5	3	3A - A319, 3B - MD88, 3C – unkwn narrow body	11:39:15	11:40:00	100.3	83.4
6	4	1A - CRJ200, 1B - A319, 3A - MD88, 3B - NB	11:43:10	11:44:30	102.0	82.9
7	3	1A - A319, 3A - MD88, 3B - NB	11:45:55	11:46:15	95.2	81.6
8	1	3A - E135	11:54:03	11:55:40	96.3	76.5
9	0	No Aircraft	11:56:15	11:56:55	86.3	70.3
10	0	No Aircraft	11:58:05	11:58:40	80.8	65.4
11	1	1 in #3 - 737	11:59:34	11:59:55	100.5	87.5
12	2	1A - B737-300 rolls to 19 for Dep., 3A - B737-300	11:59:55	12:00:15	98.3	85.1
13	0	No Aircraft	12:06:25	12:07:15	89.8	72.8
14	0	No Aircraft	12:08:00	12:09:00	84.0	66.3
15	1	1A - B757	12:09:25	12:09:44	91.4	78.6
16	2	3A - A319, 3B - E190	12:10:50	12:11:30	97.3	81.3

Unfortunately due to the amount of traffic during this measurement period, we were unable to obtain data from a single aircraft accelerating from a stop. There were only three brief times when only one aircraft was in the holding block. This measurement dataset will be useful for validation of a future taxiway model, however at present due to a commingling of noise events with various aircraft in the holding block at the same time, the data could not be used directly to extract a single noise event. A few notable events are listed in Table A-4.

Table A-4: Notable Events during DCA taxi noise measurement period

Event #	Description
3	Three similar aircraft lined-up
4	Two of same aircraft side-by-side
8	One aircraft
11	One aircraft
16	Two similar aircraft lined up

Appendix B: T.F. Green Airport (PVD) Taxi Noise Measurements

B.1. T. F. Green State Airport Taxi Noise Measurement Setup

Aircraft taxiway noise was measured at T. F. Green State Airport (PVD) on March 24, 2008. In addition to sound level meters, a video system was deployed in order to obtain aircraft speed and positional information. The accessible measurement location was selected based on the prevailing weather conditions and active runway configuration. The measurement location was adjacent to taxiway T adjacent to runway 5 (Figure B-1). The measurement site was situated approximately 234.81 feet (71.57 meters) from the point of closest approach to an operation (Figure B-2). The taxiway centerline can be seen in figure B-3 highlighted in bold yellow. One Larson Davis 824 sound level meter (SLM) was placed at position Tango1 shown in figures B-2 and B-3. The SLM was placed 1.5 m (4.9 ft) above the ground. The SLM was programmed to collect A-weighted and one-third octave band 1-second time histories.

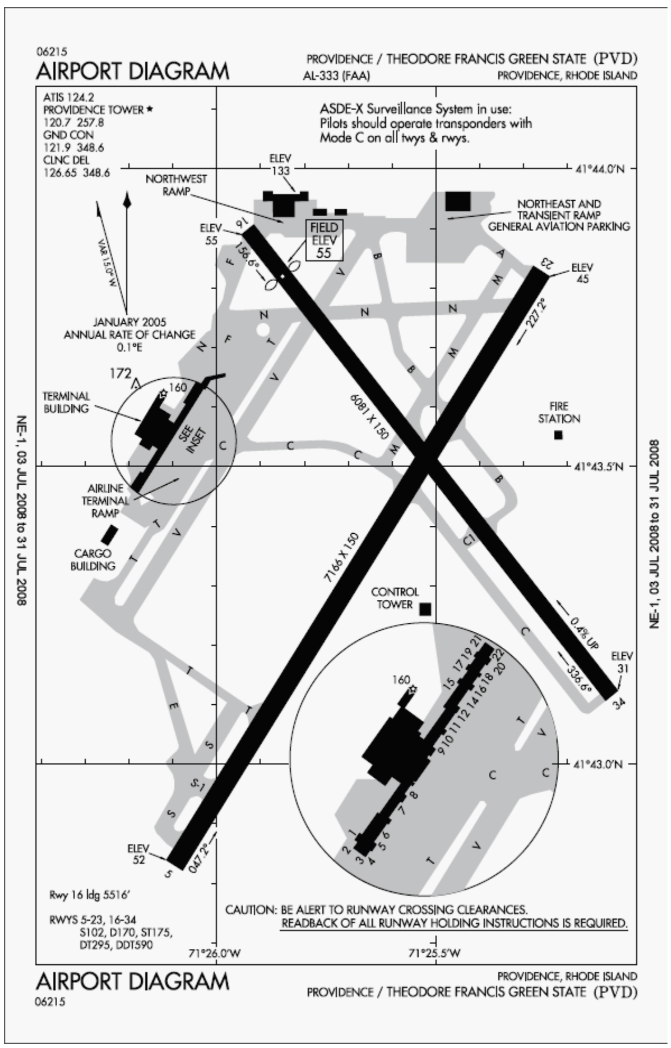

Figure B-1. T. F. Green State Airport

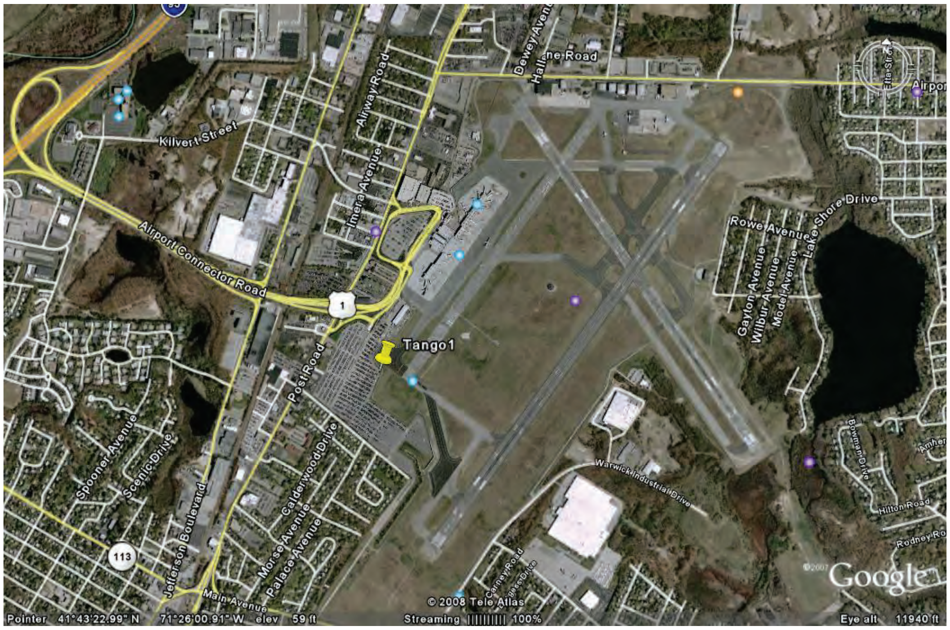

Figure B-2. Measurement setup at PVD on March 24, 2008

Figure B-3. Close-Up of Measurement setup at PVD on March 24, 2008

B.2. T. F. Green Taxi Noise Field Measurements

On March 24, 2008 Wyle measured the taxiway noise of 7 aircraft operations, ranging from a small propeller aircraft to 737-700s. Figure B-4 contains the field note log sheets from the measurements. Hourly weather data for 24 March 2008 is recorded in Table B-1. The measurement period lasted from 11:00am until 2:00pm.

Title : TF Green taxi

Name & Date : CKarner 3/24/08

Job Number : ____________

Location : TF Green Airport

Source : ____________

Pt. 153 WGS84, utm
19T
0297159
4621628 LD824-SN 1618

PXI: (I / II) Cards : _____ File Name : ________ Chans : ____@_______(samp/sec)(AC/DC)

ID	Code	Time	Comments
no camera →	small prop	11 :02:05	
no camera →	Cont exp	11 :06:02 - 11:06:36	jet. 2prop@ tail
	SW 737	12:23:16 - 12:24:37	
	US Air Exp	12 : 36:31 - 12:37:06	
	SW 737	13:10:07 - 13:12:36	
	US. Air Exp	13 :34:16 - 13:36:32	
	Cont. exp.	13 :37:08 - 13:40:20	
		: :	
		: :	
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Figure B-4. Field note log sheet for 24 March 2008

Table B-1. TF Green weather for 24 March 2008

U.S. Department of Commerce
National Oceanic & Atmospheric Administration

QUALITY CONTROLLED LOCAL CLIMATOLOGICAL DATA (final)
HOURLY OBSERVATIONS TABLE
THEODORE F GREEN STATE AIRPORT (14765)
PROVIDENCE , RI
(03/2008)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

Elevation: 52 ft. above sea level
Latitude: 41.722
Longitude: -71.433
Data Version: VER3

Date	Time (LST)	Station Type	Sky Conditions	Visibility (SM)	Weather Type	Dry Bulb Temp		Wet Bulb Temp		Dew Point Temp		Rel Humd %	Wind Speed (MPH)	Wind Dir	Wind Gusts (MPH)	Station Pressure (in. hg)	Press Tend	Net 3-hr Chg (mb)	Sea Level Pressure (in. hg)	Report Type	Precip. Total (in)	Alti-meter (in. hg)
						(F)	(C)	(F)	(C)	(F)	(C)											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
24	0051	11	CLR	10.00		31	-0.6	24	-4.2	8	-13.3	38	0	000		30.15	1	007	30.22	AA		30.22
24	0151	11	CLR	10.00		29	-1.7	24	-4.5	11	-11.7	47	5	290		30.15			30.22	AA		30.22
24	0251	11	CLR	10.00		29	-1.7	24	-4.4	12	-11.1	49	3	300		30.15			30.22	AA		30.22
24	0351	11	CLR	10.00		29	-1.7	23	-4.9	8	-13.3	41	0	000		30.16	3	001	30.22	AA		30.23
24	0451	11	FEW200	10.00		26	-3.3	22	-5.7	11	-11.7	53	3	VR		30.17			30.24	AA		30.24
24	0551	11	FEW100 SCT200	10.00		28	-2.2	23	-5.2	9	-12.8	45	7	350		30.18			30.25	AA		30.25
24	0651	11	FEW100 SCT250	10.00		30	-1.1	24	-4.3	10	-12.2	43	8	350		30.20	3	016	30.27	AA		30.27
24	0751	11	FEW100 SCT250	10.00		34	1.1	27	-2.6	12	-11.1	40	7	010		30.19			30.26	AA		30.26
24	0851	11	FEW100 SCT250	10.00		37	2.8	30	-1.1	16	-8.9	42	5	VR		30.21			30.28	AA		30.28
24	0951	11	FEW040 SCT100 SCT250	10.00		40	4.4	32	0.1	18	-7.8	41	0	000		30.21	3	002	30.28	AA		30.28
24	1051	11	FEW040 SCT100 SCT250	10.00		43	6.1	34	0.8	16	-8.9	34	0	000		30.20			30.27	AA		30.27
24	1151	11	FEW040 SCT100 BKN250	10.00		46	7.8	34	1.2	11	-11.7	24	5	VR		30.17			30.24	AA		30.24
24	1251	11	FEW045 SCT100 BKN250	10.00		46	7.8	34	1.3	12	-11.1	25	5	VR		30.15	8	021	30.22	AA		30.22
24	1351	11	FEW045 SCT100 SCT250	10.00		48	8.9	35	1.8	11	-11.7	22	11	250		30.13			30.20	AA		30.20
24	1451	11	FEW040 SCT250	10.00		48	8.9	37	2.5	17	-8.3	29	9	210		30.11			30.18	AA		30.18
24	1551	11	FEW040 SCT045 SCT250	10.00		46	7.8	35	1.8	16	-8.9	30	7	160		30.10	6	017	30.17	AA		30.17
24	1651	11	FEW050 SCT075 SCT250	10.00		47	8.3	35	1.8	14	-10.0	26	0	000		30.10			30.17	AA		30.17
24	1751	11	FEW050 SCT090 SCT250	10.00		44	6.7	34	1.3	17	-8.3	34	0	000		30.11			30.18	AA		30.18
24	1851	11	FEW050 SCT095 SCT250	10.00		40	4.4	33	0.6	21	-6.1	47	9	130		30.13	3	011	30.20	AA		30.20
24	1951	11	FEW200	10.00		39	3.9	33	0.4	22	-5.6	51	3	150		30.15			30.22	AA		30.22
24	2051	11	FEW030 SCT200	10.00		36	2.2	30	-0.8	20	-6.7	52	6	030		30.14			30.21	AA		30.21
24	2151	11	FEW200	10.00		36	2.2	30	-1.0	19	-7.2	50	6	010		30.15	1	007	30.22	AA		30.22
24	2251	11	BKN200	10.00		34	1.1	29	-1.3	21	-6.1	59	5	010		30.16			30.22	AA		30.23
24	2351	11	BKN250	10.00		35	1.7	30	-1.0	21	-6.1	57	6	330		30.15			30.22	AA		30.22

B.3. T.F. Green Taxi Noise Measurement Analysis

Table B-2 is a summary of the operations recorded during the measurement interval and the recorded SEL (dBA) event levels for the taxi event.

Table B-2. Summary of TF Green Noise events

Aircraft	Carrier	Plane Type	Speed (knots)	Time Start	Time Stop	dt	SEL	notes
1	-	small prop	-	11:01:39	11:02:31	52	68.6	did not have camera
2	Continental Express	Regional Jet	-	11:05:58	11:06:47	49	83.6	did not have camera, either a ERJ-145, ERJ-135 or CRJ200LR
3	Southwest	737-700	22.79	12:23:16	12:24:37	81	91.8	
4	US Airways Express	Embraer 170	17.82	12:35:56	12:37:14	78	93.4	
5	Southwest	737-700	19.37	13:10:53	13:12:07	74	88	
6	US Airways Express	Embraer 170	11.79	13:34:41	13:35:50	69	90.6	
7	Continental Express	Embraer ERJ-145	12.17	13:38:27	13:40:02	95	88.9	
Sound level meter placed 71.57 meters from centerline of taxiway								
Ambient levels around 45 dB: noise from other planes at gates								

APPENDIX C: Washington Dulles International Airport Breakaway Thrust Noise Measurements

C.1. Measurement Description

A characterization of breakaway thrust from taxiing aircraft noise was successfully made based on measurements conducted at Washington Dulles International Airport (IAD). This type of event occurs when certain aircraft, often very large jets, increase engine power in order to overcome static friction and begin to roll. Many smaller aircraft simply release the brakes, but an idle power setting does not provide sufficient forward thrust for some large aircraft to begin moving. The amount of increase in thrust for the start of taxi roll has not been well defined and may conceivably change from pilot to pilot. The primary goal of this measurement was to determine the general characteristics of breakaway thrust noise and provide substantiation for a recommendation that more comprehensive and detailed breakaway thrust measurements be performed.

