Rotorcraft Performance Model (RPM) for use in AEDT

November 2015

DOT- VNTSC-FAA-16-03

Prepared for:

Office of Environment and Energy
Federal Aviation Administration
U.S. Department of Transportation

U.S. Department of Transportation
John A. Volpe National Transportation Systems Center

Volpe

Notice

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE November 2015	3. REPORT TYPE AND DATES COVERED Final Report

4. TITLE AND SUBTITLE Rotorcraft Performance Model (RPM) for use in AEDT	5a. FUNDING NUMBERS FA5JC6/PJ1C1
6. AUTHOR(S) David A. Senzig, Eric R. Boeker	5b. CONTRACT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Department of Transportation John A Volpe National Transportation Systems Center Organizational Performance Division 55 Broadway Cambridge, MA 02142-1093	8. PERFORMING ORGANIZATION REPORT NUMBER DOT- VNTSC-FAA-16-03
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) US Department of Transportation Federal Aviation Administration Office of Environment and Energy 800 Independence Ave, SW Washington, DC 20591	10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT This document is available on the DOT's National Transportation Library website at: http://ntlsearch.bts.gov/	12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This report documents a rotorcraft performance model for use in the FAA's Aviation Environmental Design Tool. The new rotorcraft performance model is physics-based. This new model replaces the existing helicopter trajectory modeling methods in the Aviation Environmental Design Tool which were mode-based. The new methods enable fuel consumption and emissions modeling based on the performance data derived from information found in the helicopters' flight manuals.

14. SUBJECT TERMS Helicopter, Helicopter Performance, Aviation Environmental Design Tool, AEDT, FAA	15. NUMBER OF PAGES 68
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
oz	ounces	28.35	grams	g
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
mL	milliliters	0.034	fluid ounces	fl oz
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
g	grams	0.035	ounces	oz
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	Kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

Acknowledgments

This work was funded by the FAA's Office of Environment and Energy. We thank Sandy Liu and Becky Cointin for supporting and directing this work. We also thank Juliet Page of the Volpe Center for her insight into helicopter noise sources and providing consulting on the integration of helicopter performance and acoustics, and Seamus McGovern, also of the Volpe Center, for his helping with our understanding of the pilot's perspective of helicopter operations. Eric Greenwood and Michael Watts of NASA-Langley kindly provided helicopter flight test data. We thank Ken Brentner for his advice on improving the modeling process. We also thank Wayne Johnson for providing access to the NASA Design and Analysis of Rotorcraft software tool.

Contents

List of Figures

List of Tables

List of Acronyms

Abbreviation	Term
ACRP	Airport Cooperative Research Program
ADS-B	Automatic Dependent Surveillance - Broadcast
AEDT	Aviation Environmental Design Tool
AEE	FAA Office of Environment and Energy
AFE	Above Field Elevation
BADA	Base of Aircraft Data
BVI	Blade Vortex Interaction
CAS	Calibrated airspeed
DH	Delta Height
DOT	Department of Transportation
DT	Delta Temperature
EDMS	Emission and Dispersion Modeling System
FAA	Federal Aviation Administration
FDR	Flight Data Recorder
HIO	Helicopter, fuel injected, horizontally opposed
HNM	Heliport Noise Model
HP	Horsepower
ICAO	International Civil Aviation Organization
IGE	In Ground Effect
INM	Integrated Noise Model
IRP	Intermediate Rated Power
ISA	International Standard Atmosphere
KCAS	Knots calibrated airspeed
KTAS	Knots true airspeed
MAP	Manifold Air Pressure
MCP	Maximum Continuous Power
MSL	Mean Sea Level
MTOW	Maximum Takeoff Weight
NASA	National Aeronautics and Space Administration
NM	Nautical Miles
NPD	Noise-Power-Distance
OEM	Original Equipment Manufacturer
OEW	Operating Empty Weight
OGE	Out of Ground Effect
ROC/D	Rate of Climb/Descent
RPM	Revolutions per Minutes
RPM	Rotorcraft Performance Model
SAE	Society of Automotive Engineers
TAS	True airspeed
TEM	Total Energy Model
TIM	Time in Mode

Executive Summary

This report documents a physics-based rotorcraft performance model (RPM). This model is primarily intended for use in the FAA's Aviation Environmental Design Tool (AEDT), although the methods and data are not unique to any model. The primary purpose of this model is to allow more accurate calculation of noise, fuel consumption, and emissions generated by helicopter operations than were possible using the prior mode-based modeling found in the FAA's legacy environmental tools. The methods and processes discussed in this report are intended for use with conventional helicopters (single main rotor and a single anti-torque tail rotor).

The methods used in this proposed model are based on performance data available through the helicopter flight manuals. No proprietary data are used. The level of detail is sufficient to determine the power required for normal helicopter flight operations in the terminal area and en-route. The model is not detailed enough to determine component level noise generation, so the model may be more useful for determining helicopter noise during take-off and cruise operations than for arrival operations, since arrival noise for helicopters is often dominated by blade vortex effects, the modeling of which requires more detailed knowledge of the helicopter system than this model contains. The authors expect that helicopter approach noise modeling will continue to depend on measurements that are directly used in the AEDT.

The RPM was tested against flight test data collected by Volpe personnel in support of prior noise measurements and also against in-service measurements from the Flight Data Recorder (FDR) systems of two helicopter types. The comparison against the noise measurement flight test data showed a slight trend for over prediction of power in cruise flight (differences ranged from -2% to +6%). The comparison against the in-service FDR data showed an over-prediction of about 3% for one type and about 8% for the other. Possible reasons for these over-predictions are discussed in the body of the report.

Next steps to further improve the modeling of helicopter performance include modifying the turboshaft engine model and quantifying the required power during unsteady flight. The turboshaft engine model is currently a modification of the legacy jet/turboprop engine model without the velocity component. The unsteady (non-cruise) power required currently assumes that the change in the potential and kinetic energy states of the aircraft can be met directly by a change in the power state of the engine.

1. Introduction

The FAA's Office of Environment and Energy (AEE) began supporting the environmental analyses of helicopter operations in 1994 with the public release of the Heliport Noise Model (HMN) (Fleming, 1994). The HNM data and methods were incorporated into the FAA's Integrated Noise Model (INM) in version 7.0 (FAA, 2007). These data and methods are also incorporated in the FAA's latest environmental model, the Aviation Environmental Design Tool (AEDT) (Koopmann, J., et al., 2015), which was released to the public in May, 2015.

AEDT differs for the earlier FAA environmental models in that AEDT calculates helicopter fuel consumption and emissions as well as noise. AEDT 2b, the current version as of this writing, uses a Time-In-Mode (TIM) method for helicopter fuel consumption which has been shown for fixed wing aircraft to have lower accuracy than performance-based methods (Patterson, 2009). The need to improve helicopter fuel consumption and emission modeling led AEE to support research into developing a physics-based helicopter performance model. The results of this research are presented in this report, which documents a proposed Rotorcraft Performance Model (RPM), which AEE could potentially incorporate into AEDT.

Note that this document often refers to the flight manuals for the various helicopters, but no graphics from these manuals are reproduced in this document due to potential proprietary issues.

2. Background

This section briefly discusses some of the prior methods of modeling helicopter movements in the FAA's aviation environmental models.

2.1 Heliport Noise Model

As briefly mentioned in section 1, the Heliport Noise Model was the FAA's first environmental impact model for helicopters. The HNM used a profile point method of modeling helicopter operations; this means the helicopters' trajectory was modeled as a series of segments comprised of distances, altitudes, and speeds along a defined ground track. The noise for each segment was determined by the mode associated with each segment; this mode was used as the look-up parameter for 'power' in the Noise-Power-Distance (NPD) data.

The HNM had two fundamental differences from the then-current version of the INM. First, the HNM used NPD data for the right, center and left sides of the helicopter, unlike the INM's single axisymmetric NPD assumption. Second, the HNM allowed the user to model taxi (ground) operations.

2.2 Integrated Noise Model

The methods and data of the HNM were incorporated in INM version 7.0. From a functional standpoint, the fixed-wing INM and rotary-wing HNM methods were so different that two separate code streams were used in INM; one for fixed-wing aircraft and the other for helicopters. The results of the two code streams were merged for the calculation of the resulting noise impacts (contours or receptor point analyses). Like the HNM, the INM only calculated noise impacts, not fuel consumption or emissions.

We note that the fixed-wing performance and noise methods in the INM are supported by international standards (A-21 Committee, 1986), but the helicopter methods are not.

2.3 Emission and Dispersion Modeling System

The Emission and Dispersion Modeling System (EDMS) was the FAA's legacy method of determining fuel consumption and emissions from aircraft operations. EDMS contained a subset of the original HNM helicopter database – those helicopters which use engines in the ICAO emissions databank were included in EDMS. EDMS used a simple straight-in/straight-out method for modeling airport operations for both fixed-wing and helicopter operations.

2.4 Aviation Environmental Design Tool

AEDT uses the INM helicopter noise methods discussed in section 2.2. Because the AEDT helicopter performance is mode-based, AEDT has no available physical data upon which to base the fuel consumption – like the noise, the fuel consumption is mode-based. Without these physical data, the AEDT developers chose to set the fuel consumption to the ICAO climb-out power setting for all modes of operation. The practical results is that the fuel consumption (and hence the emissions also) are set to the 85% power setting from the ICAO emission databank for the particular engine used on the helicopter.

2.4.1 Concerns with AEDT

AEDT 2b can't capture fuel consumption and emissions as a function of the helicopter operations (e.g. flight trajectories, cruise altitudes, weights) with the fixed power setting method currently in use. The fixed power setting method also means that fuel consumption is not responsive to changes in the helicopters' environment (e.g. heliport elevation and temperature, as well as the actual altitude and temperature at which the helicopter is operating).

The current work attempts to provide a method to remove these concerns with AEDT's helicopter performance modeling and provide a fuel consumption model which correctly responses to changes in the helicopters' operations and environment.

2.4.2 Models considered for inclusion in AEDT

A number of options are available for modeling helicopter operations in AEDT. Some of these methods are discussed below.

2.4.2.1 The do-nothing option

The 'do-nothing' option would continue to use the mode-based methods as they are currently implemented in AEDT 2b. This is the zero cost option, but would also continue to use a method which is inadequate for capturing the physical influences on actual operations and is not philosophically compatible with the fixed-wing operations in AEDT where AEE has expended significant effort and resources to improve all aspects of aviation environmental modeling.

2.4.2.2 Delft method option

In 2010, students from Delft University in the Netherland worked on developing a helicopter fuel consumption method which would work with the existing mode-based methods (Haagsma & van Veggel, 2011). The Delft results showed promise, but were limited in that the preferred model assumed *a priori* knowledge of the state (e.g. horsepower, weights) of the helicopter and there were no ties to the noise characteristics of the helicopter. The present work makes use of the Delft work primarily through following their lead on focusing on data available in the helicopter flight operations manuals, as discussed below.

2.4.2.3 Gulf of Mexico/ADS-B method option

In 2013, AEE tasked staff from the Volpe Center to examine the benefits to helicopter operators from the implementation of ADS-B in the Gulf of Mexico (Senzig & Cumper, 2013). The fuel consumption analysis in that study used an expansion of the Delft method, and also analyzed the use of a derivative of a U.S. Army fuel consumption prediction method.

As with the Delft report, the methods showed promise, but without actual fuel consumption data against which the methods could be compared, the actual validity of the proposed methods remained unknown.

2.4.2.4 AEE funds development of a new method

Based on the lack of satisfaction with the methods listed above, AEE tasked staff from the Volpe Center to take a ‘clean slate’ approach to the prediction of helicopter fuel consumption and emission with the intention of eventually including the resulting methods and data in AEDT. This report on the proposed Rotorcraft Performance Module (RPM) is the first result of this work.