A small array of ground microphones and sound level meters were deployed in order to record the noise emanating from aircraft as they wait to proceed to the runway for take-off. Due to construction activity at the airport, only the two westernmost runways were operational. The measurement location is signified by the blue box south of the hold block near Runway 30 (Figure C-1). Two of the microphones in this measurement were placed directly on the concrete with half-sphere windscreens. Microphone #1 is 30 feet from the hold line and the two microphones are spaced 30 feet apart from each other as in Figure C-2. The microphone used for analysis was Microphone # 1, located at an angle from the centerline 50° from the nose of the aircraft (theta = 50°) on a 75 foot line perpendicular to the vehicle centerline intersecting the vehicle near the nose (See Figure C-2). The distance from the microphone to the nearest engine was approximately 70-75 feet. Due to lack of aircraft tracking data these dimensions are approximate.

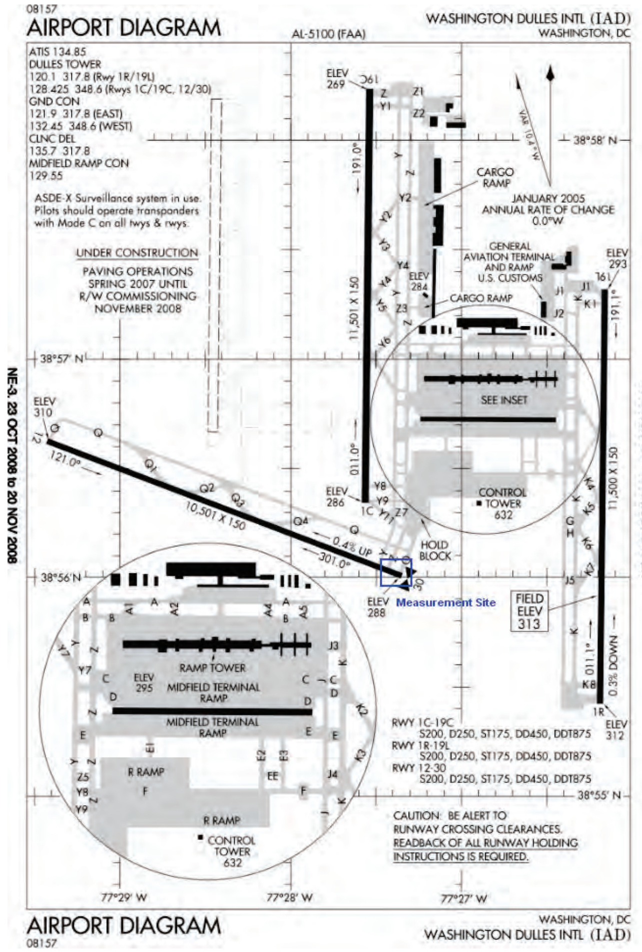

Figure C-1: Map of Washington Dulles International Airport (IAD) ***(Image credit: airnav.com)***

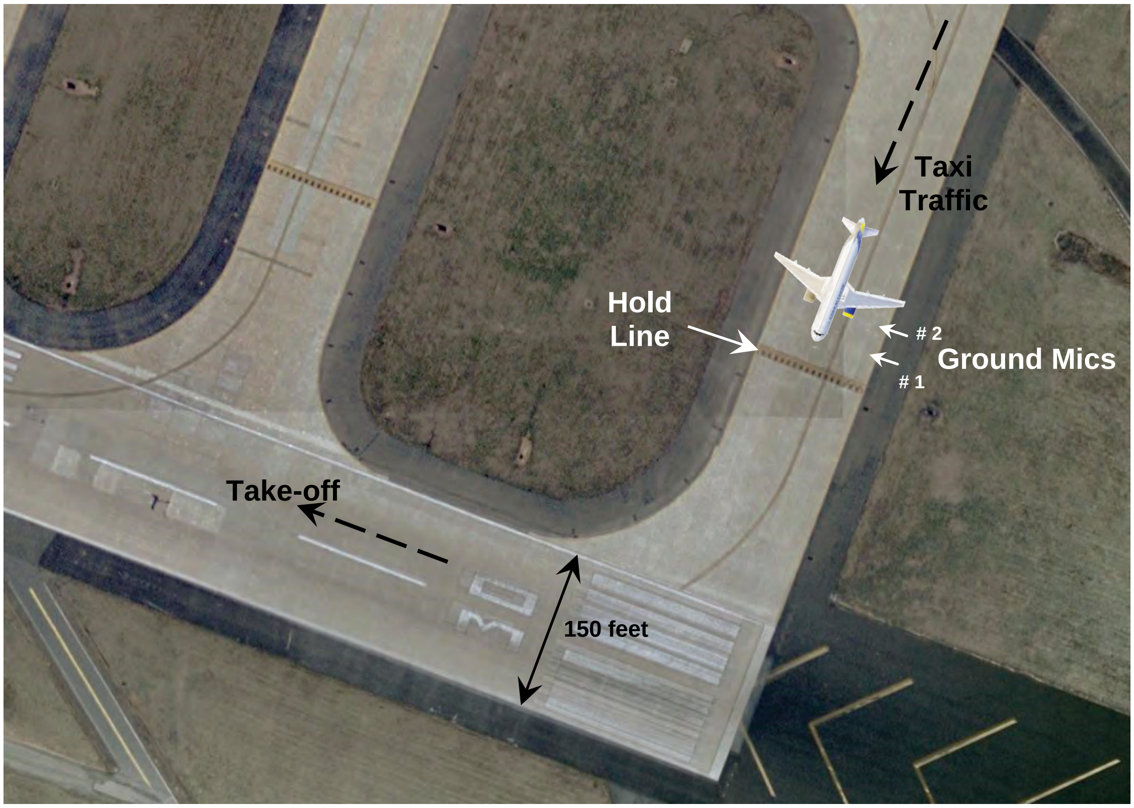

Figure C-2: IAD Taxi Noise 2 Microphone Setup (Background image Copyright 2008 Commonwealth of Virginia)

Table C-1 lists all aircraft passing the microphone array throughout the measurement period. The "x" column signifies possible breakaway thrust events. This appendix will showcase the two events highlighted in Table C-1, which are assumed to be representative of typical breakaway thrust noise events. Special attention was placed on two large aircraft – the Boeing 757 and the Airbus A320. Engineers on site were able to clearly discern the spooling up of the engines as is anticipated during application of breakaway thrust. These particular recordings were chosen because they were particularly free of unwanted noise from sources such as wind and other aircraft. In Table C-1 the Event column signifies possible breakaway thrust events. The two highlighted events for Tail Numbers 469UA and 561UA, are showcased in this appendix.

Table C-1: Aircraft passing the microphone array during the measurement period.

Event	Tail Number	Time (24-hr)	Operator	Aircraft	Engine Mfgr	Engine Type
	265QS	10:40	GA - NetJets	FALCON 2000	C F E CO	CFE 738-1-1B
	849UA	10:44	United	A319-131	IAE	V2500 SERIES
	825MJ	10:48	Delta	EMB-145LR	ALLISON	AE3007C SER
	17175	10:49	Canadair	CANADAIR CL-600-2B19	GE	CF-34-1A
	518FX	10:51	GA Bombardier	BD-100-1A10	HONEYWELL	AS907-1-1A
x	216WR	10:52	Southwest	737-7H4	CFM INTL	CFM56 SERIES
	258JB	10:56	JetBlue	EMBRAER ERJ 190-100 IGW	GE	CF34-10E6
	953AT	10:57	AirTran	Boeing 717-200	BMW ROLLS	BR 700 SERIES
	659UA	10:58	United	Boeing 767-322	P&W	PW4000 SER
	819JR	11:02	GA Autoflight	HAWKER 900	HONEYWELL	TFE731-50R
	955DL	11:07	Delta	MD-88	P & W	JT8D SERIES
x	379PH	11:07	Continental Connection	DHC-8-202 (Dash 8)	P&W Canada	PW123
	183JB	11:20	JetBlue	EMBRAER ERJ 190-100	UNKNOWN	UNKNOWN ENG

				IGW		
	227AA	11:32	American	DC-9-82(MD-82)	P & W	JT8D SERIES
	375P	11:37	GA - Private	PIPER PA-28-161	LYCOMING	0-320 SERIES
	139SK	11:40	GA - Private	LEARJET 55	GARRETT	TFE 731 SER
	803TA	11:54	GA - Flight Options	HAWKER 800XP	ALLIEDSIGN	TFE731-5BR
	691WN	12:15	Southwest	Boeing 737-3G7	CFM INTL	CFM56 SERIES
x	75996	12:18	United Express / Mesa	CANADAIR CL-600-2B19	GE	CF34 SERIES
	654UA	12:24	United Airlines	Boeing 767-322	Pratt & Whitney	PW4000 SER
	351UA	12:25	United Airlines	Boeing 737-322	CFM INTL	CFM56 SERIES
	27172	12:27	United Express	CANADAIR CL-600-2B19	GE	CF34 SERIES
	17156	12:28	United Express	CANADAIR CL-600-2B19	GE	CF34 SERIES
	508QS	12:28	GA - Private	Gulfstream GV	BMW ROLLS	BR 700 SERI
	470UA	12:30	United Airlines	Airbus A320-232	IAE	V2500 SERIES
	242CJ	12:37	United Express	SAAB 340B	GE	CT7-Series
	854UA	12:37	United Airlines	Airbus A319-131	IAE	V2500 SERIES
x	512MJ	12:40	United Express/Mesa	CL-600-2C10	GE	CF34 SERIES
	UNK	12:40	United Express	UNK	UNK	UNK
x	196CJ	12:42	United Express / Colgan Air	SAAB 340B	GE	CT7-9B
x	469UA	12:43	United Airlines	Airbus A320-232	IAE	V2500 SERIES
	933UA	12:45	United Airlines	Boeing 737-522	CFM INTL	CFM56 SERIES
	290SK	12:46	United Express	Embraer EMB-145LR	Rolls Royce /Allison	AE 3007A1P
x	809HK	12:49	Trans States Airlines	Embraer EMB-145EP	Rolls Royce /Allison	AE 3007A
	856RW	12:49	United Express	Embraer ERJ 170-100 SE	GE	CF34 SERIES
	210CJ	12:53	United Express/Colgan Air	SAAB 340B	GE	CT7-Series
	292SK	12:54	United Express	Embraer EMB-145LR	Rolls Royce /Allison	AE 3007A1P
	220MJ	12:55	United Express / Colgan Air	SAAB 340B	GE	CT7-SER
	37208	12:56	United Express	CL-600-2B19	GE	CF34 SERIES
	311CE	12:57	United Express	SAAB 340B	GE	CT7-SER
x	561UA	12:58	United Airlines	Boeing 757-222	Pratt & Whitney	PW2040
	341CJ	12:59	United Express / Colgan Air	SAAB 340B	GE	CT7-SER
	679DA	13:03	Delta	Boeing 757-232	Pratt & Whitney	PW2037
	845HK	13:05	United Express / Trans States	EMB-145LR	Rolls Royce /Allison	AE3007 SER
	835HK	13:07	United Express	EMB-145LR	Rolls Royce /Allison	AE3007 SER
	977RP	13:09	United Express	EMB-145	Rolls Royce /Allison	AE 3007A1P
x	47202	13:14	United Express	CL-600-2B19	GE	CF34 SERIES
	849HK	13:15	United Express	EMB-145LR	Rolls Royce /Allison	AE3007 SER
	982NA	13:16	GA Private	Cessna 550	P&W Canada	JT15D-4
x	555AN	13:17	American Airlines	DC-9-82(MD-82)	Pratt & Whitney	JT8D SERIES
	346SW	13:23	Southwest	Boeing 737-3H4	CFM INTL	CFM56 SERIES
	840HK	13:25	United Express	EMB-145LR	Rolls Royce /Allison	AE3007 SER

C.2. Analysis

A certain challenge in analysis of this data was deciphering the noise from departing aircraft from the desired breakaway thrust noise component. Often it seemed the waiting pilot's cue to engage the engines to initiate a taxi roll was when the departing plane's pilot throttled the engines to take-off power to begin departure. This means the number of "clean" events was significantly reduced and that the analyzed recordings required some careful listening and close attention to the spectral aspects of the noise. For jets, engine noise is generally broadband, but, as a departing plane gets further away, the high-frequency components diminish due to atmospheric absorption, allowing special attention to be focused on the steady-state noise of the near-by aircraft as it begins its taxi roll.

Two other aspects to consider with moving vehicles are engine noise directivity and the noise sources' proximity to the microphones. It can be assumed that the noise characteristics of an engine may change as the microphone's position relative to the engine changes. Also, as the vehicle begins to move forward, the engine's distance to the microphone decreases and the sound pressure will increase due to spherical wave divergence. These two elements' impact on the data may be minimized by using Microphone # 1. Since it is further away from the engine when the aircraft is stationary, it will be less susceptible to spherical divergence, which behaves exponentially, and thus decreases the chance of an increase in acoustic level being attributed to the wrong cause. The forward position of Microphone # 1 will also make it less susceptible to the changes in noise characteristics due to engine directivity and simple geometry.

For these two large, jet-powered vehicles – the B757 and the A320 – the pilot would spool up the engines, increasing the rotational rate of the turbines, and at some point in time the aircraft begins to move forward. From a listener's perspective, it seemed the thrust was held constant for the taxi operation and often it seemed the pilot would pull the throttle back down towards idle power once the vehicle was able to maintain forward momentum for the short taxi to the start of the runway. Special attention, therefore, is placed on the increase in overall acoustic level which takes place as the tonal aspects of the noise increase in frequency. This segment of time is representative of an engine increasing in rotational rate and therefore increasing thrust.

Due to lack of data, it is not possible to know for sure if rolling commenced before the thrust level was stabilized. If time-synched tracking and thrust data were available, then the increase in acoustic level due to spherical divergence would be distinguishable from the increase caused by thrust increase alone. This analysis will assume vehicle rolling commences at the same time the thrust stabilizes, and, if rolling does begin prior to that, a decreasing distance between source and receiver will be at a very slow rate and thus a negligible contributor to acoustic level increase.

C.2.1. Airbus A320-232

This particular event was of interest because the waiting pilot did not apply breakaway thrust for a significant amount of time after the aircraft on the runway took off. Figure C-3 shows the overall flat and A-weighted levels of this recording segment. Grey vertical bars at times 36 and 42 seconds enclose a period where the aircraft is stationary and sound level increases are believed to be due solely to thrust increase. The aircraft remains at idle power and at 97 dB overall sound pressure level (OASPL) until the time in the recording reaches 36 seconds. At this point, the engine power is increased, which causes an increase in OASPL that peaks at 105 dB at a time of 46 seconds. As the vehicle rolls past the microphone and begins to turn onto the runway the acoustic level is diminished as the vehicle gets further away and the pilot spools down the throttle for taxi.

The main peak in Figure C-3 likely coincides with the closest point of approach of the noise source to the microphone. To extract the acoustic level increase due solely to engine spool up a spectral representation such as Figure C-4 displaying frequency versus time with a monochrome scale for acoustic level is a good tool. Grey vertical bars at time equals 36 and 42 seconds enclose a period where tonal components increase in frequency due to an increase in the engine's rotational rate. This is when the thrust is being increased by the pilot.

A look at this time period for the overall sound pressure graph (Figure C-3) correlates to an increase in un-weighted overall acoustic level of 4 dB, from 97 dB to 101 dB. Past 42 seconds the tones remain constant in frequency but the overall level of the noise increases as the vehicle moves closer to the microphone. The acoustic level then decreases not only due to the airplane then moving away from the microphone, but also due to the fact that the pilot has now decreased the thrust to prepare to wait in idle power for permission to take off. The spool-down occurs at 50 seconds. In the far-field, this event would be perceived as an increase in noise of 4 dB over the course of 10 seconds, and can be contributed almost entirely to breakaway thrust. Figure C-5 shows the one-third octave band spectra for the A320 during idle and with the engine throttled to a breakaway thrust level. When the engine is throttled the one-third octave band spectrum shows the main tonal component of the jet engine in band number 29 (800 Hz) 5 dB above the rest of the broadband noise.

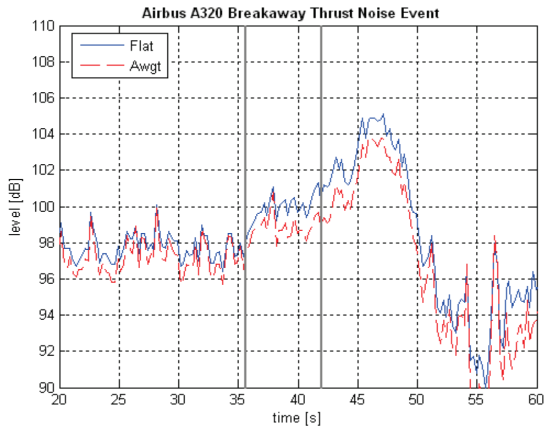

Figure C-3: OASPL (dB) versus time for Airbus A320 breakaway thrust noise event.

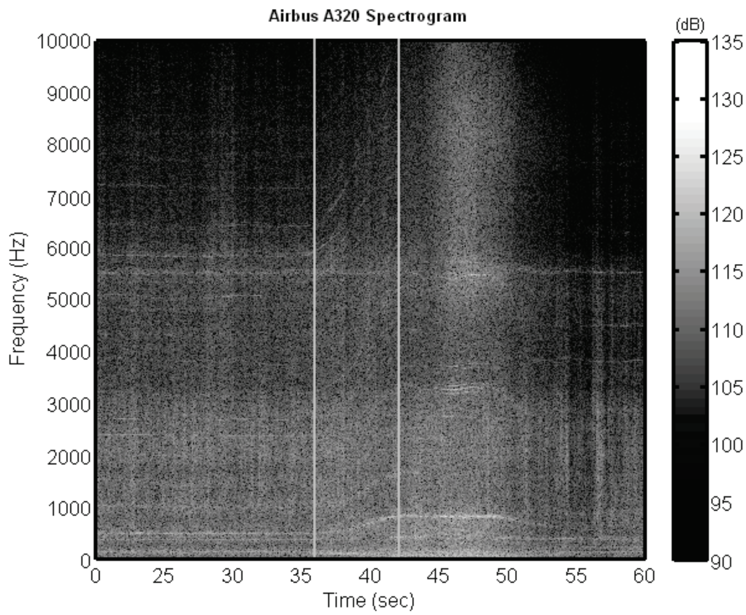

Figure C-4. Airbus A320 Taxi Event Spectrogram

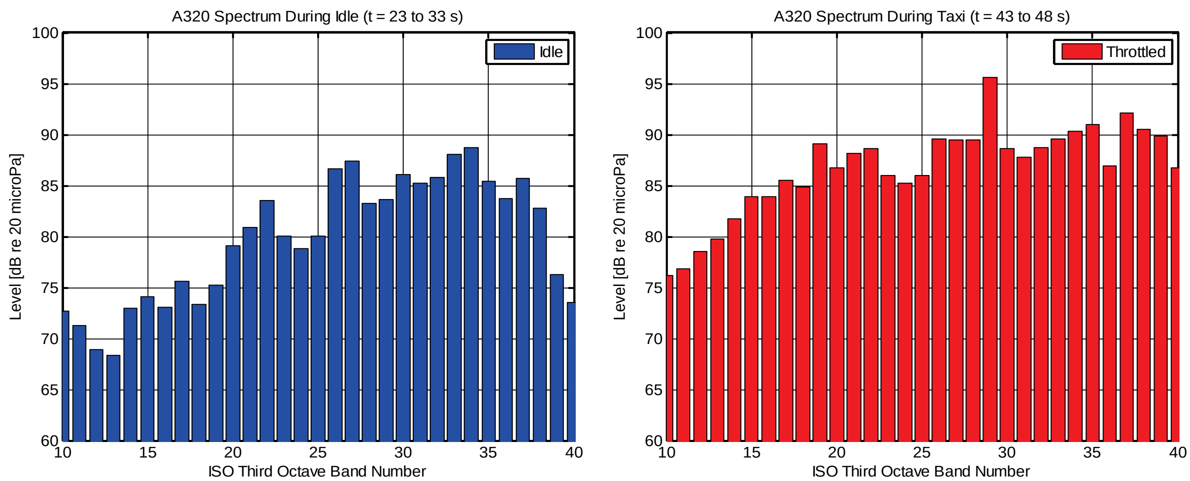

Figure C-5. Airbus A320 third-octave band spectra for an idling and taxiing engine.

C.2.2. Boeing B757-222

The second representative noise event for breakaway thrust is portrayed below in Figures C-6 and C-7. A tonal frequency increase occurs from time equals 36 to 44 seconds. This corresponds to a 7 dB increase in A-weighted OASPL from 97 dB to 104 dB. A-weighted levels were considered due to some low-frequency contamination from the entrails of a takeoff noise event leading up to this period. The spool-down period for this vehicle begins just after the throttle ascension ceases at time equals 45 seconds. The vertical grey bars at time equals 36 and 44 seconds encompass the region of breakaway thrust noise.

This B757 event would also be perceived as an increase in far-field level on the order of 10 seconds, and the increase of 7 dB far surpasses the 4 dB increase exhibited by the A320. However, the two events differ in that the A320 noise increases, maintains, and spools completely down over the course of 10 seconds, whereas the B757 takes about 8 seconds to spool up and then as it spools down it takes another 4 seconds to reach the original idle-power acoustic noise level. It is the author's opinion that the two events, while characteristically different, would be perceived as similar levels of annoyance by a listener.

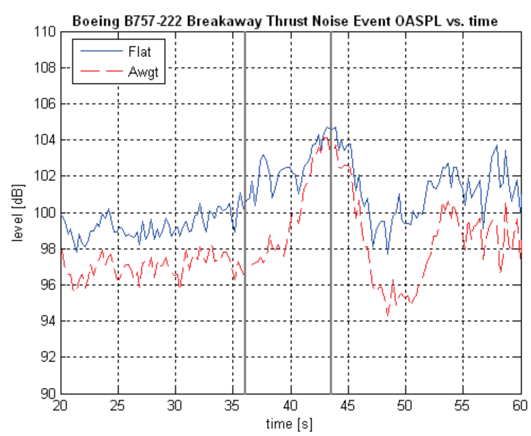

Figure C-6. OASPL (dB) versus time for Airbus B757 breakaway thrust noise event.

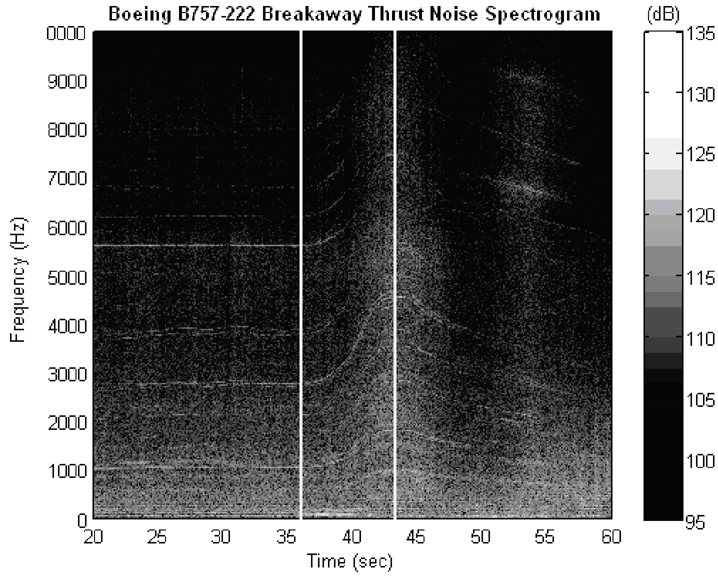

Figure C-7. Boeing B757 Taxi Event Spectrogram

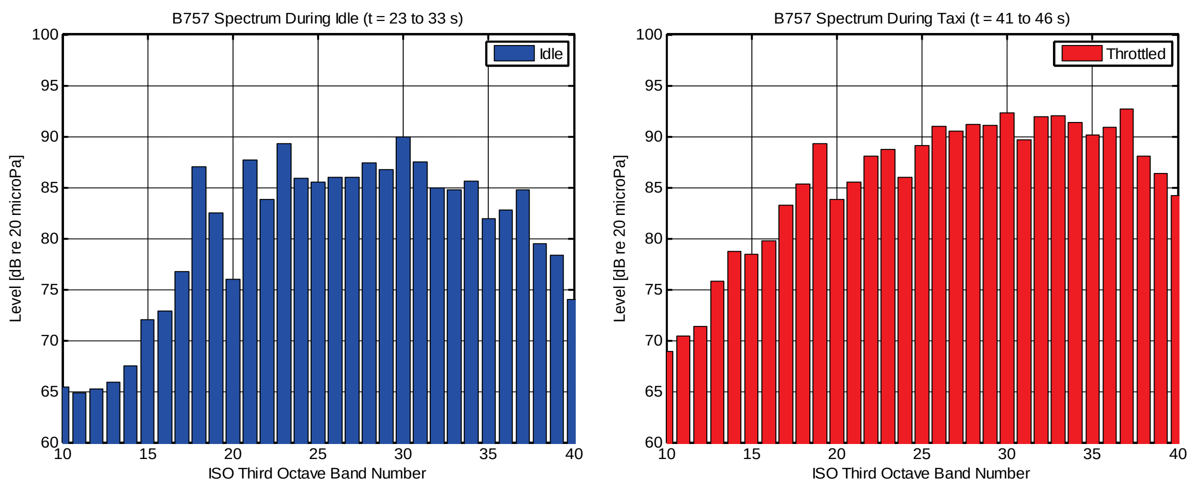

Figure C8. Airbus A320 one-third octave band spectra for an idling and taxiing engine

C.3. Conclusions

Breakaway thrust has been determined to be apparent and distinguishable from normal taxi noise through measurement and analysis. For an Airbus A320-232 and a Boeing B757-222 breakaway thrust noise has been quantified from a stop-and-go taxi operation for each vehicle as they stopped to wait for a plane in front of them to take off. The microphone used for analysis was located at an angle from the centerline 50° from the nose of the aircraft (theta = 50°) on a 75 foot line perpendicular to the vehicle centerline intersecting the vehicle near the nose (Figure C-2). The distance from the microphone to the nearest engine was 70-75 feet. Due to lack of tracking data these dimensions are approximate and apply to both vehicles.

The A320-232 was found to exhibit an increase of un-weighted overall sound pressure level of 4 dB over the course of 10 seconds. The static aircraft spooled up its engines from idle power to begin roll, maintained an increased thrust level for 10 seconds, then spooled-down its engines while rolling to the runway.

The B757-222 had an A-weighted increase of 7 dB, and maneuvered slightly differently from the A320 in that the increased thrust was only maintained for 1 second. However, the spool-down behavior of these particular engines may lend itself to require less time of maintained increased thrust. This is evident in the B757 spectrogram (Figure C-7) by the gentle slope down spectrally from time equals 45 to 60 seconds.

Two events were analyzed completely for the sake of this appendix and both aircraft were found to exhibit breakaway thrust noise level increases. These two aircraft – the A320 and the B757-222 – are very common to IAD and many other airports. Table C-1 shows when the field personnel perceived a breakaway thrust noise event in the first column. Other aircraft which may potentially capture breakaway thrust noise events include the Dash-8, CL-600, EMB-145, B737, and DC-9.