2.5 Rotorcraft performance analyses

Engineers and designers have been concerned with the performance of rotary wing aircraft since the first vehicles of this type flew. The earliest rigorous treatment of the subject appears to be from the mid-1920s and dealt with autogyros (Glauert, 1926). The Second World War accelerated the development of all aircraft; the first practical helicopters were produced in this period and the analytical performance methods were refined (Bailey, 1941). The basic methods used in this report were developed in the early 1950s when turboshaft engines became the primary helicopter power source (Gessow, 1985). Similar treatments of helicopter performance methods can be found in more modern works (Johnson, 1994), (Stepniewski, 1984).

3. Requirements

Before beginning the research on the proposed method, AEE and Volpe staff developed a list of 'hard' and 'soft' requirement. Hard requirements are those which *must* be met. Soft requirements are those which *should* be met.

3.1 Hard requirements

The model must, at a minimum, meet these requirements:

- Model noise at the same level of fidelity as helicopters in AEDT
- Model fuel consumption and emissions at the same level of fidelity as fixed aircraft in AEDT (Senzig, Fleming, & Iovinelli, 2009)
- Allow users of AEDT to analyze trades between noise and fuel consumption/emissions
- Make use of existing AEDT operational procedures
- Work within the current AEDT structure (though new methods and databases are expected)

3.2 Soft requirements

The model should do this:

- Have the ability to improve the modeling of helicopter noise
- Have the ability to eventually move to component-level noise modeling
- Model not just helicopters, but all rotary-wing aircraft (e.g. tilt-rotors)
- Data for individual helicopters must not rely on proprietary data

Note that the first soft requirement means that the methods developed should mesh with the requirements of ACRP 02-44, "Helicopter Community Noise Prediction Methodology for INM/AEDT". This ARCP project is, as of the writing of this report, being developed to provide a road-map for up-dating and improving rotary-wing (not just helicopters) noise modeling. For completeness, we include below a paraphrased list of the 02-44 proposed improvement in priority order.

1. The model should compute the standard noise metrics
2. The model should calculate lateral source characteristics
3. The model should include one-third bands down to 10 Hz
4. The model should include the effects of approach path flight angle
5. The model should calculate the change in noise from maneuvering flight
6. The model should calculate the effects of tilt-rotor mode transitions
7. The model should include higher fidelity atmospheric and terrain modeling

Note that this list is exclusively focused on improving community noise modeling of helicopter operations. Items 1, 2, and 3 are independent of performance modeling methods. Items 4, 5, and 6 are fundamentally dependent on performance, though we note here that the methods documented in this report are concerned exclusively with conventional helicopter performance; the methods could be expanded to account for the helicopter phase of tilt-rotor operations but the authors currently have no data available to support development of a tilt-rotor performance model. Item 7 is 'up-stream' from the performance model; improving the atmospheric model will benefit both the performance and the acoustic models.

Also note that the final soft requirement for non-proprietary data is a practical one. The FAA and the Volpe Center do not depend on the support of the helicopter manufacturers to generate data for use in INM or AEDT. That is, because the FAA and the Volpe Center generate noise data for use in INM/AEDT without the support of the OEMs (with the exception of the Bell Helicopter data added in INM 7.0d) through flight test measurements, we also need to be able to generate the performance data for these helicopters without their explicit support. Note that this need to develop helicopter data independently of OEM support dates back to the collection of the data for the initial HNM model (Newman, Rickley, & Ford, 1981), (Newman J. S., Rickley, Bland, & Beattie, 1984), (Rickley, Jones, Keller, & Fleming, 1993).

4. Development of the Rotorcraft Performance Model

The criteria for determining the success of the RPM are:

1. The method must be better than the current methods
2. The methods must be accurate enough to successfully model trades of noise, fuel consumption and emissions
3. The method must be advanced enough so that the FAA's investment in this method will not be rendered obsolete in the foreseeable future.

Research into potential methods turned up a method developed by the U.S. Army in the early 1990s which seems to provide the accuracy required (Kiwan, 1994). We will refer to this model as 'the Army model'. Note that this Army model is not the same as those methods discussed in section 2.4.2 above. The method discussed in section 2.4.2 above only dealt with fuel consumption - not with determining the power requirements or the flight trajectory of the helicopter. The Army model relies on proprietary data, but with the loosening some of the requirements to eliminate reliance on proprietary data, the authors believe a model of this type is sufficiently accurate for environmental noise, fuel consumption and emission modeling purposes.

4.1 The U.S. Army model

The Army model is based on the use of non-dimensional thrust and power coefficients to model the performance of the helicopter. In the report, only the data and methods for the Sikorsky UH-60 Blackhawk are presented in detail. The Army model also contains data on the rotor system of the UH-60 which the RPM will not have available for helicopters in the AEDT database. With the availability of these rotor system data, the Army model could be used to calculate the power requirements of both the main and tail rotor systems. Note that if AEE changes the current soft requirement for component level modeling to a hard requirement, the current method can be upgraded to meet this, provided that the data for the rotor systems are available.
The Army model was developed so that it can use an existing helicopter as a baseline for estimating the performance of similar helicopters. That is, the method is not just intended to calculate the performance of known helicopters, but if a new or proposed helicopter does not have existing performance data, the changes from the baseline to the new helicopter can be used to predict the performance of the new helicopter. This is possible through the use of the non-dimensional performance parameters. We can make use of this for modeling helicopter performance for those helicopters which have an insufficient set of the necessary data.

4.2 Modifications to the U.S. Army model for the RPM

As mentioned above, the Army model contains proprietary rotor system data which we do not need in the RPM (unless we eventually move to incorporate component-level noise sources in AEDT). We do, however, make use of the ability to use existing helicopters as a baseline dataset for new helicopters. When we have insufficient data to model a helicopter, we can modify the non-dimensional performance data of a similar helicopter based on scaling from known differences in the two helicopters. This method was used to develop the data for the Airbus EC-130 from the original noise flight test data (Reherman, 2005). This method is discussed in more detail in section 7.1.

AEDT, and therefore the RPM, has the requirement to model ground operations. This requirement does not exist in the Army model, which is strictly an in-flight method. The RPM also needs to model in-flight transitions (e.g. an accelerating climb during departure). So the Army model provides a framework for the RPM, but does not provide performance modeling methods sufficiently detailed to calculate noise during terminal area operations where transitional modes are the rule, not the exception.

The Army model assumes data are available for in-ground-effect (IGE) and out-of-ground-effect (OGE) hover. While the helicopter performance charts from the OEMs usually do provide hover data, we found these data not useful for this process, since these OEM hover data are intended to be used by the pilots at the extremes of the performance envelop (maximum and minimum temperatures and maximum altitudes). For this reason, we use alternative methods of determining hover performance as discussed in section 6.2 below.

4.3 Development of data for the RPM

The Army model assumes that the thrust and power coefficients for the particular helicopter are available. This is clearly not the case for the current AEDT helicopters. Most helicopters (though not all) have sufficient data available in their flight manuals so that the required performance data for the RPM can be extracted. Other required data, such as the physical dimensions and the weights of the helicopter, if not in the flight manual, can be found in public domain sources.

Extracting the required performance data for the RPM from the flight manuals is not a trivial process. The development of these data for two helicopters (a light piston, and a medium turbine) is presented in detail in section 6.

5. Flight Procedure Modeling

The underlying premise of the RPM is that in cruise flight at a particular weight, the power required to fly at a particular airspeed is known – even if that airspeed is zero as when the helicopter is hovering. The analogy with the fixed-wing model in the AEDT is for each fixed-wing configuration (i.e. a particular flap setting configuration) we know the associated drag/lift value (the non-dimensional 'R' value). Knowing the 'R' value and the airplane weight allows the model to calculate either the thrust or the flight path when the other parameter is known. The fixed-wing model in AEDT does *not* calculate the 'R' value for the particular configuration; the 'R' value is provided in the database. Similarly, the RPM does not calculate the required power for cruise; the required power is provided in the database. What the RPM does calculate are the changes in the required power as the flight modes differ from the cruise power baseline.

What this implies is that the RPM needs data on the cruise power requirements as a function of both airspeed and weight. We need these data in a general form so that changes in helicopter performance with atmospheric conditions (i.e. temperature and altitude) can be calculated by the model. These general forms of the data are the non-dimensional speed, thrust and power coefficients. The non-dimensional speed is mu (µ), which is the true airspeed of the helicopter (in feet/sec) divided by the main rotor blade tip speed relative to the rotor hub. The notation used here is that Ω is the rotational speed of the main rotor in radians/sec and R is the radius of the blades in feet. The non-dimensional thrust is the weight (a force, not a mass) divided by a term which has the units of force, which is the same in the English system of measurement as mass times acceleration. The non-dimensional power is the non-dimensional thrust modified by terms to include distance and time (since power is a measure of work per time, which is the same as a measure of force multiplied by distance per time). These non-dimensional parameters are given below; the non-dimensional thrust is the C_T coefficient, the non-dimensional power is the C_P coefficient.

$$\mu = \frac{V_{True}}{(\Omega R)}$$

$$C_T = \frac{T}{\rho \pi R^2 (\Omega R)^2}$$

$$C_P = \frac{P}{\rho \pi R^2 (\Omega R)^3}$$

These non-dimensional coefficients and their definitions can be found in any standard reference on helicopter aerodynamics. Also note that the C_P coefficient has the same definition as C_Q, the non-dimensional torque coefficient.

As with the fixed-wing force balance equations which use the assumption that the lift of the airplane is equal to the weight, the RPM assumes that the thrust of the helicopter is equal to the weight. Note that we can further scale the power coefficient to the more familiar units of horsepower, as opposed to the actual English system units of foot-pounds per second.

The three fundamental units above are combined into tabular form in the RPM database. While the original Army report had one table for each rotor speed of the helicopter, the RPM assumes the same rotor speed (100%) is used for all operations. The RPM therefore has one table of these data for each helicopter. The mu and C_T data are the independent data (i.e. each row of data represents the same mu; each column represents the same C_T). The C_P data are the dependent data, i.e. given a mu and a C_T, we can look up, via interpolation, the resulting C_P. These data are referred to below as the C_TC_P tabular data. We can state that the power required for steady state flight is a function of the mu and C_T terms (from the C_TC_P tabular data), and then can convert that steady state power required to horsepower:

$$C_P = f(\mu, C_T)$$

$$HP_{\text{steady}} = \frac{C_P \rho \pi R^2 {V_{tip}}^3}{550.}$$

Also note that the model uses both In Ground Effect (IGE) and Out of Ground Effect (OGE) hover. The lower boundary of the C_TC_P tabular data is set by OGE hover which has a mu of zero.

The following sub-sections discuss how the C_TC_P tabular data are combined with the other available data to model the performance of the helicopter in the particular flight region.

For the actual non-steady state performance model equation itself, we use an energy balance – the same total energy model (TEM) equation used in EUROCONTROL's BADA3 and BADA4 families of aircraft performance (EUROCONTROL Experimental Centre, 2011). The TEM equation is given below:

$$(T - D)V_{TAS} = W\frac{dH}{dt} + \frac{W}{g}V_{TAS}\frac{dV_{TAS}}{dt}$$

The form of the equation is slightly different from the BADA form, since we are using weight (W), rather than mass, in the equation.

We use an energy balance equation, rather than a force balance equation such as found in the INM, because we don't necessarily know the vectors (i.e. the angles) associated with the thrust and drag forces acting on the helicopter. We do make the assumption with the energy balance equation that the change (if any) in the potential and kinetic energy of the helicopter are attributable to the difference (if any) between the power available to the helicopter and the power required to maintain a steady state. As discussed above, we can find the power required to maintain this steady state directly from the C_TC_P tabular data.