The measurement location was ideal for an operating airport. Meteorological and operational factors, however, preclude a significant portion of the data from analysis. In order to fully quantify noise level increases due to breakaway thrust, a parametric study would need to be performed to understand the relative sensitivities of variables such as aircraft types, pilot operational tendencies, airport operational factors, and engine directivity and type.

Appendix D EDMS Modeling of Airside Operations

D.1. Introduction

EDMS[D1,D2] is a combined emissions and dispersion model for assessing air quality at airports. The model was developed by the Federal Aviation Administration (FAA) in cooperation with the United States Air Force (USAF). The model is used to produce an inventory of emissions generated by sources on and around the airport or air base, and to calculate pollutant concentrations in these environments. Within EDMS, taxiway emissions are modeled for on-ground, non-runway operations of an aircraft. These operations are discretely defined along with the other modes as indicated below:

- Taxi Out (& Idle)
- Takeoff
- Climb Out
- Approach
- Taxi In (& Idle)

Included within the taxiing operations are idling times where the aircraft is not moving but the engines are still on. The EDMS user is required to specify the number of operations for these modes. This can be accomplished in one of two ways. The Landing and Takeoff (LTO) cycles can be specified as a whole for each aircraft-engine in which case the number of departures and arrivals are identical (i.e., LTO cycles = departures = arrivals), or the departures and arrivals can be specified separately (i.e., number of departures and arrivals are different). Often, quarter-hour profiles are used to distribute the operations across the 96 quarter hours in a day, the 7 days in a week, and the 12 months in a year.

This appendix outlines a set of methods used to model aircraft operations in EDMS 5.x. Since aircraft engine emissions depend on the thrust setting and runtime, accurate inventory estimation requires modeling of both. EDMS has two options to model times-in-mode of aircraft operations. Moreover, EDMS has two modes of operations: inventory and dispersion, with significantly different data requirements. This appendix aims to briefly describe modeling options and data requirements without going into specifics of the supporting algorithms.

There are two basic modes in modeling of airport operations:

Emissions Inventory and

Dispersion modeling

Samples studies are: dispersion modeling for elevated mobile sources are provided in reference D.13 and an estimate of aircraft emissions for future traffic scenarios may be found in reference D.14. Both modes are further elaborated below.

D.2. Emissions Inventory

An emissions inventory is a report on cumulative assessment of pollutants generated by all active emission sources included in the study (e.g., aircraft, APU, GSE). To perform an emissions inventory, the user needs to identify emission sources and the annual activity for each of the sources. Moreover, emission factors are required if the user opts to create user-defined sources (e.g., aircraft, APU, GSE).

EDMS calculates the total annual pollutant emissions for each of the identified sources and presents it in both a summarized report and a detailed report. The following pollutants are considered[D1]:

- **CO2** (carbon dioxide) for aircraft only,
- **CO** (carbon monoxide),
- **THC** (total hydrocarbons) for aircraft and APUs only,
- **NMHC** (non-methane hydrocarbons),
- **VOC** (volatile organic compounds),
- **TOG** (total organic compounds),
- **NOx** (nitrogen oxides),
- **SOx** (sulfur oxides),
- **PM-10** (particulate matter, 10 microns)
- **PM-2.5** (particulate matter, 2.5 microns), and
- 395 **Speciated Hydrocarbons** (44 HAPs, and 351 non-toxic compounds).

As it could be noted from the description above, if EDMS is being used to run an emissions only analysis, the user is not required to provide neither detailed layout of the airport nor detailed weather data. Thus, in this mode EDMS does not model individual aircraft movements. To calculate the total annual pollutant emissions EDMS uses a (pseudo)schedule and input information on the amount of time each aircraft spends in each mode of operation (portion of a landing and takeoff (LTO) cycle). EDMS divides LTO cycles into six phases: approach, taxi-in, startup, taxi-out, takeoff, and climb-out. Out of these, approach, takeoff and climb-out are airborne phases. The landing roll part of the approach segment is incorporated into the taxi-in time.

The six modes of operation involved in the LTO cycle can be described as follows[D1]:

1. **Approach**: The airborne segment of an aircraft's arrival extending from the start of the flight profile (or the mixing height, whichever is lower) to touchdown on the runway.
2. **Taxi In**: The landing ground roll segment (from touchdown to the runway exit) of an arriving aircraft, including reverse thrust, and the taxiing from the runway exit to a gate.
3. **Startup**: Aircraft main engine startup occurs at the gate. This methodology is only applied to aircraft with ICAO certified engines. All other aircraft will not have startup emissions. Aircraft main engine startup produces only HC, VOC, NMHC, and TOG emissions. A detailed speciated hydrocarbons profile does not exist for main engine startup emissions.
4. **Taxi Out**: The taxiing from the gate to a runway end.
5. **Takeoff**: The portion from the start of the ground roll on the runway, through wheels off, and the airborne portion of the ascent up to cutback during which the aircraft operates at maximum thrust.
6. **Climb Out**: The portion from engine cutback to the end of the flight profile (or the mixing height, whichever is lower).

Generally, there are two options for determining times in mode for LTO cycle:

- *Performance Based* (SAE AIR 1845)[D12] and
- *ICAO/USEPA* Default[D3]

Performance based modeling uses the specific airframe and engine characteristics along with weather data to model each flight dynamically resulting in non-constant times-in-mode. ICAO/USEPA defaults are standardized values read from a table (Table D.1). The user can modify these times if necessary through input dialogs for all aircraft or for each study aircraft. Within EDMS, a study aircraft refers to a specific group of aircraft operations performed by a single aircraft-engine combination. These operations have a set of common characteristics such as: aircraft performance and engine characteristics, are serviced by the same set of GSEs, have the same APU, etc.

Table D-1. ICAO Time in mode for landing and take-off (LTO) cycle

Phase of flight	Operation Time [min]
Take-off	0.7
Climb-out	2.2
Approach	4.0
Taxi-out	19.0
Taxi-in	7.0

Sample studies have used performance based times-in-mode[D4,D7] and using both methods[D6] to obtain times in mode. A sample study in which the user modified time-in-mode data (ICAO/USEPA recommendations for taxi-in and taxi-out times are modified) is outlined in Reference D.5.

For emissions inventory development, just the total time attributed to idling and taxiing operations can be used. The EDMS user can supply this information from various sources including flight schedules and tower logs. The following defaults from ICAO[D3] can also be used:

- Taxi Out: 19 min
- Taxi In: 7 min

Taxi emissions are modeled using engine-specific emissions indices and fuel flow rates corresponding to the lowest (7%) of the standard power settings from the ICAO emissions databank:

- Idle (& taxi): 7%
- Approach: 30%
- Climb Out: 85%
- Takeoff: 100%

D.3. Dispersion Modeling

EDMS dispersion modeling requires knowledge of both when and where emissions took place. Thus, when modeling aircraft operations, the user is required to use:

- performance based aircraft modeling of airborne operations *(SAE AIR 1845)* and
- Detailed modeling of aircraft surface movements (queuing/sequencing).

For dispersion modeling, EDMS uses the following third party components:

- AERMOD dispersion model
- Two AERMOD processors:
- AERMET – meteorology
- AERMAP – terrain

In 2000. the US Environmental Protection Agency (EPA) developed AERMOD[D8,D9,D10,D11] as the newest generation of short-range steady-state atmospheric dispersion models. Although it was not originally intended to model elevated mobile sources, AERMOD has been integrated into EDMS[D4] since 2001. AERMOD is a plume model that is used for modeling concentrations of pollutants stemming from various sources which may be represented as ideal point, area or volume sources.

EDMS can calculate hourly emissions, and generate AERMOD input files for the following pollutants:

- **CO** (carbon monoxide),
- **THC** (total hydrocarbons) for aircraft and APUs only,
- **NMHC** (non-methane hydrocarbons),
- **VOC** (volatile organic compounds),
- **TOG** (total organic compounds),
- **NOx** (nitrogen oxides),
- **SOx** (sulfur oxides),
- **PM-10** (particulate matter, 10 microns), and
- **PM-2.5** (particulate matter, 2.5 microns).

The amount of data required to perform a dispersion analysis is significantly greater than the data necessary for just an emissions inventory. The additional information required for a successful dispersion analysis includes:

1. Detailed (pseudo-)schedule,
2. Aircraft performance modeling (SAE AIR 1845),
3. Airside delay and sequencing modeling,
4. Hourly weather data,
5. Placement of receptors.

An aircraft delay and sequencing modeling requires:

- Detailed airport layout, and
- A set of airport configurations and activation method.

Airside delay and sequencing model data flow[D2] is depicted in Figure D-1.

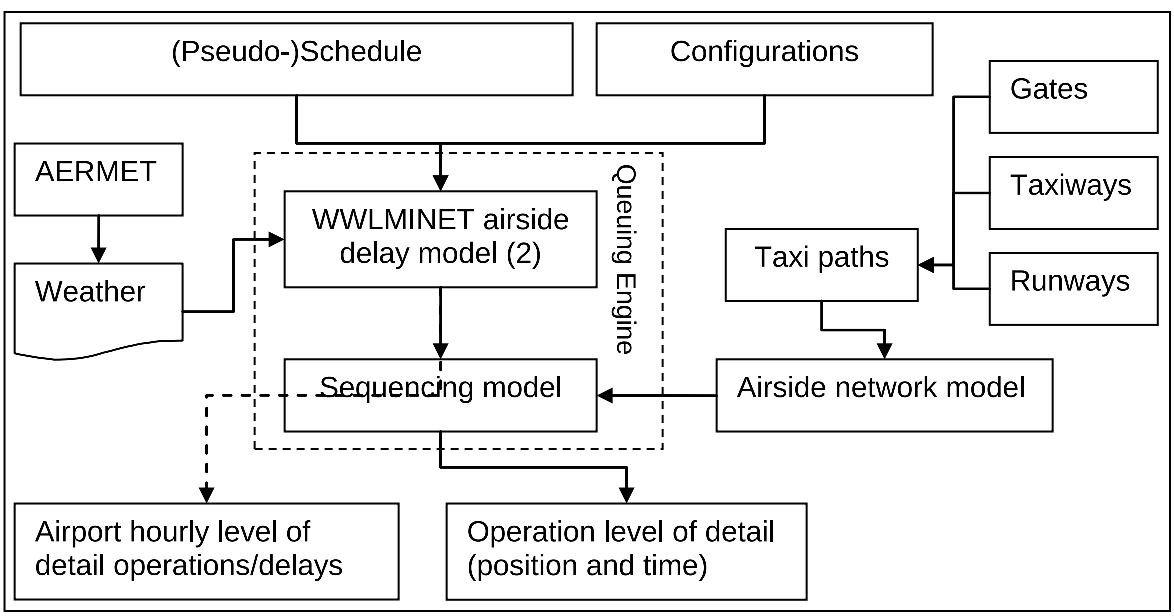

Figure D-1. Airside delay and sequencing model data flow

An emissions inventory must first be generated before dispersion can be performed, since the set of emissions that are dispersed is the same as that produced from the annual inventory. More details on algorithms implemented in EDMS can be found in Reference D2.

As is outlined above, the EDMS dispersion modeling requires a large quantity of data per airport. Thus, it is suitable for local studies (a single or a few adjacent airports). EDMS is not designed for global analysis. However, the user may elect to use EDMS to calculate emissions in many airports. In order to complete a multi airport project with EDMS, some simplification of the input data may be required to reduce the modeling and run time. The System for Assessing Aviation's Global Emissions (SAGE)[D.15] is a tool aimed to predict aircraft fuel burn and emissions for commercial flights globally.

D.4. Delay and Sequence Modeling

The aircraft delay and sequencing models embedded in EDMS are designed to process five years of traffic/weather data, and calculate the aircraft taxi times in a reasonable amount of time. As a part of future improvements, for the case where the user would require a more detailed simulation of airport operations, the outputs of a more detailed simulation models (e.g., TAAM/SIMMOD) could be imported into EDMS and AEDT to provide even more realistic times-in-mode.

The Queuing/Sequencing model requires the user to input an airport layout. However, the level of details entered is solely the user's choice. For example, the user may opt to approximate a taxiway with a straight line, or neglect less used runways, etc.

Using capacity information, delay modeling is conducted through the use of WWLMINET, a queuing model developed by the Logistics Management Institute (LMI). The modeled delays are used to adjust the push-back time for departures and the touchdown times for arrivals. Queues are also formed as part of this delay modeling to realistically account for the line of aircraft waiting along taxiways to use a runway. Although this is done for departures, arriving aircraft are assumed to have unimpeded taxi movements to the gate (no queue formation).

Using a combination of the configuration information, the operational profiles, a delay module, and a sequencing module, detailed modeling of runway and taxi-way usage can be conducted taking into account the capacity at an airport. The user needs to specify one or more points (departures/hr versus arrivals/hr) along a Pareto frontier to define the capacity at the airport.

The sequencing module models the movement of aircraft along taxiways including any queues that are formed. Along with the geometry, the user can provide an average movement speed specific to each taxiway (not specific to aircraft type). The default speed is 15 knots (17.26 mph). This allows the determination of how long each aircraft spent on each taxiway segment for proper calculation and allocation of emissions for dispersion modeling. In addition, aircraft-specific (or aircraft category-specific) dispersion parameters can be properly applied to the taxiway segment.

EDMS contains a sequencing module that utilizes a delay model (WWLMINET) which predicts the formation of queues on taxiways. To engage the sequencing module, the user would have to provide the following:

1. Airport capacity data (essentially through departure per hour versus arrival per hour points along a Pareto Frontier)
2. Airport operations / LTOs
3. Taxiway geometry.
4. Speeds for each taxiway segment.

Using this data, the sequencing module predicts the time-in-mode for each taxiway segment which is then used to calculate emissions. At present these calculations are done internally within EDMS so that the user only sees the final results (emissions). For the prediction of taxi noise, CSSI could potentially output the TIM values as necessary. For integration purposes within AEDT, the TIM values for each segment would be available. For emissions it is just the total time spent within each taxiway segment that enters into the calculation since results doesn't depend on whether the aircraft is sitting idle or moving on a taxiway. Internally both stationary and moving conditions are modeled using the same fuel flow and emissions indices at 7% power. But the code could be made to distinguish between idle time and movement time for each aircraft. At present, movement times are based on using the user-supplied constant speed values for each segment. No acceleration or deceleration movements are modeled.