We note that the power available is not necessarily *all* available to change the state of the helicopter – the excess power (the amount of power available less the power required) has to be converted from the power at the engine shaft(s) to thrust. This is not a lossless process. The RPM does account for some of the losses by calculating a drag coefficient for forward flight from the C_TC_P tabular data. We assume that parasitic drag at the highest mu values in the table controls the power required. Parasitic drag can be modeled with the standard non-compressible drag equation:

$$D = C_D \frac{1}{2} \rho V^2 S$$

In the above equation, the characteristic area S is the frontal area of the helicopter. The calculation of the C_D term is based on the change in the power required from the $C_T C_P$ tabular data – the actual drag increase may not be correctly captured by this method, but what should be captured is the actual power required to increase the airspeed from one mu value to the next.

At this point, we know the drag and the weight of the helicopter for the given flight condition, so we can calculate the power required to change the state of the aircraft. Note that this power required for the state change is added to the power required for the steady state flight found from the $C_T C_P$ tabular data.

$$TV_{TAS} = HP_{\text{non-steady}} = W\frac{dH}{dt} + \frac{W}{g}V_{TAS}\frac{dV_{TAS}}{dt} + DV_{TAS}$$

This non-steady power-required equation will under-predict the actual increase in required power, since losses associated with the translation from shaft power at the engine to thrust from the blades are not included. Also not included are losses from extracting the additional power for the anti-torque system (i.e. the power to drive the increased thrust of the tail rotor which is required to overcome the increase in torque from the main rotor).

5.1 Level flight

The basic methods of the RPM are best demonstrated by considering the simplest case of level, unaccelerated flight. In level flight, the RPM uses the known weight, true airspeed, and atmosphere conditions to calculate the μ and C_T directly. From these values, the C_P is found from a table look-up and interpolation. The RPM converts the C_P back to a horsepower. This horsepower is then used to calculate the fuel flow of the engine from an internal interpolation of known engine power/fuel flow data. The steps to calculate fuel flow in level flight are therefore:

1. Determine μ from airspeed
2. Determine C_T from weight and atmospherics
3. Look-up C_P from μ and C_T
4. Calculate HP from C_P
5. Calculate fuel flow from HP

The 'Level Fly' procedure steps for the AEDT standard helicopter departure and arrival operations are defined with a segment length ('Track Distance') as a user input. The RPM does not use this distance directly, but rather breaks this distance into one nautical mile (nm) segments if the segment is longer than one nm. This allows for finer resolution in the calculation of the weight decrement from fuel consumption. The RPM level flight module loops the above five steps for each one nautical mile subsegment, plus whatever ending distance remains to reach the user defined segment length. The RPM outputs the state and position vector for each of the sub-segments. Note that these one nm sub-segments are significantly shorter than the 100 nm en-route cruise segments used for fixed-wing aircraft in the AEDT BADA4 cruise method; the cruise parts of the approach and departures for the standard helicopter procedures in the AEDT are on the order of 10 nm.

5.2 Ground and flight idle

Ground and Flight idle power settings are not calculated from the force and power requirements. Ground idle in the RPM currently uses the standard ICAO idle condition of 7% of the maximum power available. Flight idle uses an empirically determined 30% of the maximum power. This flight idle power setting is approximately the highest of the power settings used on the helicopters for which the Volpe Center has conducted noise measurements. These measurement data are shown in Table 1 below. Fuel flows in these conditions are calculated from interpolating the power/fuel flow data available for the particular engine.

Table 1, Ground and flight idle power setting from measurement tests

Helicopter	Ground Idle setting	Flight Idle setting
B407	10% Torque	29% Torque
S-300C	11.5" MAP	15" MAP
EC-130	9% Torque	11% Torque

5.3 Vertical ascent

The first step in the standard helicopter departure procedures in AEDT is a vertical ascent to a relatively low initial altitude above the helipad. The dynamics of this initial vertical ascent are set by the total power available for the helicopter offset by IGE power requirements. The excess power available is used to vertically accelerate the helicopter. Note that the RPM assumes that the helicopter accelerates to half the distance of the final altitude, then decelerates back to zero speed over the final half of the hover altitude change. The rate of climb used in the vertical ascent is half that the calculated maximum rate of climb – the assumption is that the helicopter accelerates vertically from a hover to the maximum rate and then decelerates back to hover at the top of the ascent. This acceleration and deceleration occurs over a very short distance and time – the standard helicopter departures in the AEDT database have an initial vertical ascent to 15 feet above the helipad.

5.4 Horizontal acceleration

Helicopters normally accelerate horizontally after the initial brief vertical ascent. This horizontal acceleration is a safety measure to avoid the regions of the "deadman's curve" where the helicopter is either too low and/or too slow to safely auto-rotate in the event of an engine failure. Note that a horizontal acceleration step is also used at the top of the final climb to accelerate to the final cruise speed in the AEDT standard departure procedures.

The RPM module which calculates the horizontal acceleration uses the difference between the user input airspeed at the end of the segment and the prior segment's final airspeed. The RPM uses a two-step process to determine the parameters of the horizontal accelerations. First, a constant acceleration from the beginning to the ending speed is assumed to occur over the distance defined in the AEDT procedure step. If the helicopter has enough power to physically meet this acceleration, the required power is reported and the step is complete. If the helicopter does not have enough power to complete the acceleration in the defined step distance, the maximum continuous power (MCP) of the helicopter is used to accelerate the helicopter, and the resulting distance is changed from the distance in the step definition to the distance calculated from the TEM equation. This distance is calculated by the RPM module looping through the acceleration from the initial to the final airspeed in 1 knot increments. This allows the drag changes of the helicopter with increasing airspeed to be small enough to be assumed constant within each step. The acceleration loop ends when the final speed is reached, not when the track distance is reached. We use airspeed as the determining factor for ending the segment, since airspeed appears to be the primary predictor of noise in departure and cruise regions, as discussed in section 9. That is, we consider matching the final speed of the acceleration more important for correct modeling than matching the distance over which the acceleration can occur.

The horizontal acceleration step also uses the concept of translational lift to determine if the helicopter is using the maximum available power or the maximum continuous power. Note that in the RPM the maximum available power is sometimes referred to in the literature as the intermediate rated power (IRP) – this is the power available for short increments of time, such as during takeoff. The highest maximum available power (i.e. higher than MCP or IRP) is military or emergency power, which is not used in the RPM. During the initial vertical climb and at speeds below the translational lift speed, the maximum *available* power is assumed to be required. At speeds above the translational lift speed (in or out of ground effect), the maximum *continuous* power is assumed to be used. The code currently uses a hard-wired translational lift speed of 20 knots for all helicopters – we intend for the translational lift velocity to be a function of the particular helicopter and its state vector when we have the data to support this change.

5.5 Ascending acceleration

After reaching a safe speed, the helicopters will typically accelerate to a climb speed while initiating the climb. Similar to the horizontal acceleration step, the RPM first calculates the power required to meet the ascending acceleration parameters. If the helicopter has more available power than required power, the required power is reported and the step ends at the final stated altitude and airspeed.

If the helicopter has less than the required power, the RPM accelerates the helicopter in 1 knot increases in airspeed using the maximum continuous power. In the current version of the RPM, flight angle is set constant (the flight angle is calculated from the track distance and the reported final altitude), and the final altitude is allowed to vary. That is, using the maximum continuous power setting for the helicopter, the helicopter accelerates to the final airspeed at a known flight angle. When the helicopter reaches the final airspeed, the segment ends; airspeed is used to determine the segment end, not altitude or track distance.

Note that this method differs from the SAE-1845 method for fixed wing aircraft. In the SAE-1845 method, the altitudes and airspeeds are the inputs and the distance is the calculated value, so the climb angle is also an output of the process.

5.6 Constant airspeed climb

The helicopters will climb to the final cruise altitude at the climb speed set in the prior procedure step. After reaching this altitude, the AEDT standard departure procedure for helicopters uses a horizontal acceleration from the constant calibrated airspeed climb to the level segment cruise airspeed.

If the helicopter does not have sufficient power to climb to the final altitude in the distance specified, the RPM uses altitude as the looping parameter; the climb performance is calculated every 10 feet of altitude gain using the helicopter's maximum continuous power. Unlike the ascending acceleration step, the flight angle is an output from the process, not an input based on the track distance and final altitude.

The airspeeds in the standard AEDT procedure steps are true airspeeds, not calibrated or indicated airspeeds. This means that the constant airspeed climb in the standard AEDT procedure step has no changes in kinetic energy. If the current AEDT procedure step process changes from the current system based on external characteristics of the flight (e.g. true airspeed, distance over the ground) to a pilot-centric system (e.g. calibrated airspeeds, rates of climb/descent), then this step would also need to consider the change in kinetic energy due to changes in true airspeed. Note that the SAE-AIR-1845 system is a hybrid system, where pilot-centric parameters (KCAS, ROC/D) are used to define the flight procedures, but the trajectory of the aircraft is relative to the ground (via hard-wired assumptions of a unidirectional 8 knot headwind, and a climb at a fixed reference speed), not relative to the air-mass in which the vehicle travels.

5.7 Horizontal Deceleration

The horizontal deceleration is the first part of the approach after the cruise in the AEDT standard arrival procedures. Note that while the helicopter performance parameters (e.g. power required, airspeed) may reasonably be used as predictors of noise in the departure and cruise segments, these performance parameters are unlikely to accurately correlate with noise during the approach segments, where blade – vortex interaction (BVI) may be the dominate noise source.

The power required at the beginning of the segment is found from the beginning speed, the power required at the end from the user-defined ending speed. The physics of the approach is maintained in that the decrease in the kinetic energy of the helicopter is subtracted from the power required to fly the helicopter at the particular airspeed. Note that the RPM contains no second step looping in any of the approach segments; we assume the helicopters are always capable of decelerating and/or descending at the rate determined by the profile parameters.

5.8 Constant airspeed descent

In this step the helicopter descends to an altitude defined in the current procedure step at the airspeed set in the prior procedure step. The RPM uses the standard procedure inputs of altitude and distance; the required power for this defined angle descent is a calculated value. The reduction in potential energy due to the altitude decrease is used to modify the power requirements from that given in the C_TC_P tabular data. Note that standard AEDT procedure steps use true airspeed as the speed parameter. As discussed in section 5.6 above, if the data in the AEDT procedure steps changes from KTAS to KCAS, this module would also need to be modified to account for the kinetic energy change.

5.9 Descending Deceleration

The descending deceleration is one of the descent modes where the performance state of the helicopter will not be used to determine the noise (though the performance state will determine the fuel flow and emission predictions). While the current proposal is to continue to use the descent mode as the look-up into the NPD data, we expect the noise modeling to eventually be predicted by the flight angle of the helicopter, with the possible expansion of the prediction method to include those performance parameters which help estimate the BVI noise. AEDT is not intended to be a first principles acoustics model, so BVI prediction will likely rely (when implemented) on look-up tables of BVI effects. These BVI tables may be pre-computed by higher fidelity first principles models – the actual methods will depend on the results of the ACRP project discussed in section 3.2 above.

As with the other approach procedure steps, the descending deceleration uses the C_TC_P tabular data modified by the decrease in the required power due to the decrease in both potential energy and kinetic energy.

5.10 Vertical Descent

The vertical descent is the mirror image of the vertical ascent discussed in section 5.3 above. The required hover power is reduced by the change in the potential energy due to the decrease in altitude over the given time. Note that the time required for this decrease in altitude is an input from the standard AEDT procedure step process.

6. Data Development

The prior section assumed that the data for the helicopters already exists. Clearly, this is not the initial condition. Someone must generate the mu, C_T, and C_P tabular data prior to using them in the RPM. The fuel flow data also must be generated when an engine does not exist in the ICAO emissions databank. This section discusses how to develop these data.

6.1 Flight manual data

The primary source for the mu, C_T, and C_P data are the flight manuals for the particular helicopter. For the helicopters used in the development of the RPM, the authors have seen data in two general formats: endurance data and fuel flow data. The following sub-sections discuss how to convert the data contained in these formats into the C_TC_P tabular data which RPM requires.

6.1.1 Endurance data

The endurance data for the helicopter of interest presents the endurance (time aloft) for the helicopter as a function of the airspeed and weight of the helicopter. So for a given weight and airspeed, and knowledge of the volume of fuel the helicopter can carry, we can determine the fuel consumption (rate of fuel flow) of the helicopter for the given conditions.

While normally we work from a given power setting to fuel consumption, in this case we take known fuel consumption data and use those data to determine the associated power setting.

As an example, the performance charts for the Schweizer 300C (SC300C) show that this helicopter has a maximum endurance of 7.4 hours at a 4000 foot cruise altitude (ISA conditions) while traveling at 40 knots with no reserves. The SC300C has a total capacity of 64 gallons of fuel in both the main and auxiliary tanks; the fuel flow rate at maximum endurance is 64 gallons/7.4 hours = 8.65 gallons per hour or 51.9 lb/hour (Avgas weighs about 6 lb/gallon). Using the Lycoming HIO-360D1A engine data for this aircraft, we find that the maximum endurance fuel flow rate corresponds to a 55% power setting. The engine is rated at 190 HP, so the power required under these conditions is about 105 HP. This represents just one point on the endurance curve. The data in the SC300C endurance graphs are sufficient to populate two columns in the C_TC_P tabular data.

6.1.2 Fuel Flow data

The second primary source of C_TC_P tabular data are fuel consumption graphics from the OEM's flight manuals. As with the endurance data, the data are typically presented for different helicopter weights and airspeeds for a given environmental condition (altitude and temperature). The authors have found some performance data also contains the percent of the maximum torque setting for the helicopter, which makes these graphics particularly valuable – the translation between torque (which is a direct measure of engine power when the engine/rotor RPM is set) and fuel consumption on the graphic mean the C_TC_P tabular data and the fuel consumption data are available in one location.

As an example, for the Bell 407, the MSL ISA fuel flow vs. airspeed graphic provides data for airspeeds from 50 knots to 130 knots. The weight data range from 3000 pounds to the helicopter's maximum weight of 5250 pounds. Unlike the endurance charts, the data can be read directly from the graphic – no translation other than from % torque to horsepower is required (though we do translate the parameters to their non-dimensional forms as expressed above). We note that the Bell 407 has a maximum continuous power torque limit of 93%; with a rated power of 813 HP, the resulting MCP for the helicopter is 756 HP.

6.2 Hover data

The lower boundary of the C_TC_P tabular data is set by the hover data (where airspeed and mu are zero). The hover data are typically presented in the flight manuals in a form which is more useful to the pilots than to performance analyses. In particular, pilots are interested in knowing if the helicopter can lift a certain amount of weight for a given environmental condition (altitude and temperature). The assumption is generally that the engine will need to develop the maximum amount of power available at these conditions. This means that the OEM hover data are given at the extremes of the performance envelope of the helicopter – the authors have found that extrapolating these data back to the more typical operating condition of helicopter leads to large errors. Rather than using the OEM data which requires extrapolation, we use a method presented in (Gessow, 1985) and modified by (Johnson, 1994) to find the out-of-ground effect (OGE) hover, then modify this with the methods of Hayden, as presented in (Johnson, 2009), to determine the in-ground effect (IGE) hover. These methods are discussed below.

6.2.1 OGE data

The calculation of the hover is based on the concept that the power required for the helicopter to stay aloft has three components: profile power, induced power, and parasitic power. Profile power is the power required to spin the main rotor blades through the air at the flight rotation speed without producing lift. The induced power is the power required to overcome the induced drag which results from producing lift. Parasitic power is due to the drag when the helicopter is in forward flight, and so does not contribute to the power required to hover.

$$P_{\text{required}} = P_{\text{profile}} + P_{\text{induced}} + P_{\text{parasitic}}$$

When the helicopter is operating at the maximum weight (which may be the maximum weight with an external payload, which is why these data are required), the assumption is that the helicopter is operating at or close to the maximum power required to hover out of ground effect. The profile drag, and therefore the profile power, is largely independent of the loading of the rotor; we can treat the profile power as a constant. The induced drag is a function of the load. The takeoff power at maximum weight is therefore equal to the sum of the profile and maximum induced powers.

$$P_{\text{IRP}} = P_{\text{profile}} + P_{\text{induced}_{\text{Max}}}$$

Johnson (1994) provides an induced power equation for hover:

$$C_{Q_I} = \frac{\kappa C_T^{2/3}}{\sqrt{2}}$$

In this equation κ is an empirical constant equal to 1.15 which is used to account for losses in the system. Knowing the IRP power and the C_T at maximum weight allows $P_{Profile}$ to be determined. Once we have $P_{Profile}$, we can find the power required for any other hover weight; we find these for the weights associated with the C_T values in the C_TC_P tabular data.

6.2.2 IGE data

Once we know the CP data for the OGE hover, we can modify those data via the IGE effects given by the Hayden ground effect model as given in (Johnson, 2009) to determine the CP for IGE hover. The IGE effects are a function of the distance between the main rotor plane and the ground. This represents an improvement over the Army method where IGE was considered a binary effect: the helicopter is either in ground effect or it is out of ground effect; the Army also does not contain a distinguishing altitude to differentiate IGE and OGE. With the current methods, the ground effect has a more realistic dependence on the actual height of the helicopter about the ground.

A graphic of the Hayden ground effect model is shown in Figure 1 below. The horizontal axis represents the ratio of the rotor plane distance above the ground to the rotor diameter. The Z parameter is the distance of the main rotor plane to the ground; this is the distance from the hub to the bottom of the landing gear, plus the altitude of the helicopter above the ground. The vertical axis represents the ratio of the required IGE power to the required OGE thrust; the curve shows that the lower the helicopter is to the ground, the less power is required to maintain hovering flight. Note that the curve shown here is the inverse of the curve shown in (Johnson, 2009): we define the ground effect as the reduction in the required power, not the increase in the apparent power shown in Johnson's work.

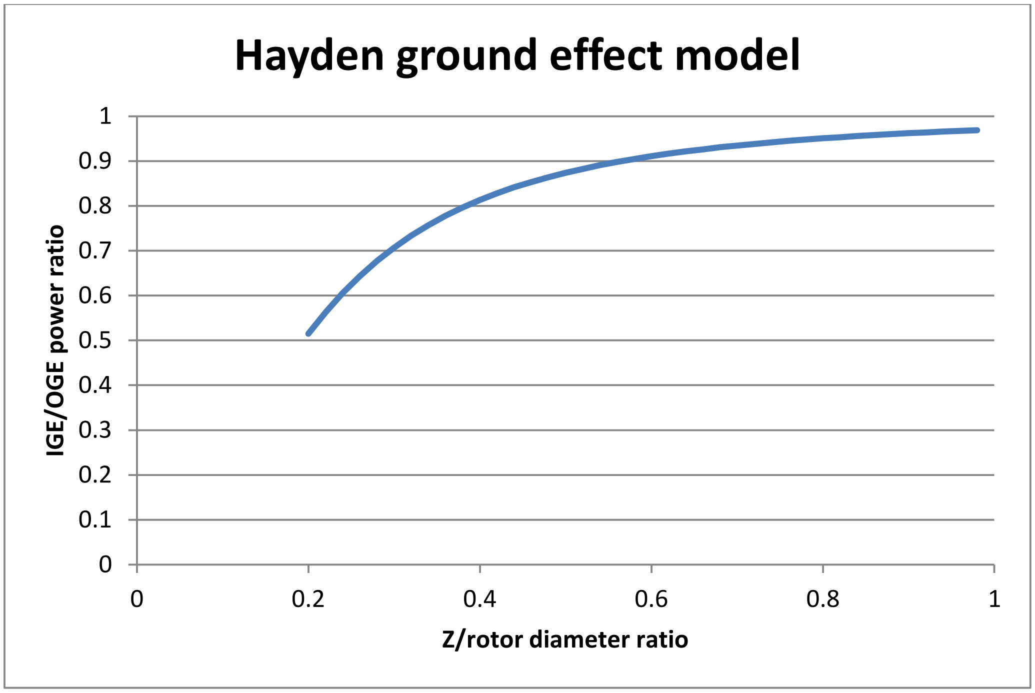

Figure 1, Hayden ground effect model for hovering flight

6.3 Helicopter weights data

As with fixed-wing aircraft in the AEDT, the performance of the helicopters in the RPM is directly influenced by their weight. RPM uses four weights in the performance calculations: the Operating Empty Weight (OEW), which is the weight of the airframe with no usable fuel or payload onboard; the Maximum Takeoff Weight (MTOW), which is the maximum weight at which the helicopter can lift off with an internal load; the maximum takeoff weight with an external load; and the weight of the fuel with tanks full. For helicopters which have no external load data, we use the MTOW.

6.4 Helicopter engine data

Helicopters in the AEDT fleet use one of two types of engines: piston or turboshaft. We discuss some of the characteristics and differences between these engines below. We also discuss some implications of helicopter transmissions limitations.

6.4.1 Piston engine

Helicopter piston engines are primarily manufactured by Lycoming. Lycoming provides performance charts for its engine which allow a determination of power output when environmental conditions, engine RPM, and intake manifold air pressure are known. Manifold air pressure (MAP) is typically reported in terms of inches of Mercury, and is often available in the cockpit as an engine power indication. All piston engine helicopters for which Volpe has conducted noise tests were powered by Lycoming engines, and all used a combination of MAP and RPM for power indication.

6.4.1.1 Atmospheric properties

The power available from piston engines varies directly with the density of the air and the amount of throttling (to increase or reduce MAP). For our purposes, we consider the Lycoming performance charts to be adequate for predicting how changes in atmospheric conditions impacts the horsepower output of the engines.

6.4.1.2 Fuel consumption data

Data from Lycoming usually contains fuel consumption as a function of the power produced by the engine. For example, for the Lycoming HIO-360D engine used on the Schweizer 300C, Lycoming provides fuel flow as a function of percentage of engine power from 45% to 100%. The Lycoming data are presented in terms of pounds per hour; we change this to the AEDT standard fuel flow metric of kilograms per second in the RPM database.

6.4.2 Turbine engines

The power available from a helicopter's gas turbine (turboshaft) engine is a function of the mass of air flowing into the engine. The power parameter itself is usually a measure of the torque output of the engine.

6.4.2.1 Atmospheric properties

Turbine engines are normally flat-rated below a particular temperature. This means that at sea level conditions, the engines can supply a fixed amount of power up until a particular ambient temperature is reached, after which the engine will decrease in power as the density of the air falls off with increasing temperature.

The Army model uses a simple turboshaft engine performance prediction which is similar to the SAE-AIR-1845 turbofan engine performance equation. The U.S. Army prediction can be written – using the notation of SAE-AIR-1845 – as:

$$\mathrm{HP} = E + G \times \mathrm{Altitude} + H \times \mathrm{Temperature}$$

The equation will have different coefficient values for the IRP and MCP engine settings. Note that the equation has no airspeed term, and is linear (not quadratic) with altitude.

6.4.3 Transmission issues

The helicopter transmission converts the high speed, low torque engine output to the low speed, high torque requirements of the rotor systems. For twin engine helicopters, the transmission may limit how much power can be delivered to the rotors in the event of an engine failure. Because this type of limitation is a non-standard condition, we don't include this limitation in the RPM; we assume the helicopter is operating normally, and the transmission limits are never reached.

6.5 Helicopter physical data

The helicopter physical data are those data related to the size and capabilities of the helicopter. The number of engines, the distance from the main rotor to the tail rotor, and the flat plate areas of the front and the top of the helicopter are included in these data. In addition to the flat plate data of the front and top, which are necessary to determine the drag of the helicopter in different flight modes, we also include the drag coefficients for the top of the helicopter. In the current version of the RPM, we assume that the top drag coefficient does not vary considerably from the helicopter used as the basis for the Army method. That is, we assume the top area drag of the helicopters varies due to their size, not due to their aerodynamic cleanliness.