D.5. Airport (Airside) Delay Model

EDMS models airside operations in two steps:

1. using WWLMINET, which determines airport throughput
2. using Sequencing model, which determines for each operation actual times of reaching significant points on the airside network. The airside network is an artificial representation of the airport layout.

While modeling aircraft movements, the EDMS determines the active runway configuration that is used at each hour of the year based on meteorological information and the user-specified activation parameters in order to determine the associated airport capacity at each hour of the year. This airport capacity information along with demand information from the aircraft operational profiles or schedule are provided to the WWLMINET delay model to determine the airport throughput. Additionally, the EDMS's sequencing module adjusts the estimated gate push-back time (for departures) and estimated touchdown time (for arrivals) into actual times that are possibly delayed. The sequencing module further models the movements of aircraft along the taxiways (or taxipaths) between runways and gates for both arriving and departing aircraft. WWLMINET and its purpose in EDMS are described in the following paragraphs.

WWLMINET is the airport airside queuing model developed by LMI[D16, D17]. It models airside queuing by using a queuing network shown in Figure D-2.

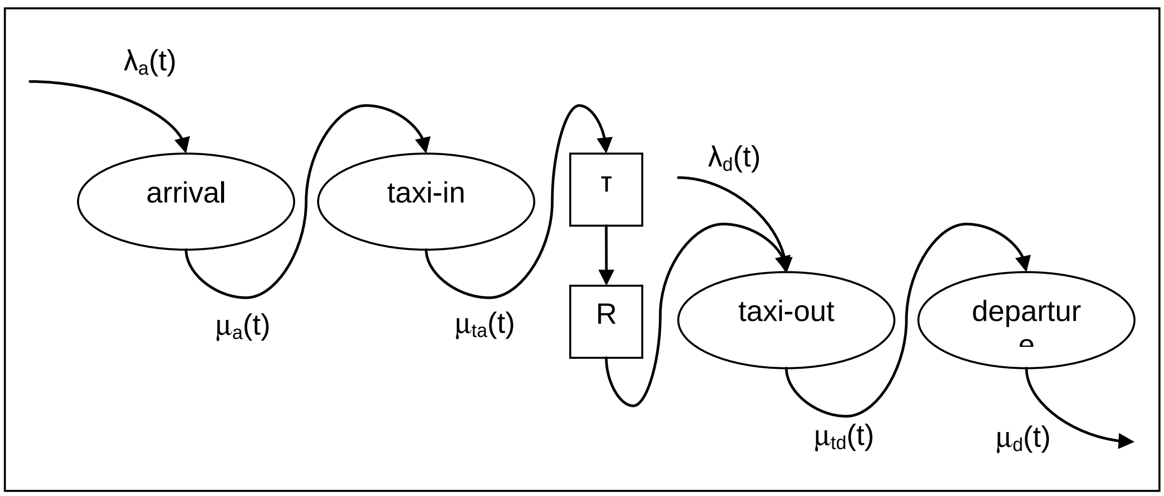

Figure D-2. Airside queuing in WWLMINET

Figure D-2 depicts two queuing processes: one for arrivals and another for departures. The arrival and departure processes are dependent. Thus, a departure may be released only if there is an available aircraft in the reservoir (R). The purpose of the reservoir is to balance the total number of arrivals and departures over time. Arriving aircraft enter the arrival queue as Poisson process with parameter $\lambda_a(t)$. After being processed by the arrival server, an arriving aircraft enters the taxi-in queue. Upon processing by the taxi-in server, arriving aircraft are delayed for a service time (τ) and released into the reservoir (R).

Departing aircraft are processed by two servers as well. The departure process is driven by: a Poisson process with parameter $\lambda_d(t)$, and the state of the reservoir (R). After being processed by the taxi-out server, departure aircraft enter the departure queue and, after processing, are released.

Arrival and departure servers may be modeled as M/M/1 or M/Ek/1 queues. Taxi times (both taxi-in and taxi-out) may be modeled as M/M/1 queues only. Arrival $\lambda_a(t)$ and departure $\lambda_d(t)$ demands are determined directly from the (pseudo)schedule. The arrival and departure service rates are determined by taking into account the appropriate airport capacity Pareto frontier (Figure D-3) based on the hourly surface weather observations.

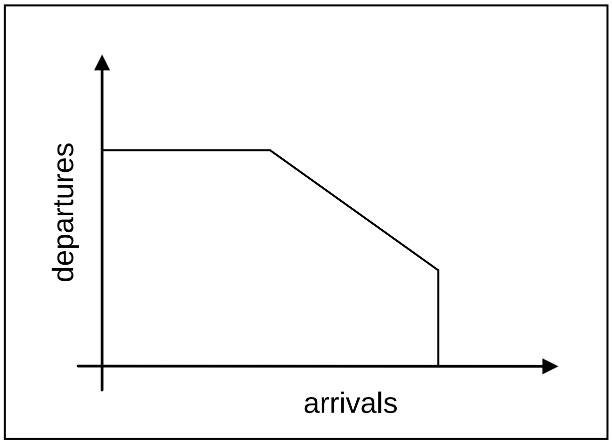

Figure D-3. Capacity Pareto frontier

The WWLMINET is used to determine, for each operation, a time bin when the operation is released as well as an average delay time acquired during each time bin.

D.6. Equipment Modeling

Aircraft types are specified through a comprehensive list of equipment names developed as part of the EDMS system databases. These aircraft are then assigned internally to the smaller set of actual performance models. Similarly, the selected engines are internally assigned to a Unique Identification Number (UID) from the International Civil Aviation Organization's (ICAO's) emissions databank.

D.7. Modeling of Taxi Paths

EDMS 5.x provides two options of modeling aircraft taxiing operations:

- User-specified taxi times for each aircraft
- Detailed modeling of aircraft movements along taxipaths (Queuing/Sequencing)

The user-specified taxi times option may be used to calculate an annual emissions inventory. This option may not be used for dispersion analysis, thus, the user is not required to provide an airport layout. The detailed modeling of aircraft movements option may be used to calculate an annual emissions inventory and for dispersion modeling (using AERMOD[D.8, D.9, D.10]). Thus, in addition to the aircraft schedule, the user is required to provide the following:

- Detailed airport layout (gates, taxiways, runways, etc.)
- A set of taxi paths[1] connecting gates to runways and runway exits to gates
- Airport configurations
- Hourly weather
- Location of receptors

Each operation (departure or arrival) is characterized, among the others, with its assigned gate and its expected (scheduled) operation time. Based on the weather input file, EDMS identifies the most appropriate airport configuration for each hour, which further identifies: 1) the airport runway capacity and 2) the aircraft runway distribution (based on the aircraft weight class).

EDMS allows users to identify one (1) taxi path for each gate-runway pair (departures) and runway-exit-gate (arrivals). Therefore, each departure gets assigned a unique taxi path when the appropriate gate-runway pair is identified. Also, each arrival operation gets assigned a unique taxi path when the appropriate runway-exit-gate pair is identified. EDMS then models the movements of individual aircraft along the taxi paths.

EDMS requires the user to identify:

- All gates (as polygons)
- All taxi ways (each as a sequence of straight lines)
- All runways
- All taxi paths

For the dispersion modeling, it is important to allocate emissions along the taxi paths spatially and temporally. Thus, it is necessary to model the aircraft movements in detail. Moreover, because EDMS uses AERMOD for dispersion modeling which is not designed to model elevated mobile sources, a taxiway network (a set of gates, taxiways, and runways) needs to be split into a set of emission (area) sources. Emissions from a given arrival/departure operation are distributed within an individual source proportional to the amount of time spent in that source, which is a method for aggregation of aircraft operations.

For atmospheric dispersion modeling, both the spatial and temporal characteristics of emissions need to be identified. Therefore, the user supplied total taxi times cannot be used, and the full pathway from the terminal to the runway needs to be specified. In order to do this, the user must define the gates, taxiways, taxi paths, and runways (including configurations). A gate represents the location where an aircraft is parked at the terminal and also serves as the emissions source location for various ground service equipment (GSE) and auxiliary power units (APU). Because of all of these emissions, gate locations are generally specified as level polygonal areas (several contiguous XYZ values) although a single point can also be specified (in which case, a volume source is internally created by EDMS). A taxiway is defined as one or more segments with XYZ points at each end that define part or all of a taxi path that connects a gate to a runway end. Typically, several taxiways are specified to allow different combinations to be used in creating taxi paths. Hence, a taxi path is defined by one gate, one runway end and one or more taxiways. Taxi paths are also differentiated between outbound (gate to runway) and inbound (runway to gate) usage. Runways are specified by providing the XYZ coordinates of each end. Runway configurations allow the user to specify weather conditions (e.g., wind direction) and times under which the runway assignments are made using distributions based on aircraft size categories (e.g., small, large, etc.).

[1] EDMS 5.x[D.1] defines a taxi path as an ordered list of taxiways which connects a gate to a runway (outbound) or a runway exit to a gate (inbound)

D.8. References

D.1. FAA, Emissions and Dispersion Modeling System (EDMS) User's Manual, 2008.

D.2. FAA, Emissions and Dispersion Modeling System (EDMS) Technical Manual, 2008.

D.3. ICAO, International Standards and Recommended Practice, Environmental Protection, Annex 16, Volume II – Aircraft Engine Emissions, 1993.

D.4. Thrasher, T., Nguyen, A., Hall, C., Fleming, G., Roof, C., Balasubramanian, S., Grandi, F., Usdrowski, S., Dinges, E., Burleson, C., Maurice, L., Iovinelli, R., AEDT Global NOx Demonstration, 7th USA/Europe ATM R&D Seminar, Barcelona, Spain, 2007.

D.5. Ohsfeldt, M., Thrasher, T., Waitz, I., Ratliff, G., Sequeira, C., Thompson, T., Graham, M., Cointin, R., Gillette, W., Gupta, M., Quantifying the Relationship between Air Traffic Management Inefficiency, Fuel Burn and Air Pollutant Emissions, 7th USA/Europe ATM R&D Seminar, Barcelona, Spain, 2007.

D.6. Hall, C., Thrasher, T., Draper, J., A Validation of Aircraft Times in Mode in the Emissions and Dispersion Modeling System (EDMS) Version 4.2, Air and Waste Management Association 98th Annual Conference and Exhibition, June 2005.

D.7. Hall, C., Mondoloni, S., Thrasher, T., Estimating the Impact of Reduced Thrust Takeoff on Annual NOx Emissions at Airports, Air and Waste Management Association 96th Annual Conference and Exhibition, June 2003.

D.8. Cimorelli, A.J., Perry, S.G., Venkatram, A., Weil, J.C., Paine, R.J., Wilson, R.B., Lee, R.F., Peters, W.D., Brode R.W., Paumier, J.O., AERMOD: Description of Model Formulation. Prepared for Office of Air Quality Planning and Standards Emissions Monitoring and Analysis Division Research Triangle Park, North Carolina 2004. (EPA-454/R-03-004)

D.9. Cimorelli, A.J., Perry, S.G., Venkatram, A., Weil, J.C., Paine, R.J., Wilson, R.B., Lee, R.F., Peters, W.D., Brode R.W., AERMOD: A dispersion model for industrial source applications. Part I: General model formulation and boundary layer characterization, Journal of applied meteorology, 2005, 44, (5), 682-693.

D.10. Perry, S.G., Cimorelli, A.J., Paine, R.J, Brode R.W., Weil, J.C., Venkatram, A., Wilson, R.B., Lee, R.F., Peters, W.D., AERMOD: A dispersion model for industrial source applications. Part II: Model Performance against 17 Field Study Databases, Journal of applied meteorology, 2005, 44, (5), 694-708.

D.11. Hanna S. R., Egan, B. A., Purdum, J., Wagler, J., Evaluation of the ADMS, AERMOD, and ISC3 dispersion models with the OPTEX, Duke Forest, Kincaid, Indianapolis and Lovett field datasets, International Journal of Environment and Pollution, 2001, 16, 301-314.

D.12. SAE Committee A-21, Aircraft Noise, "Procedure for the Calculation of Aircraft Noise in the Vicinity of Airports," SAE Aerospace Information Report SAE AIR 1845, Society of Automotive Engineers, 1986.

D.13. Lucic, P., Hall, C., Thrasher, T., Iovinelli, R., Holsclaw, C., Peters, W., Dispersion Modeling for Aircraft: A Comparison of Area versus Volume Sources, Air and Waste Management Association 99th Annual Conference and Exhibition, June 2006.

D.14. CSSI, JPDO-NextGen-TDM23: Investigation of Aviation Emissions, Air Quality Impacts, Draft Report, 2008.

D.15. FAA, SAGE System for accessing Aviation's Global Emissions, Version 1.5, Technical Manual, 2005.

D.16. Long, D., Lee, D., Johnson, J., Gaier, E., and Kostiuk, P., Modeling Air Traffic Management Technologies With a Queuing Network Model of the National Airspace System, NASA/CR-1999-208988, Logistics Management Institute, McLean, Virginia, 1999.

D.17. Stouffer, V., WWLMINET User Guide, Logistics Management Institute, McLean, Virginia, 2002.

Appendix E. Algorithms Employed in the Processing of the European FDR Data

A query-based analysis was developed by Wyle and executed by Volpe on a dataset containing detailed flight data recorder data from 2359 commercial flight operations (aircraft startup to shut down) from a major European Airline. The aircraft types represented in this database are listed in Table E-1.