6.6 Helicopter rotor-system data

The helicopter rotor system data needed for the current version of the RPM are all non-proprietary. The data are usually available from three-view drawings given in the flight manuals. The rotor system data which RPM needs are the blade count and the chord for the main and tail rotors, and the rotational speed of the main rotor.

The current RPM database does include entries for proprietary aerodynamic blade data which would allow the direct calculation of main and tail rotor torque and power. These proprietary data are not used in the current model, since we don't expect to have access to it; these data would have to come from the manufacturers.

6.7 Helicopter fuel data

While the engine power data relies on knowledge of both the engine characteristics and the environmental conditions, once the engine power is known, we use a simple piecewise linear fit to determine the fuel flow. Note that the fuel flow as a function of the engine power isn't necessarily linear over the range of power settings - we use a linear interpolation between the known points of the engine power/fuel flow relationship to estimate the fuel flow.

7. Sample Helicopter Data

Section 6 discussed the data used in the model. This section presents those data already developed for the Schweizer 300C, the Bell 407, and the Eurocopter EC-130. We also present the data for the S-70 (UH-60) as given in the U.S. Army report in some of the tables below. The data below are presented in the tabular formats that we would expect the AEDT database to use, though these formats are not finalized as of the writing of this report.

7.1 C_TC_P tables

The C_TC_P tabular data are presented below for the Schweizer 300C (SC300C) and the Bell 407 (B407). Note that these two helicopters have significantly different capabilities – the SC300C has a top speed of about 80 knots, while the Bell 407 has a top speed of about 130 knots. The non-dimensional mu values will therefore have different ranges for these helicopters. For database consistency, we expect a fixed number of mu values – not all mu values will have populated C_P entries in the final AEDT implementation. Note that the mu values of zero in the tables below represent the OGE hover condition.

We also note that the number of C_T entries will vary by helicopter – the SC300C only has endurance data for two weights, therefore only two C_T columns can be populated. The Bell 407 has seven weights reported in the OEM fuel flow versus airspeed chart; we use three to define the C_TC_P tables, with the assumption that capturing the lightest, heaviest, and a representative middle weight will allow for reasonable interpolation between the C_T values. In the tables, the left column contains the mu values; the top row contains the C_T values. The body of the table contains the C_P values. The C_T values are scaled by 10^4; the C_P values are scaled by 10^5.

Table 2, Bell 407 C_TC_P tabular data

Mu\C$_T$	22.9	40.08	50.99
0	48.18	44.47	53.48
0.112	14.88	21.65	28.69
0.134	15.33	20.75	26.97
0.156	16.24	21.2	26.97
0.178	17.59	22.55	28.11
0.201	20.29	24.8	30.41
0.223	23	27.51	32.7
0.245	27.06	30.67	37.29
0.268	31.12	35.18	42.46
0.29	36.98	41.04	50.49

Table 3, Schweizer 300C C_TC_P tabular data

Mu\C_T	32.49	39.18
0	26.46	31.27
0.064	19.39	23.69
0.076	17.91	22.01
0.089	17.14	20.65
0.102	16.41	19.74
0.115	16.58	19.39
0.127	17.14	19.56
0.14	17.71	19.91
0.153	18.57	21.03
0.166	20.27	21.76
0.178	21.53	23.09
0.191	23.09	24.44
0.204	24.94	26.85
0.217	28.6	29.56

The RPM does not use tabular IGE data, since these data are calculated from the empirical Hayden equation discussed in Section 6.2.2 above.

7.1.1 C_TC_P tables from limited source data

The EC-130 flight manual does not contain sufficient information to develop the C_TC_P tables. For this helicopter, we have fuel consumption data for a number of helicopter weights, but only at a single airspeed (the recommended 120 knot cruise speed of the helicopter). For the EC-130, we use the Bell 407 C_TC_P tables as a baseline, then scale those data based on the differences in C_P between the Bell 407 and the EC-130 at the same mu and C_T. So the steps for the scaling are:

1. Determine the C_T values of the EC-130 for representative weights
2. Using the EC-130 fuel flows, determine the EC-130 power required
3. Determine the C_P corresponding to the C_T values
4. Interpolate the Bell 407 data to find the C_P at the same mu and C_T
5. Scale the Bell 407 data based on the difference in the C_P values.

These steps are detailed below. The data in the steps are from the EC-130 flight manual.

7.1.1.1 Determining the C_T values

The EC-130 has flight performance data available at multiple weights. We use the lightest and heaviest weights given in the flight manual. The rotational speed of the main rotor is 394 RPM and the helicopter cruise speed is 120 knots. The table below shows the progression the calculation of C_T – starting with weight, and ending with the scaled C_T.

Table 4, C_T calculation for EC-130

Mass (kg)	Weight (lb)	KTAS	Ω (rad/sec)	Tip speed (ft/sec)	mu	C_T	C_Te5
1800	3968	120	41.26	723.5	.27995	.003302	33.02
2427	5351	120	41.26	723.5	.27995	.004452	44.52

7.1.1.2 Determine the power required

The fuel flows are used to determine the power required. The flight manual gives the fuel consumption as a function of the altitude at which the helicopter is operating. We use this data to calculate the power vs fuel flow, using the assumption that the power decreases with deceasing air density. The graphic below shows the calculated fuel flow as a function of power from the EC-130 flight manual and also the data in the ICAO databank for the AEDT engine assigned to this helicopter (the Honeywell TPE-331-5; the actual engine used on this helicopter, the Turbomecca Arriel, is not available in the ICAO databank, and therefore not in AEDT either). The trend line through the actual EC-130 is also shown.

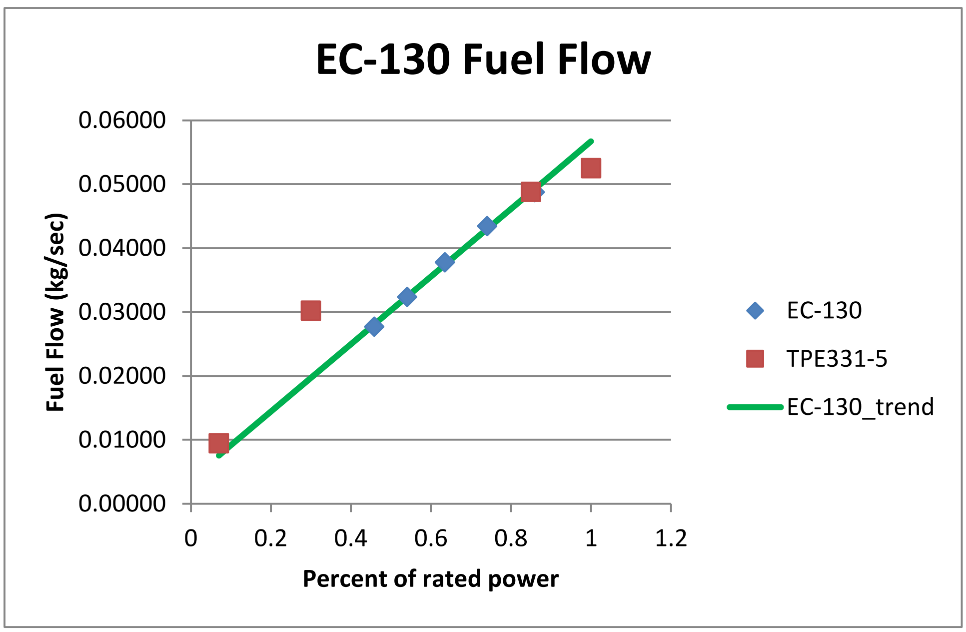

Figure 2, EC-130 fuel flow

We use the above trend line from the EC-130 flight manual to determine the power required, given a fuel flow.

7.1.1.3 Determine the C_T values.

For the weights given above in Table 4, we know the fuel flow from the flight manual and the power required from the trend line in Figure 2. We use these data to step through the left-to-right sequence shown in Table 5, C_P calculation for EC-130 below to arrive at the scaled C_P for this helicopter.

Table 5, C_P calculation for EC-130

Weight (lb)	KTAS	Fuel Flow (lb/hour)	Percent Power	Power (HP)	C_P	C_Pe5
3968	120	327	0.7011	593.8	.000376	37.56
5351	120	347	0.7527	637.5	.000403	40.33

7.1.1.4 Interpolate the Bell 407 data to find the C_T

Interpolating the Bell 407 data on both mu and C_T, we find the Bell 407 and EC-130 C_P values as given in the body of Table 6 below. Note that the first row of data are the C_T values, the bottom two rows represent the C_P data. The sum of the differences of the C_P values is -0.31. We use this value to scale the Bell 407 C_TC_P tables for the EC-130.

Table 6, Result of Bell 407 interpolation

Helicopter	C_Te4	
	33.02	44.52
Bell 407	36.69	41.81
EC-130	37.56	40.32

7.1.1.5 Scale the Bell 407 data

The results of this scaling process are given in Table 7 below. Note that the C_P scaling reduction of -0.31 is about a 1% reduction in the power required for a given flight procedure. Given the errors inherent in this type of scaling, we could have just used the Bell 407 C_TC_P tabular data directly with little loss of fidelity.

Table 7, EC-130 C_TC_P tabular data

Mu\ C_T	22.9	40.08	50.99
0	47.87	44.16	53.17
0.112	14.57	21.34	28.38
0.134	15.02	20.44	26.66
0.156	15.93	20.89	26.66
0.178	17.28	22.24	27.80
0.201	19.98	24.49	30.10
0.223	22.69	27.20	32.39
0.245	26.75	30.36	36.98
0.268	30.81	34.87	42.15
0.29	36.67	40.73	50.18

With the creation of the C_TC_P tabular data for the EC-130, we can now compare the modeled cruise power requirement for this aircraft against the power measured in the original Volpe flight test. This comparison is given in Figure 3 below. Note that the series numbers in the figure refer to the series of the noise event passes for which the performance data were captured; each series is intended to have identical performance data, but in practice, this does not happen. In the EC-130 noise measurement flight test, the helicopter was nominally flown at four different cruise speeds, which are represented by the four series in the figures. The figure also shows the average speed and power for the four series and the RPM reported required power for the average speed.

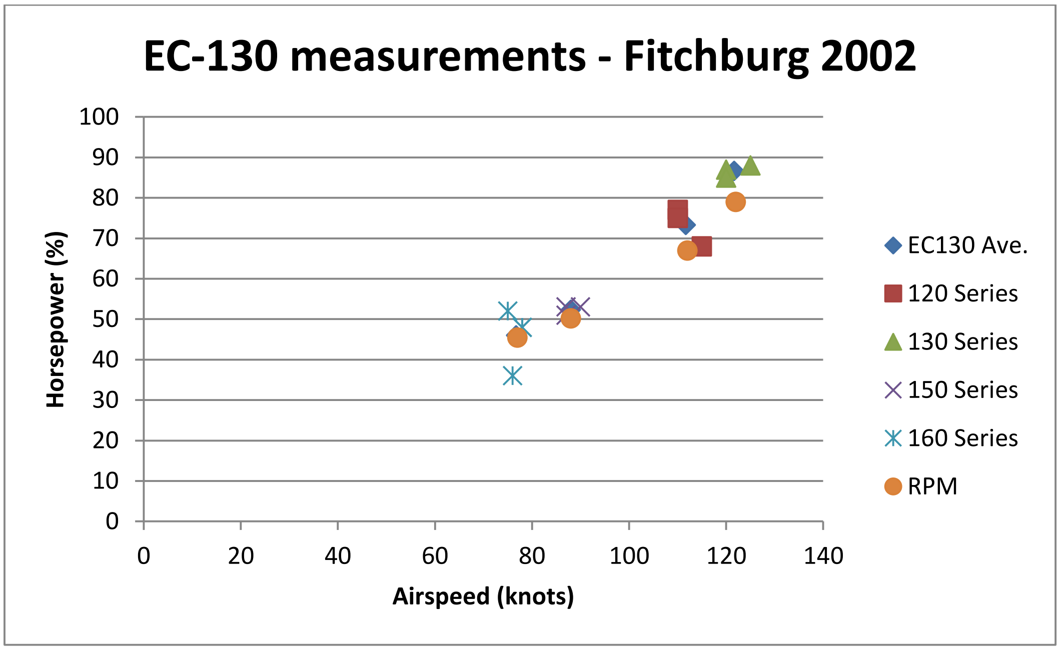

Figure 3, EC-130 modeled and measured cruise power

The data in Figure 3 show that the RPM method predicts the power required in cruise very well at the three lowest airspeed/power passes, but under-predicts at the highest airspeed/power pass series.

7.2 Dimensional table

Table 8 below presents the dimensional data for the helicopters currently in the RPM database. The frontal and top areas have the units of square feet, the tail arm and the vertical landing-gear-to-hub (HUB_Z) distance have the units of feet, and the drag coefficient of the top area of the helicopter is dimensionless. Note that the RPM currently assumes all helicopters are equally aerodynamically 'clean' for ascending flight (where the C_{D_Top} parameter is used). Note that there is no corresponding C_{D_Front} in the table. This is because the drag coefficient for the front of the helicopter is calculated from the change in the C_P values as a function of mu. That is, the drag of the helicopter in normal flight is implicit in the C_TC_P tabular data, so only the frontal area needs to be given by the user.

The HUB_Z data in the table is the vertical distance from the bottom of the landing gear system to the rotor hub. The landing gear system can be a skid system, or a fixed or retractable wheel system. This distance is required for the IGE hover calculation, where the distance from the rotor hub to the ground is required to determine the change in power required due to the decrease in required thrust when the helicopter in operating IGE, as discussed in section 6.2.2 above.

Table 8, Helicopter dimensional data

HELI	FRONTAL_AREA	TOP_AREA	TAIL_ARM	HUB_Z	CD_TOP
S70	74.55	206	32.57	12.79	0.234
SC300C	23.76	35.06	15.29	8.72	0.234
B407	29.8	48.98	21.68	9.95	0.234
EC130	37.11	86.05	22.00	10.11	0.234

7.3 Weight table

Table 9 below presents the weight data for the helicopters currently in the RPM database. The units for the Operating Empty Weight (OEW), the Maximum Takeoff Weight (MTOW), the maximum weight with an external load (MAX_EXT), and the fuel weight are all in pounds. We assume 6.8 lb/gallon for Jet fuel and 6.0 lb/gallon for aviation gasoline.

Note that the maximum external weight is used to develop the hover C_Q data.

Table 9, Helicopter weight data

HELI	OEW	MTOW	MAX_EXT	FUEL_WT
S70	11790	22000	23500	2443
SC300C	1100	2050	2050	384
B407	2676	5000	6000	869
EC130	3036	5351	6172	972

7.4 Engine table

Table 10 below presents the engine data for the turboshaft powered helicopters currently in the RPM database. The engine ID data are from the ICAO emissions databank. The Intermediate Rated Power (IRP) is the maximum power available ('Intermediate' is a misnomer for civilian helicopter where military/emergency power is not available). The Maximum Continuous Power (MCP) is the highest power that can be used for an unlimited period of time. The DH and DT tags indicate the Delta Height (altitude) and Delta Temperature, respectively. Note that the DH terms correspond to the G term, and the DT terms correspond to the H term in section 6.4.2 above. The DH and DT nomenclature originates with the Army model and is retained in the RPM.

Table 10, Helicopter turboshaft engine data

HELI	ENG_ID	NUM_ENG	TYPE	IRP	MCP	IRP_DH	MCP_DH	IRP_DT	MCP_DT
S70	T700	2	T	1540	1254	-0.0387	-0.0265	-3.6819	-3.9563
B407	RR250C47B	1	T	813	756.1	-0.0204	-0.016	-1.9438	-2.3855
EC130	ARRIEL2B1	1	T	847	728	-0.024	-0.024	-1.9991	-1.9991

Table 11 below presents the engine data for the single piston powered helicopter currently in the RPM database. The data represent sea level conditions; the extrapolation to higher altitudes is based on the ISA decrease in density. The data can also account for a flat rating altitude: the HIO-360-D engine is flat rated to 190 horsepower up to 4000 feet.

Table 11, Helicopter piston engine data

ENG_ID	RPM	LOW_MP	LOW_HP	HIGH_MP	HIGH_HP
HIO360D	3000	20.2	110.0	27.3	190.0
HIO360D	3200	19.0	110.0	26.0	190.0

7.5 Rotor system table

The main and tail rotors use the same data structures. The RPM data structures do include the aerodynamic characteristics of the blades defined by the Army method, but because those data are not used in RPM, and the authors believe that those data are considered proprietary by the OEMs, they are not presented here.

7.5.1 Main rotor

Table 12 below presents the main rotor system data for the helicopters currently in the RPM database. The units of the radius are feet. The dimensionless sigma value represents the solidity of the rotor system – the area occupied by the blades divided by the total swept area.

$$\sigma = \frac{\text{Blade Area}}{\text{Swept Area}} = \frac{\text{N}_{\text{blades}} \times \text{radius} \times \text{chord}}{\pi \times \text{radius}^2}$$

Table 12, Helicopter main rotor data

HELI	N_ROTORS	NUM_BLADES	RADIUS	RPM	SIGMA
S70	1	4	26.83	257.9	0.0826
SC300C	1	3	13.42	471	0.041186
B407	1	4	17.5	413	0.065178
EC130	1	3	17.54	394	0.062818

7.5.2 Tail rotor

Table 13 below presents the tail rotor system data for the helicopters currently in the RPM database. The tail rotor rotational speed is included in the required data, but is not currently used the model. We expect this data to be on value if AEE decides to move to a component-level noise prediction, since the noise of the tail rotor is typically a dominant contributor to the noise when the helicopter passes overhead.

Table 13, Helicopter tail rotor data

HELI	N_ROTORS	NUM_BLADES	RADIUS	RPM	SIGMA
S70	1	4	5.5	1200	0.1875
SC300C	1	2	2.125	3095	0.09916
B407	1	2	2.71	2500	0.12431
EC130	1	10	1.64	2500	0.15

7.6 Fuel table

Table 14 below presents the fuel flow data for the helicopters currently in the RPM database.

The first row of data in Table 14 represents the percentage of engine power. The power data are generally in 10% increments, but the table also includes the 7% and 85% data, since these power settings are used in the ICAO emissions databank. The data in the body of the table represent the fuel consumption per engine in kilograms per second at the particular power setting.

Table 14, Helicopter fuel flow data

HELI	ENG_ID	7	10	20	30	40	50	60	70	80	85	90	100
S70	T700	0.0164	0.0164	0.0390	0.0615	0.0635	0.0655	0.0675	0.0695	0.0715	0.0725	0.0773	0.0869
SC300C	HIO360D	0.0032	0.0035	0.0041	0.0048	0.0055	0.0062	0.0070	0.0080	0.0098	0.0104	0.0108	0.0117
B407	RR250C47B	0.0203	0.0209	0.0231	0.025	0.0286	0.0314	0.0347	0.0381	0.0422	0.0443	0.0461	0.0515
EC130	ARRIEL2B1	0.0076	0.0091	0.0144	0.0197	0.0250	0.0303	0.0356	0.0408	0.0461	0.0488	0.0514	0.0567

8. Comparison of modeled, measured, and standard performance data

The Volpe Center conducted noise measurement tests with the Bell 407 and Schweizer 300C from October 7 through 11, 2008 at the Crisfield municipal airport in Maryland (Lau, 2010). At the time of the test, AEE and Volpe were immediately concerned with the noise measurements; the issue of the performance of the helicopters was secondary. The performance data collected in the cockpit during the tests was, however, sufficient to support the current performance analysis. The following two sub-sections discuss the measured performance data collected at Crisfield and the modeled performance data generated by the RPM. In addition, comparisons to the standard AEDT procedures are also presented.

8.1 Schweizer 300C

The Schweizer 300C (SC300C) is a light training helicopter originally designed by Hughes Helicopters in the early 1960s. The SC300C is currently marketed and supported by Sikorsky Aircraft. It has a 3 blade main rotor and is powered by a single Lycoming HIO-360 piston engine. It is designed to carry 1 pilot and up to 2 passengers.

8.1.1 Departure profile comparison

Using the methods discussed in section 5, and the data that supports those methods as given in sections 6 and 7 above, we can compare the calculated performance with that from the standard AEDT departures. Note that the data in Figure 4 below were developed from the Crisfield data, but do not represent any actual flight test – the data are from the RPM and the current standard departure profile in AEDT. The figure shows that the RPM model can mimic the standard departure profile in AEDT almost exactly – the two curves are indistinguishable.

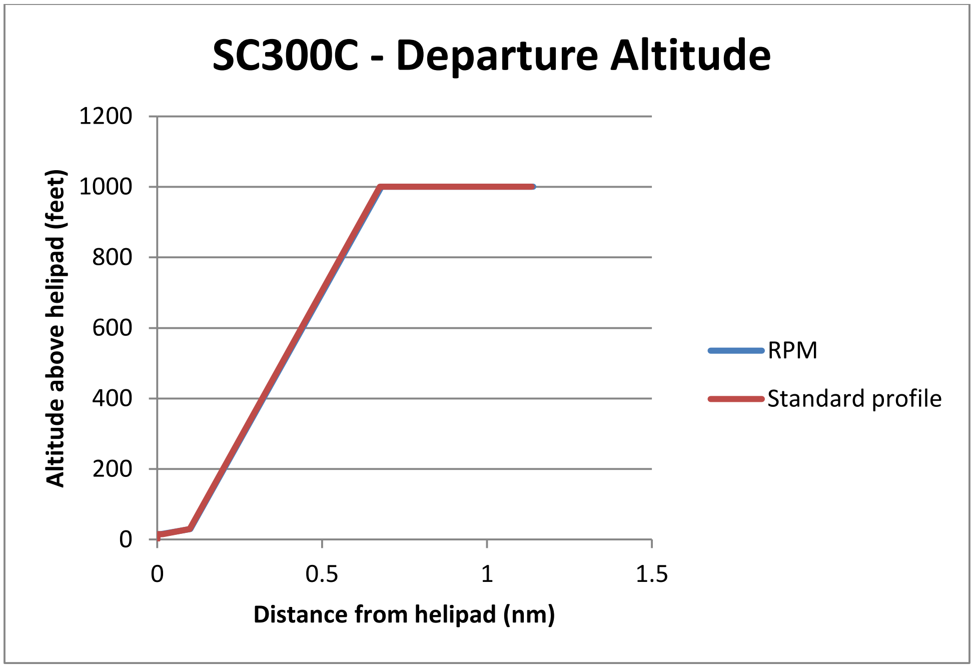

Figure 4, SC300C modeled departure profiles

The speed profile of the SC300C is similar; the standard profile and the RPM speeds are essentially identical. The RPM model reports that the SC300C departure profile exceeds the power available at two points in the profile: during the initial horizontal acceleration from hover to 30 knots in 500 feet, and during the constant speed climb to 1000 feet at 39 knots. The current implementation of the RPM does not stop processing when the power required exceeds the power available, but reports a warning that this condition exists to the user.

The AEDT profiles are not from the manufacturers, but rather represent generic, standard profiles, which date back to the original HNM. These standard profiles are the same for all helicopters (except for the speed data), i.e. the track distances and altitudes are the same for all departure profiles and for all arrival profiles.

8.1.2 Cruise power comparison

Figure 5 below shows the comparison of the SC300C engine power measured during the Crisfield noise tests and the results of the running the RPM model at representative airspeeds in cruise condition. In this case, the Crisfield data *do* represent the actual flight test data, not AEDT standard profiles.