Table E-1. European Airline Fleet Summary

Aircraft	Engines	Engine UID
A319-112	CFM56-5B6/2P	3CM022
A320-214	CFM56-5B4/2P	3CM021
A321-111	CFM56-5B1/2P	3CM020
A330-223 (old; ver 9S)	P&W 4168A	4PW067
A330-243 (old version)	RR Trent 772B-60/16	2RR023
A340-313	CFM56-5C4	2CM015
757-200 RR (757-3)	RR RB211-535E4	3RR028
A330-202	GE CF6-80E1A4	4GE081
A330-243	RR Trent 772B-60/16	3RR030
767-300 GE (767-3A)	GE CF6-80C2B7F	2GE055
777-3FXER GE (D01)	GE90-115B1	7GE099
A340-541	RR Trent 553	
ARJ100 (DAR 512)	LF507-1F	1TL004
ARJ85 (DAR 512)	LF507-1F	1TL004

Analysis differentiated between taxi operations for departing and arriving aircraft. Query results include assessment of the parameters listed below for each aircraft and operation type.

- Engine usage when moving and stationary
- Average and standard deviation of thrust while moving and stationary
- Breakaway Thrust for operations where it could be successfully identified
- Average and standard deviation of groundspeed while moving
- Average and standard deviation of lateral and longitudinal acceleration
- Assessment of the frequency of rolling takeoffs versus non-rolling takeoffs
- Amount of time spent idling / running up before takeoff movement begins

E.1. Flight Segment Parsing

To develop the summary data, the flight record was split into operational segments for the entire flight from gate to gate: departure, enroute flight and arrival. This included segments such as parked at the gate, pushback, taxi to the runway (including any holding queues encountered), and departure operation on the runway. On ground FDR data is spaced 5 seconds apart. The departure segment was further examined and aircraft with "rolling departures" were separated from those who "held" at the end of the runway before departing. The next segment was the runway takeoff, followed by the enroute flight segment. At the destination region, the records were split up to include approach up to the touchdown point along with the runway deceleration period. A segment where the aircraft had left the runway and was on a taxiway (regardless of speed) was included arrival taxi segment. The aircraft at the gate was considered part of the taxi segment up until the time when the fuel flow was reported as zero for all engines. Operations at the gate while engines were spooling down (and thrust

/ operating state parameters were reported as non-zero) were not included in the taxi segment. Subsequent examination of the average operational parameters for stationary portions (or holds) included this stationary gate portion of the taxi operation.

The departure taxi segment and the arrival taxi segments were assessed separately. An assessment of the use of engines expressed as a function of total taxi time was performed in order to determine whether single or multiple engine operations could be a factor in taxi analysis. Stationary segments were defined as those with reported ground speed less than 1 knot and moving segments those with speeds at or above 1 knot. During these stationary and moving segments average ground speed and thrust parameters were obtained from the FDR data. One would expect that taxi speeds immediately after leaving the runway on arrivals to be greater than those for departing aircraft as is indicated in the average and standard deviation of ground speed (Table 2-1). Table 2-2 itemizes the average and standard deviation of ground speed for both moving and stationary segments during departure and arrival taxi operations. The engine operating state parameters as reported in the FDR data is presented in Table 2-3. The following description of the meaning and units of the engine operating state parameters are as follows:

- N1avg: N1, average (all engines, percent of maximum) at start of event
- %Thrust: percent of maximum thrust at start of event
- EMS Thrust: EMS thrust per engine, averaged over all engines at start of event, lbs
- EMS enhanced: EMS enhanced thrust per engine, averaged over all engines at start of event, lbs

To be considered moving, the aircraft FDR recorded groundspeed exceeded 1 knot. Groundspeeds of 1 knot or lower indicated a stationary aircraft. This 1 knot threshold was selected based on a visual assessment of raw data while considering the acceleration, thrust, latitude and longitude along with other parameters in conjunction. Initial attempts to solely use groundspeed = 0 to identify a stationary aircraft, as we had in the past, was an inaccurate way to identify the state.

The first attempt at obtaining average engine thrust settings yielded suspiciously low values. Upon closer inspection it was determined that those computations included many records where the aircraft was parked at the gate and the engines were slowly winding down after being shut down. This necessitated the creation of a filter to ignore any data points where the total fuel flow was zero.

Due to licensing restrictions the full FDR dataset could not be accessed directly by Wyle engineers. While ultimately successful, development of the data queries and macro algorithms was problematic due to the inability for our engineers to actually “see” the raw FDR data other than a few sample flight operations. As is common when working with real data (as opposed to simulated data) a variety of unexpected situations were encountered which necessitated modification of the algorithms. Examples of this included data drop-outs, uncalibrated accelerometer sensors, inconsistent file formatting in occasional FDR files, bad data fields, extended taxi periods with groundspeed values like 0.125 and 0.0625 knots, (which effectively should be zero) and records with negative Percent Thrust values, and negative EMS Thrust values.

E.2. Description of the Taxi Hold Processor

The ground taxi processor is a macro written in Visual Basic contained within an Excel workbook. The input parameters are specified as lines on the "Input" sheet of this workbook. The input parameters specify the input file path and name, output file path and name, arrival/departure indicator ("A" or "D"), groundspeed cutoff threshold (specifies what groundspeed qualifies as a moving aircraft; groundspeed is often 0.25 or 0.5 knots), and the acceleration threshold (used to isolate actual acceleration/deceleration from what is apparently accelerometer background noise).

The macro processes each input file, one at a time. It first opens the input file, forcing it to a specific .CSV format, saves it in that format, and then reads the entire input file into memory, storing it in an array. The departure segment (called "Segment 0", from the beginning of the flight until the aircraft is accelerating on the runway for takeoff) and the arrival segment (called "Segment 9", from the time the aircraft leaves the runway after touchdown until it is parked at the gate) were previously parsed into separate files.

For the initial processing of a file, the program must determine the nature of the data at the end of the file to process it accordingly.

If the specified input file is an arrival, processing starts at the last line of data and moves toward the beginning, ignoring all records until reaching the first record that has a Total Fuel Flow that is non-zero. This process was incorporated to properly process files in which after parking at the gate, the data recorder continued to record data after the fuel flow moved to zero, while the engines were winding down to zero rpm or after they had reached zero rpm.

If the specified input file is a departure, processing starts from the last line of data, which represents the last data before the aircraft has begun the takeoff roll. If the last or second-to-last record has a groundspeed lower than Groundspeed Threshold parameter, the flight is considered to be a non-rolling departure, and the time of the last record is considered to be the end point of a hold.

A "hold" is defined as any period in which the groundspeed is less than the specified Groundspeed Threshold. A threshold of 1 knot was used for this analysis.

If the flight is a non-rolling departure, program execution steps backward through the data until a record is found with a groundspeed above the Groundspeed Threshold. At this point the program calculates the hold time and reports all output parameters for this hold (except acceleration-related ones) to the output file.

Execution then works backwards, continuing through the rest of the input file to the beginning, finding ending points and starting points for all other holds, calculating all output parameters except acceleration-related ones.

Additionally, at the end of every hold other than the on-runway hold which occurs in a non-rolling takeoff, an acceleration period is determined and output parameters are calculated. The acceleration period includes the subsequent records, following the end of the hold, which meet the acceleration criteria. To meet the acceleration criteria, the Longitudinal Acceleration + Acceleration Offset must be greater than the Acceleration Threshold specified in the input parameters on the spreadsheet's INPUT sheet. For processing, a value of -0.001 was used. The Acceleration Offset is a calculated parameter that was introduced into the process because there were signs of positive or negative bias in the longitudinal acceleration values of many flights. The Acceleration Offset for a given flight is calculated by taking the opposite of the arithmetic mean of the acceleration values that occur when the groundspeed is below a threshold that is specified as an input parameter on the spreadsheet's INPUT sheet. For processing, a value of 0.25 knots was used for the groundspeed threshold for acceleration offset calculation.

After the start point, end point, acceleration period and all associated output parameters have been calculated for a given hold, all output parameters are written as a line in the output file. After the entire input file has been processed, the program continues on to the next line of input found on the "Input" worksheet until all lines have been processed.

E.3. Acceleration after a Hold Event

Attempts to determine aircraft acceleration after a hold event (longitudinal acceleration) also highlighted difficulties with solely using SQL queries for dataset interrogation. Acceleration data results included bias in the FDR data, clear indications of stationary aircraft (evidenced by zero ground speed) yet with non-zero accelerations in both the lateral and longitudinal directions, as well as some instances where the acceleration data just did not make sense.

The acceleration bias can be seen in a few sample flight tracks in the acceleration levels in G loads for a B767 longitudinal acceleration (Figure E-1) and in the lateral acceleration for the A319 (Figure E-2). This bias explains some of the erroneous query results from the first round of analysis – namely average speeds obtained during intervals with no acceleration were in essence derived from only a few data points rather than as intended, being a representative sample of the operational state. Based on examination of numerous flight tracks a threshold of +/- 0.02G was implemented in the analysis for differentiating between acceleration and steady motion. Prior queries with a 0.G threshold indicated that virtually no data points were present in the entire dataset.

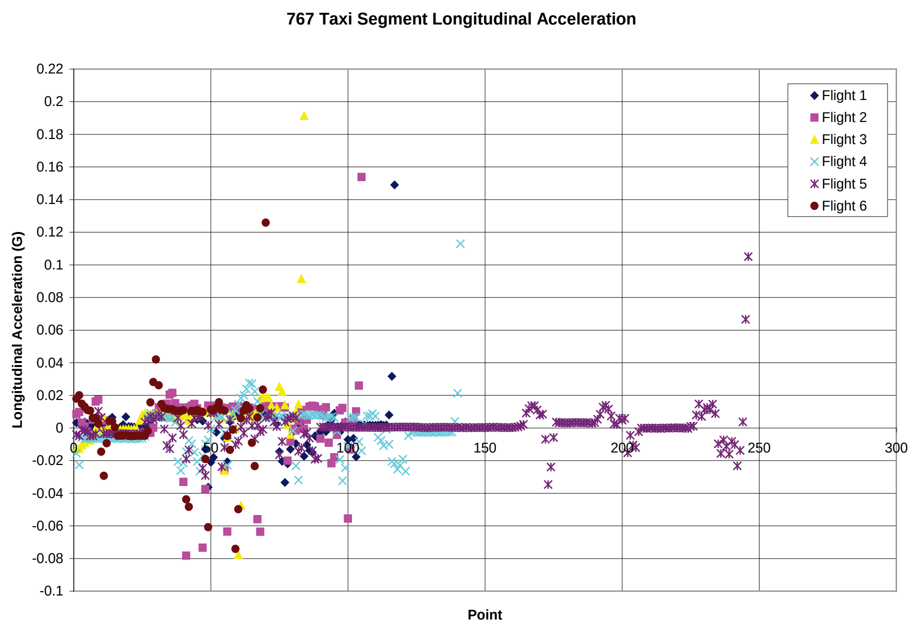

Figure E-1: B767 Longitudinal Acceleration (g)

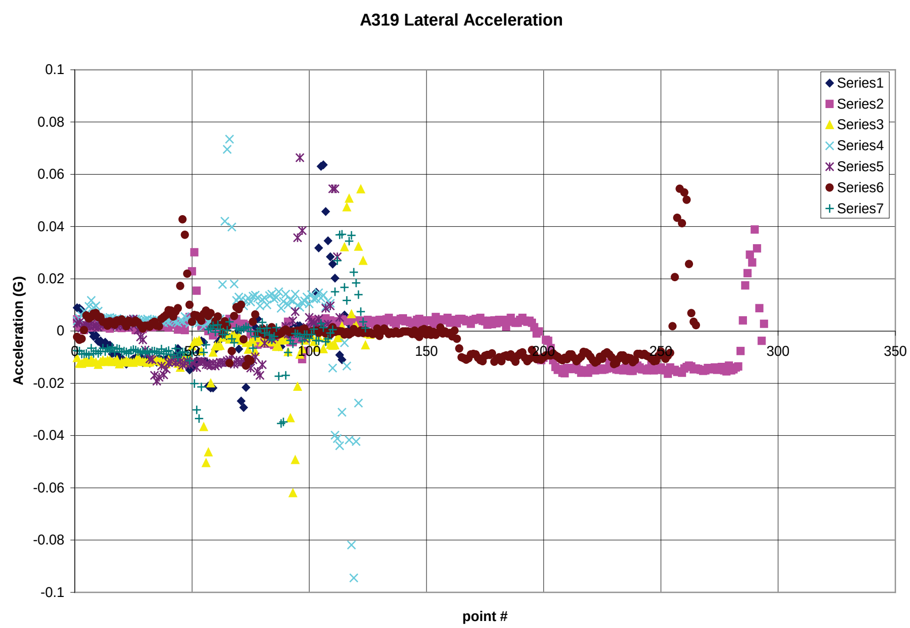

Figure E-2: A319 Longitudinal Acceleration (g)

E.4. Thrust during Acceleration after a Hold Event

A hold was defined as any period during which the aircraft speed (as reported by the ground speed indicator in the FDR data) was less than 1 knot. The cause of the hold (wait to cross a runway, queue hold due to traffic, hold after pushback etc…) could not be determined or catalogued. The Maximum Thrust was determined by searching through the time records during the stationary period immediately preceding the acceleration event, and extracting the maximum value of the indicated Thrust parameter. It is presumed that these particular acceleration events are due to the application of breakaway thrust and hence a significantly higher, yet shorter duration acceleration region than those other events with very low values of acceleration (less than .05 g) which tend to linger for long times. The resolution of the source FDR files used in this analysis all contained a 5 second time spacing hence the discrete time intervals in the figures in this section.

The following description of the meaning and units of the engine operating state parameters are as follows:

- N1avg: N1, average (all engines, percent of maximum) at start of event
- %Thrust: percent of maximum thrust at start of event
- EMS Thrust: EMS thrust per engine, averaged over all engines at start of event, lbs
- EMS enhanced: EMS enhanced thrust per engine, averaged over all engines at start of event, lbs

The following series of Figures E-3 through Figure E-13 display the Maximum % Thrust extracted from the FDR data from the time period immediately preceding and including those acceleration events which follow a hold.