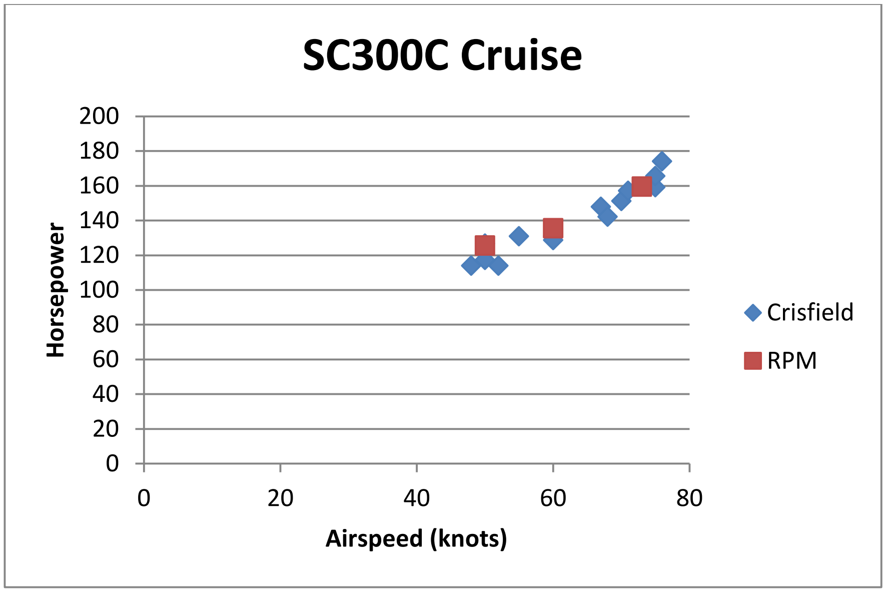

Figure 5, SC300C modeled and measured cruise power

The data in Figure 5 show the expected general trend of horsepower required increasing at a faster rate than the airspeed – we expect the horsepower required to increase as a function of the cube of the airspeed when the drag of the vehicle is predominantly parasitic drag, which is the case in high speed flight. For the SC300C flight test, three speed regions were used: a tour speed of nominally 50 knots, a normal cruise speed of 60 knots, and a high speed cruise of 70 knots. These three speeds (and their associated required power) define the three RPM markers shown in the figure. The Crisfield data which corresponds to these three flight regions are not as clearly delineated since the helicopter speeds during the test also showed variation. For the tour flight, the RPM over-predicts the average of Crisfield tour speed data by 6.4%. For the normal cruise, the RPM over-predicts the average of the Crisfield normal cruise by 4.1%. For the high speed cruise, the RPM over-predicts the average of the Crisfield high speed cruise by 1.7%. For this helicopter, the RPM tends to slightly over-predict the cruise power at low speeds, but seems accurate at the higher cruise speeds.

8.1.3 Arrival profile comparison

The modeled arrival comparison is shown in Figure 6 below for the standard AEDT profile and the RPM modeled profile. As with the departure profile shown in Figure 4 above, the RPM modeled altitude profile is indistinguishable from the AEDT standard profile. Unlike the departure, no warning messages about insufficient power occur during the standard arrival procedure – unsurprisingly, the helicopter has no available power issues during arrivals.

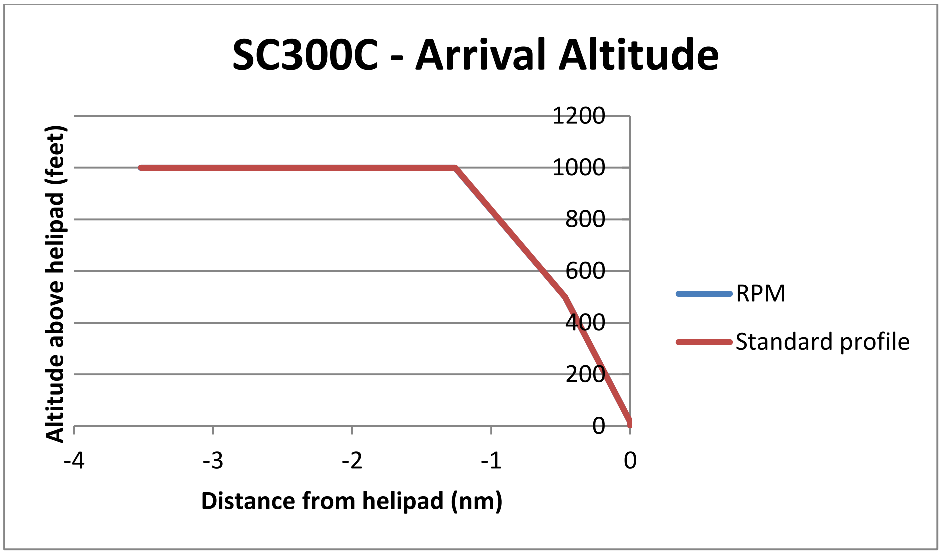

Figure 6, SC300C modeled arrival profiles

8.2 Bell 407

The Bell 407 (B407) is a civil utility helicopter introduced by Bell Helicopters in 1996. Over 1000 have been built. The B407 has a 4 blade main rotor and is powered by a single Rolls Royce 250 turboshaft engine. The helicopter is designed to carry 1 pilot and up to 6 passengers.

8.2.1 Departure profile comparison

As with the SC300C discussed above, the Bell 407 departure profile from the RPM matches the AEDT standard profile almost exactly. Again, as with the SC300C, the RPM reports that the Bell 407 has less power available than power required for some steps. In the case of the B407, the level acceleration step from the top of the climb to the final cruise speed is the step which produces the warning. We note that the data for the B407 did come from Bell, but Bell elected to use the same standard profiles as the other helicopters in the AEDT database; Bell did not provide different profile information when they updated the Bell 407 NPD data in their data submittal for this helicopter.

Because the standard profile altitude data are the same as the SC300C, the graphic for the B407 departure is the same as Figure 4, and is not repeated here.

8.2.2 Cruise power comparison

Figure 7 below shows the comparison of the Bell 407 engine power measured during the Crisfield noise tests and the results of running the RPM model at representative airspeeds in cruise condition. As with the comparable SC300C data, the B407 Crisfield data *do* represent the actual flight test data, not AEDT standard profiles.

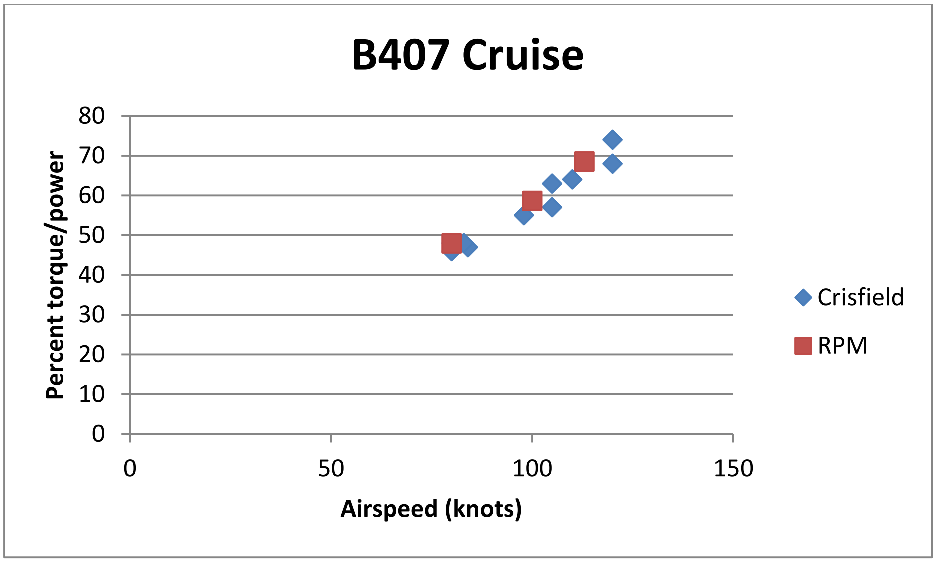

Figure 7, Bell 407 modeled and measured cruise power

The data in Figure 7 show the expected general trend of horsepower required increasing at a faster rate than the airspeed – as we noted in the companion figure for the SC300C (Figure 5). For the Bell 407 flight test, three speed regions were also used: a tour speed of nominally 80 knots, a normal cruise speed of 100 knots, and a high speed cruise of 113 knots. These three speeds (and their associated required power) define the three RPM markers shown in the figure. The Crisfield data which corresponds to these three flight regions are not as clearly delineated since the helicopter speeds during the test also showed variation. For the Bell 407 tour flight, the RPM over-predicts the average of Crisfield tour power data by 1.4%. For the normal cruise, the RPM under-predicts the average of the Crisfield normal cruise power by -1.9%. The high speed flight at Crisfield only included one pass where the speed of the helicopter was noted in the logs; based on this limited data, the authors feel a difference in the measured and modeled power levels has little meaning. For this helicopter, the RPM over- or under-prediction trends appears independent of the cruise speed.

8.2.3 Arrival profile comparison

As with the SC300C arrival data, the B407 arrival in RPM represents the AEDT standard arrival exactly and is not repeated here.

8.3 Fuel consumption validation and verification

The Volpe Center acquired sets of Flight Data Recorder (FDR) information from a major operator for two types of helicopters. The operator has asked Volpe to respect their proprietary concerns and not publish their name or the types of helicopters for which they provided data. The FDR information includes the engine torque, fuel flow, and position and state information. Note that the initial weight of the helicopter is *not* one of the known parameters, though the weight decrease with fuel consumption is known.

8.3.1 Helicopter 1 fuel consumption data

For the first of the helicopter types, the comparison of the fuel consumption from the FDR to the fuel consumption predicted by the RPM is given in Figure 8 below. Each dot represents the fuel consumption for a single operation from takeoff to landing. The position of the dot along the horizontal axis represents the measured fuel consumption of the flight from the FDR data. The position of the dot along the vertical axis represents the predicted fuel consumption from the RPM model. The solid line from the lower left to the upper right of the graphic represents the perfect fit line – if the measured and modeled fuel consumption were identical, all the data points would fall on this line.

In this case, the RPM is over-predicting the fuel consumption for this helicopter by about 8%. We note that this error has two main sources. The first is that since the FDR data do not contain the actual takeoff weights of the helicopters, we used the MTOW as the surrogate takeoff weight for each of the flights. Second, the OEM's fuel consumption data used to derive the C_TC_P tabular data for this helicopter represents a 'minimum spec' engine. This means that the fuel consumption numbers given are highest possible before the engine is removed from the helicopter for overhaul – the C_TC_P tabular data for this helicopter represent a very conservative (high) set of fuel consumption data. We note that a different manufacturer shows the degradation in power between a new engine and a minimum spec engine is 12% - in line with the differences shown in Figure 8. Both the MTOW and the minimum spec issues will tend to raise the fuel consumption prediction relative to the actual values.