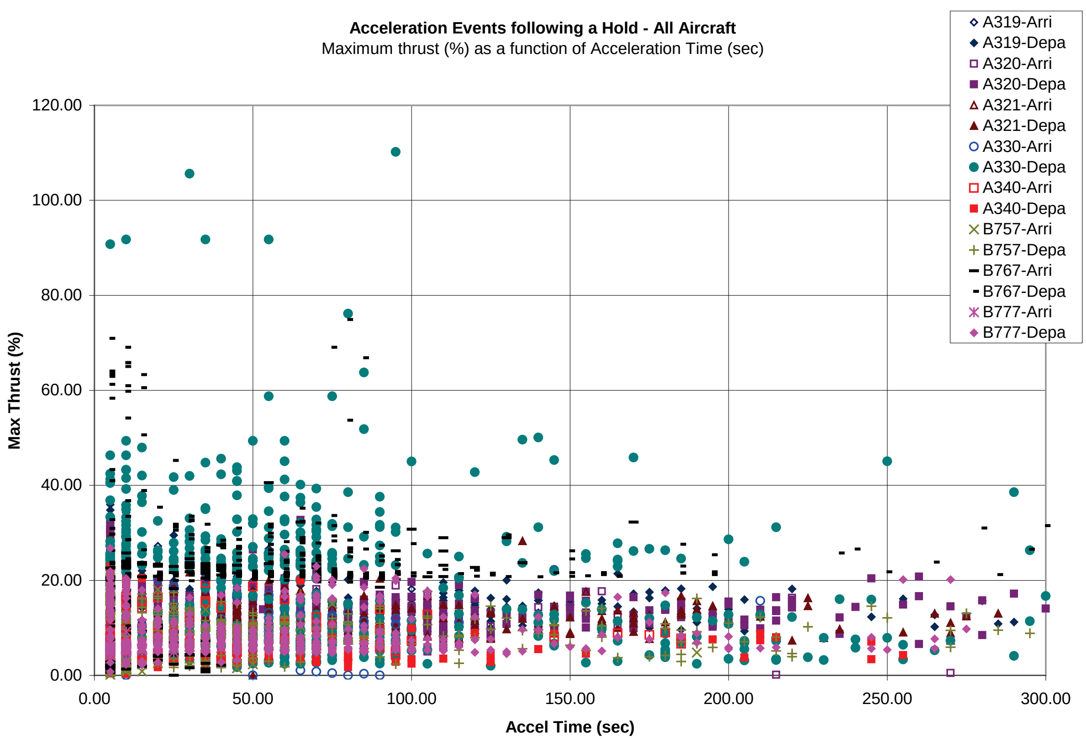

Figure E-3: Acceleration Event (Maximum % Thrust) following a Hold, All Aircraft

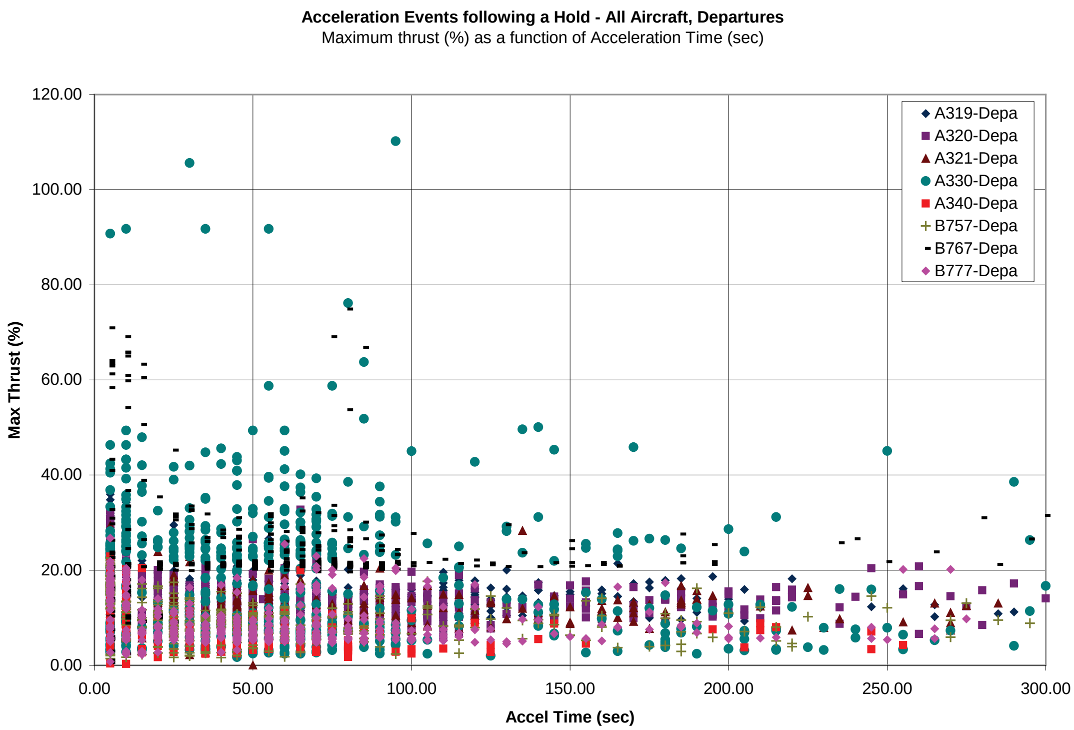

Figure E-4: Acceleration Event (Maximum % Thrust) following a Hold, Departures

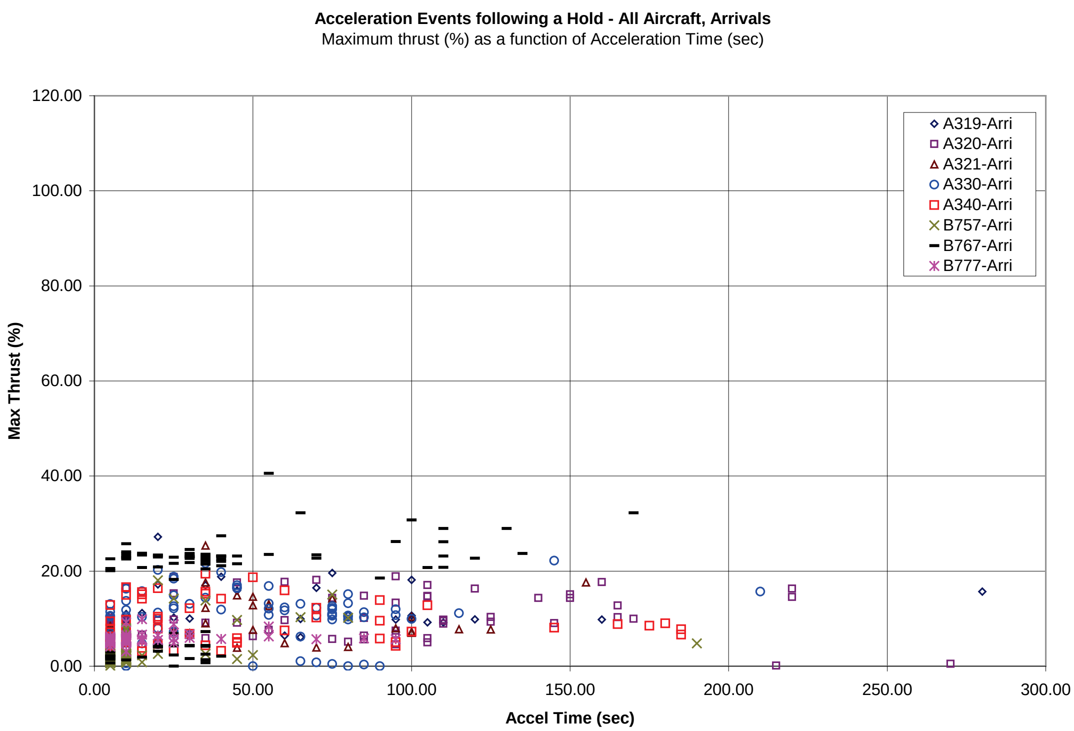

Figure E-5: Acceleration Event (Maximum % Thrust) following a Hold, Arrivals

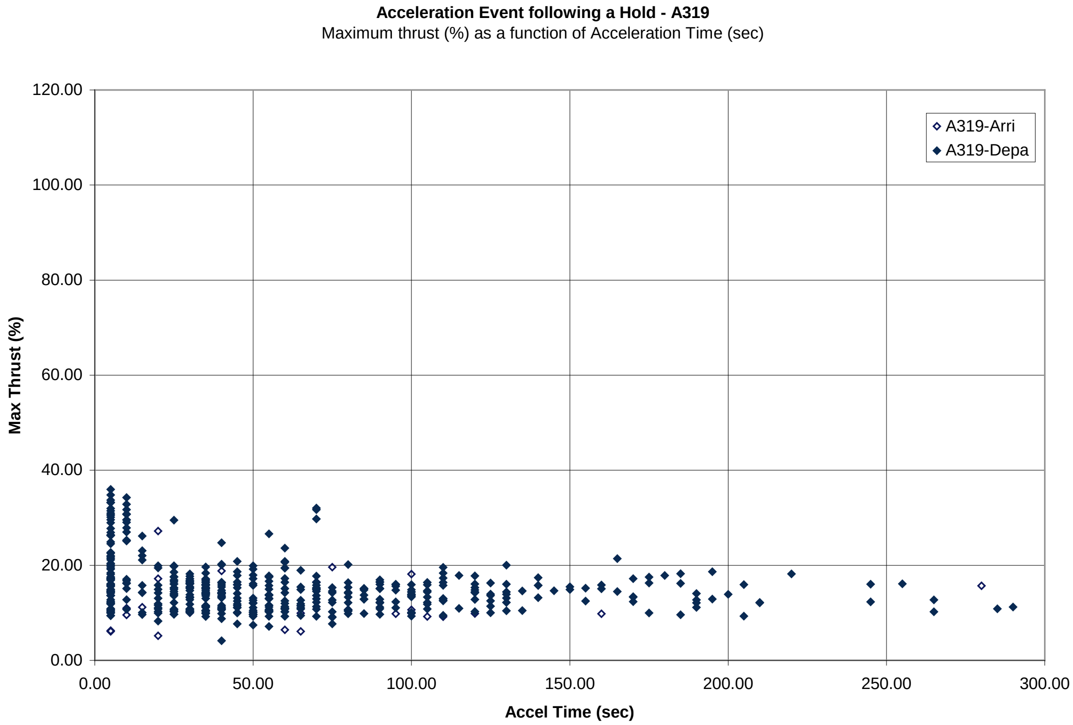

Figure E-6: Acceleration Event (Maximum % Thrust) following a Hold, A319

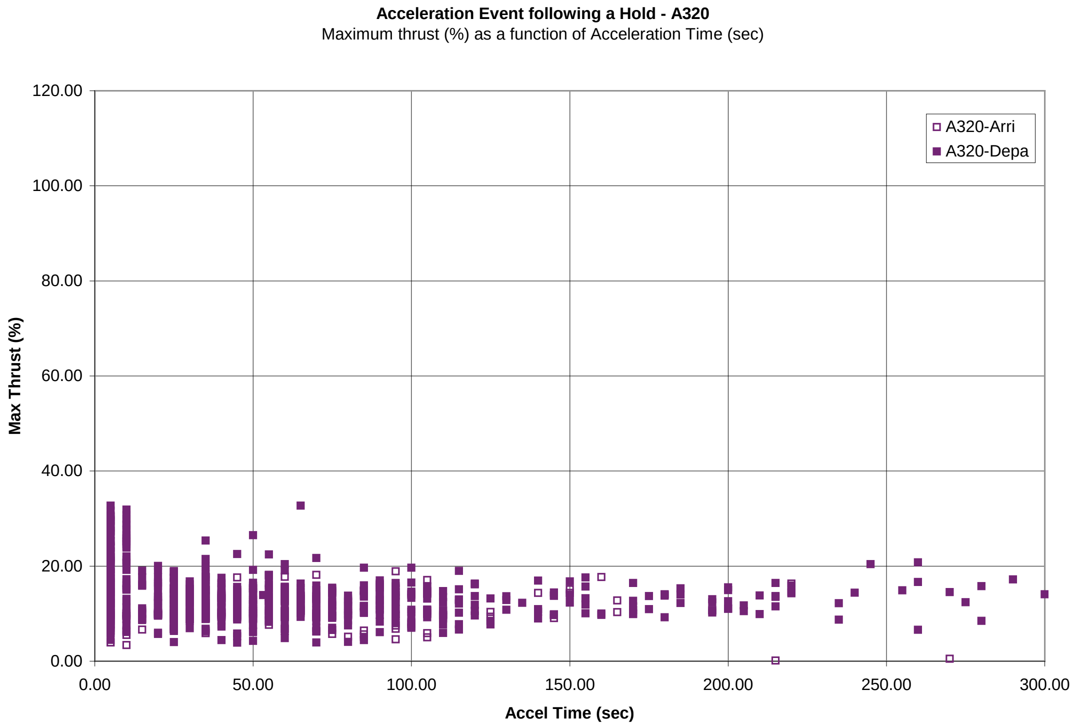

Figure E-7: Acceleration Event (Maximum % Thrust) following a Hold, A320

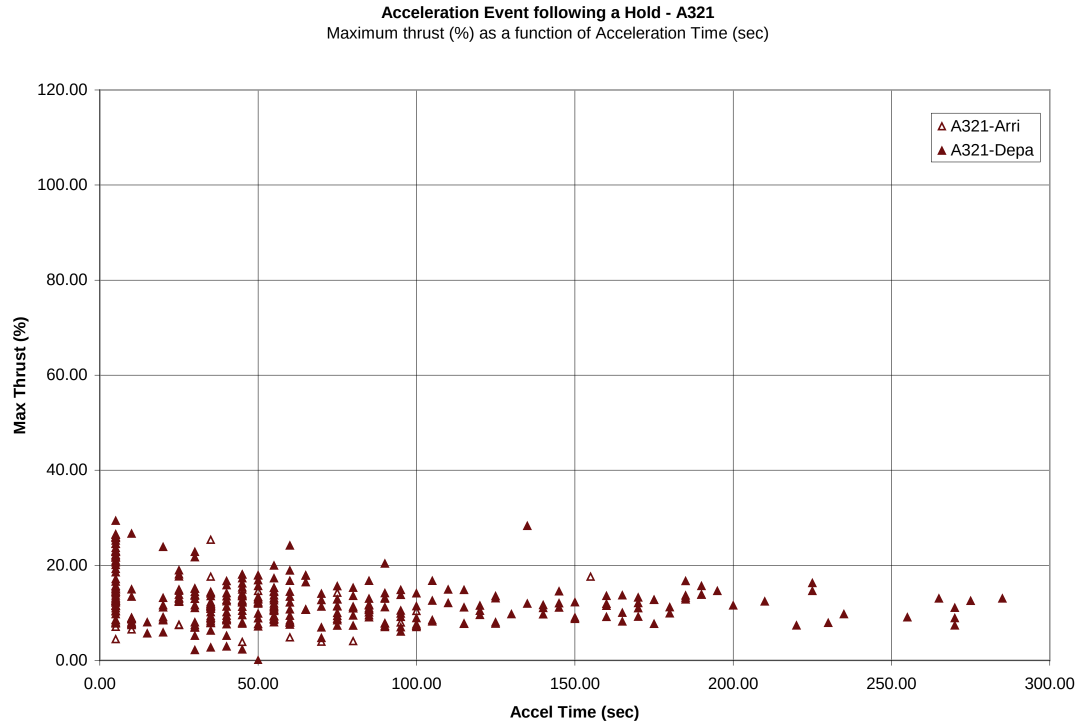

Figure E-8: Acceleration Event (Maximum % Thrust) following a Hold, A321

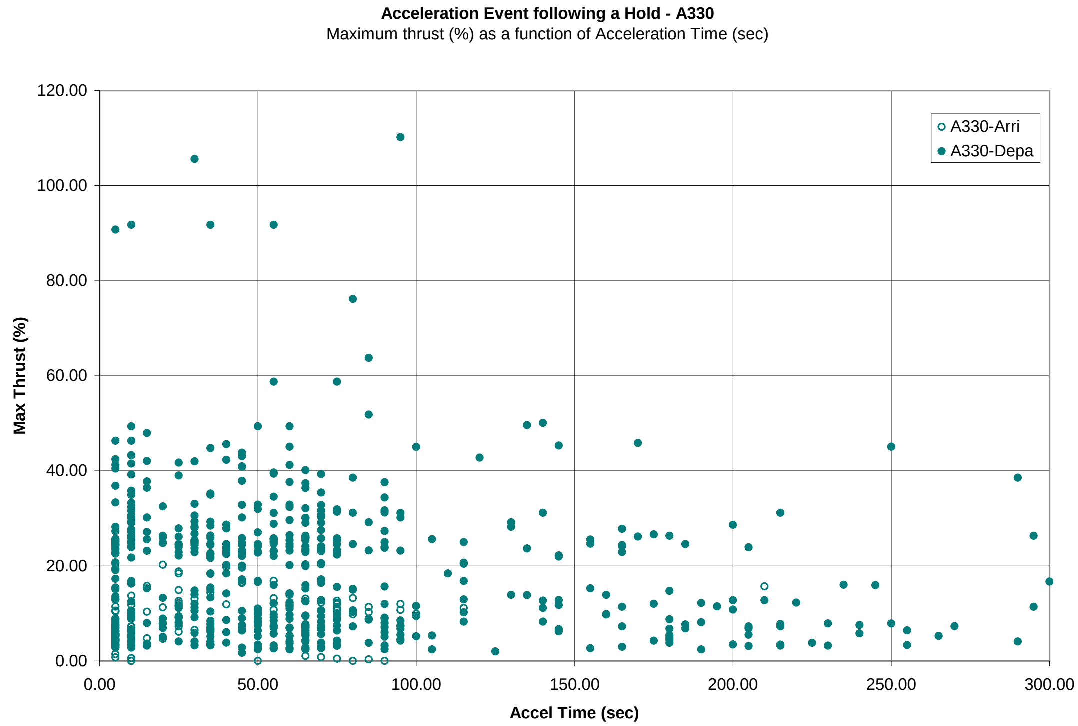

Figure E-9: Acceleration Event (Maximum % Thrust) following a Hold, A330

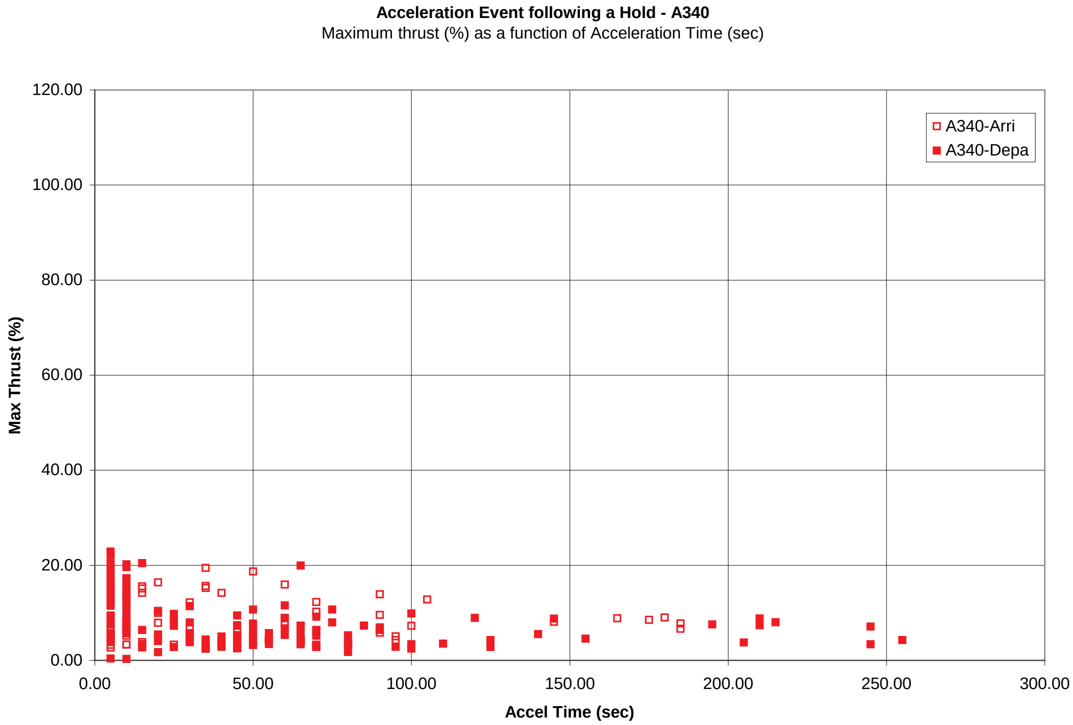

Figure E-10: Acceleration Event (Maximum % Thrust) following a Hold, A340

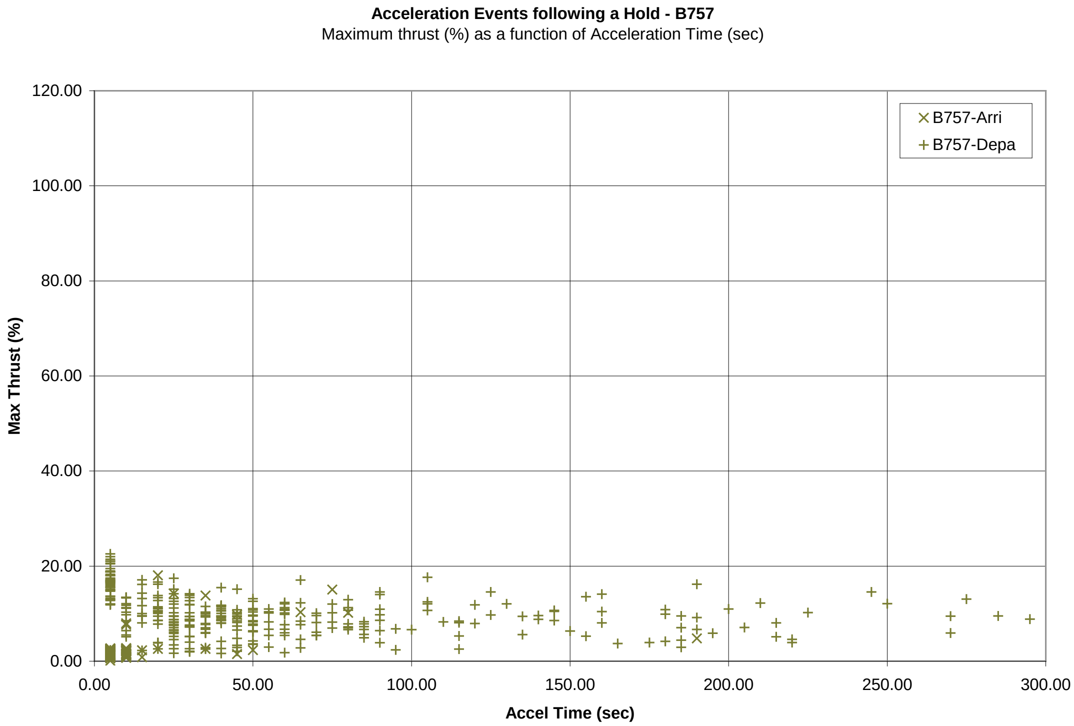

Figure E-11: Acceleration Event (Maximum % Thrust) following a Hold, B757

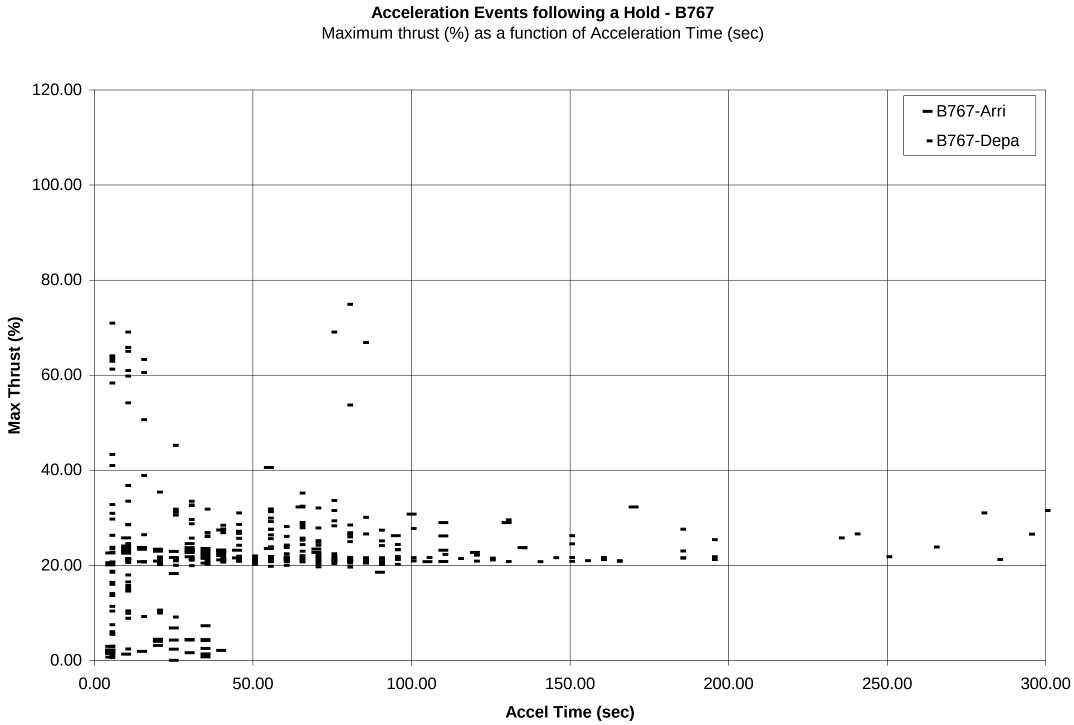

Figure E-12: Acceleration Event (Maximum % Thrust) following a Hold, B767

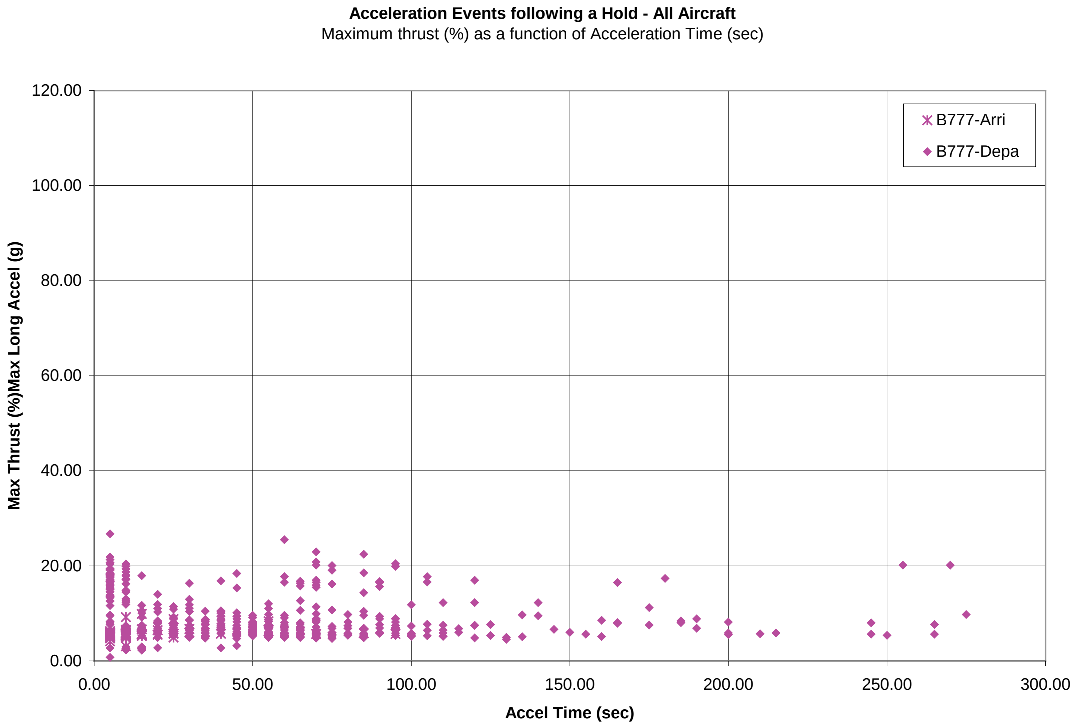

Figure E-13: Acceleration Event (Maximum % Thrust) following a Hold, B777