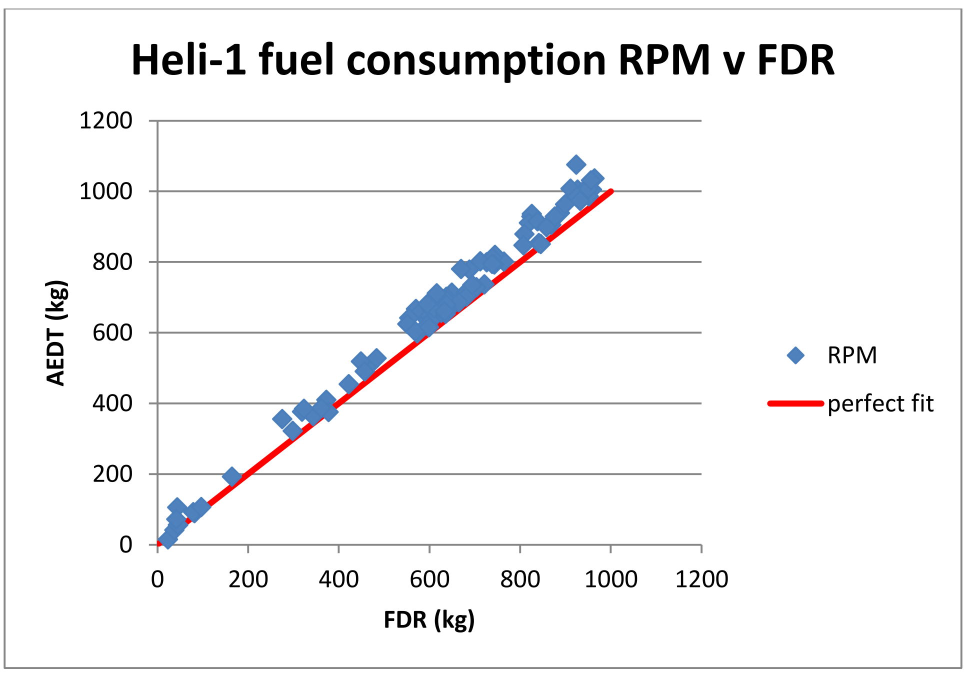

Figure 8, Comparison of measured (FDR) and modeled (RPM) fuel consumption for helicopter 1

8.3.2 Helicopter 2 fuel consumption data

The second helicopter's fuel consumption comparison between the measured FDR data and the modeled RPM data is given in Figure 9 below. The figure uses the same format as the prior figure. In this case, the C_TC_P tabular data are not minimum spec data, but the assumption of using the MTOW for the takeoff weight is still used. The over-prediction of the fuel consumption is about 3% for this helicopter.

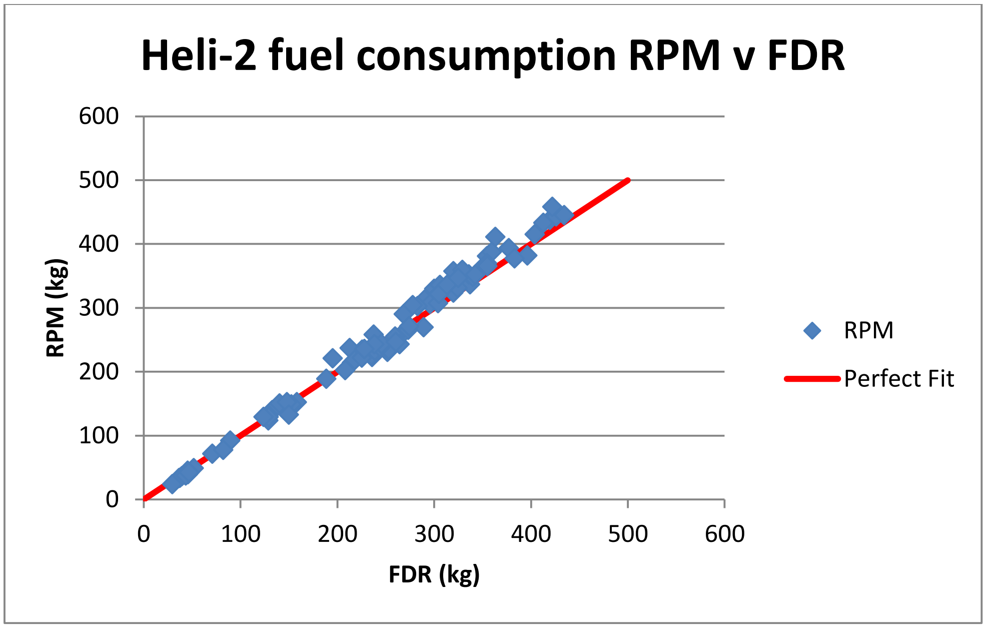

Figure 9, Comparison of measured (FDR) and modeled (RPM) fuel consumption for helicopter 2

Based on the validation with these two helicopter types, the authors believe the RPM provides a reasonably accurate fuel consumption method. We note in particular that the fuel consumption prediction trend at low total values are not significantly different than the trend at high total. The low total represent show flights, the high totals represent long flights. The ability of RPM to successfully model short range operations indicates that the RPM method of extrapolation of the cruise fuel consumption from the flight manuals to unsteady terminal operations (which dominate short range operations) is acceptable.

9. Correlation of noise to modeled performance parameters

This section presents an introduction to the correlation between the performance and noise characteristics of the two sample helicopters examined in the prior section. We restrict our analysis to the departure and cruise modes, since the arrival noise may be dominated by BVI noise, which the simplified performance methods in RPM will not capture.

9.1 Schweizer 300C

The SC300C noise data was collected during the Crisfield noise measurement tests. The performance data collected during that test are presented in Appendix A below. The noise data are available in the Crisfield report (Lau, 2010).

9.1.1 Departure comparison

Departure data, both noise and performance, were collected during the flight test. Two departure types were flown using two different technics: one a constant airspeed climb, the other an accelerating climb. Given the differences in the two departures, the authors felt trying to segregate which performance parameter is most useful for predicting departure noise would not yield meaningful results – with only two data points a curve can be drawn, but no indication of the precision of the data can be given.

9.1.2 Cruise comparison

The flight test included four cruise modes, each run at a different nominal airspeed. For our analyses, we also include the OGE hover, since that dataset represents the lower boundary of the cruise data, for a total of five data sets. Figure 10 below shows the cruise airspeed and power relationship. We note that the horsepower shown here was taken from the cockpit measurements; these power data are *not* from the performance methods discussed in this document.

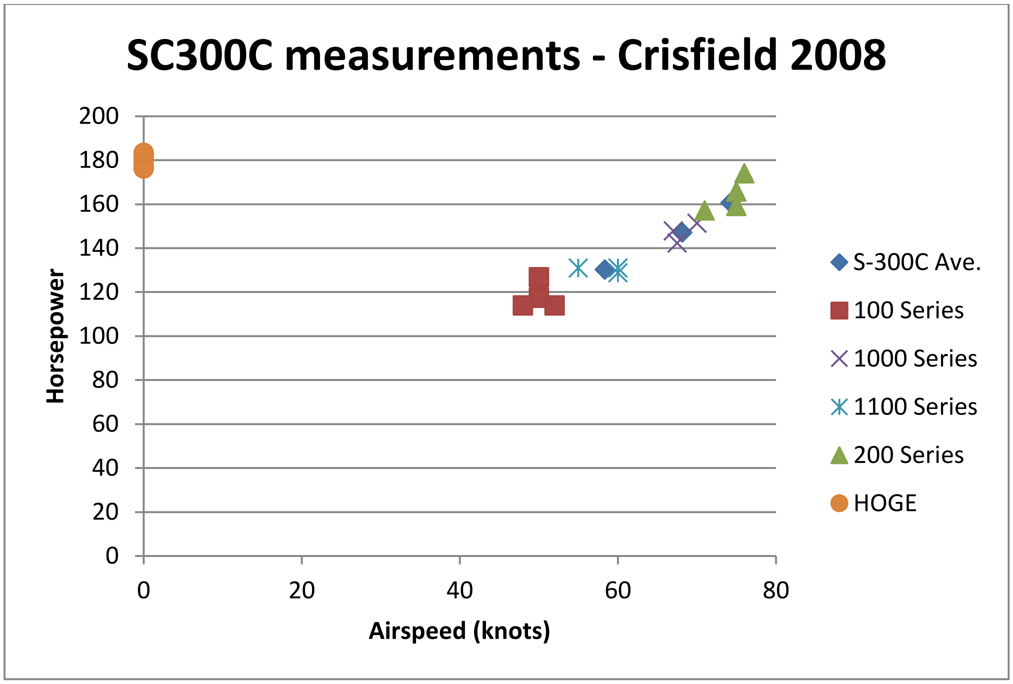

Figure 10, SC300C cruise airspeed and power

The data shown in Figure 10 also includes the average of the data from each series. These average values are used in the following graphics. The definition and data for the S-300C flight test series can be found in Appendix A.

The following figures show the correlation of the L_{max} noise metric with the particular performance metric. We use the L_{max} metric to avoid possible issues with speed effects in the integrated metrics, such as SEL.

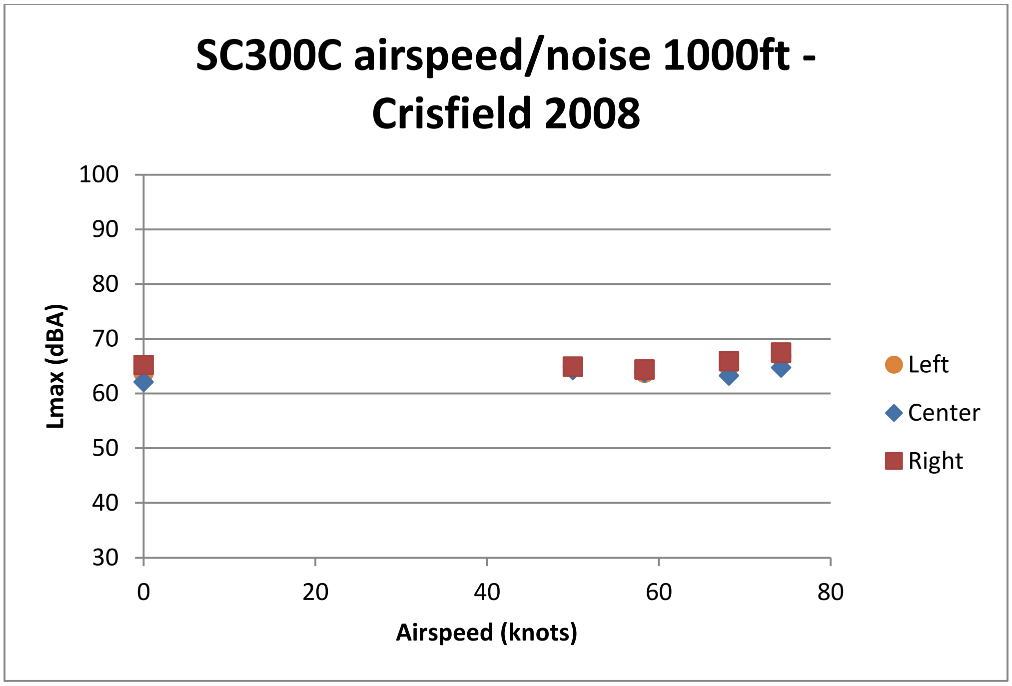

Figure 11, S-300C level flight noise as a function of airspeed, 1000 feet distance

Figure 11 above shows the AEDT-modeled, unaccelerated, level flight (cruise) noise for the SC300C is relatively flat with respect to the airspeed. That is, the maximum noise level is not greatly influenced by how fast the helicopter is flying. The SC300C is not a particularly fast helicopter, so the increase in the blade tip Mach number will not be greatly changed by the helicopter's forward speed. The Mach factor defined in the SAE standard for helicopter noise estimation (A-21 Committee, 1989) for this helicopter is about 2.0 – indicating a relatively low dependence on the blade tip speed. The predicted changed in L_{MAX} from the increase in cruise speed from 50 to 80 knots using the methods of SAE-ARP-1989 is 0.7 dB.

Note that the data points represent the noise data at a slant distance on 1000 feet, and the data from the left, center, and right side of the helicopter – as found in the AEDT database – show little variation from side to side. This lack of lateral variation would also correlate with the advancing and retreating blades not exhibiting large acoustic differences due to the low forward speed of the helicopter. We note that the Hover data is based on the HOGE NPD with the given directivity (±90 degrees from the helicopter's nose).

Figure 12 below shows the same data as Figure 11, but plotted as a function of the engine power. Note that for this helicopter, the hover condition demands the greatest required power. The correlation of increasing power generating increasing noise (even if a slight correlation) breaks down at the highest power setting (hover). For this helicopter, the airspeed provides a better (more linear) predictor of cruise noise than the engine power setting, though with the small change in noise levels, the dependence itself is small.

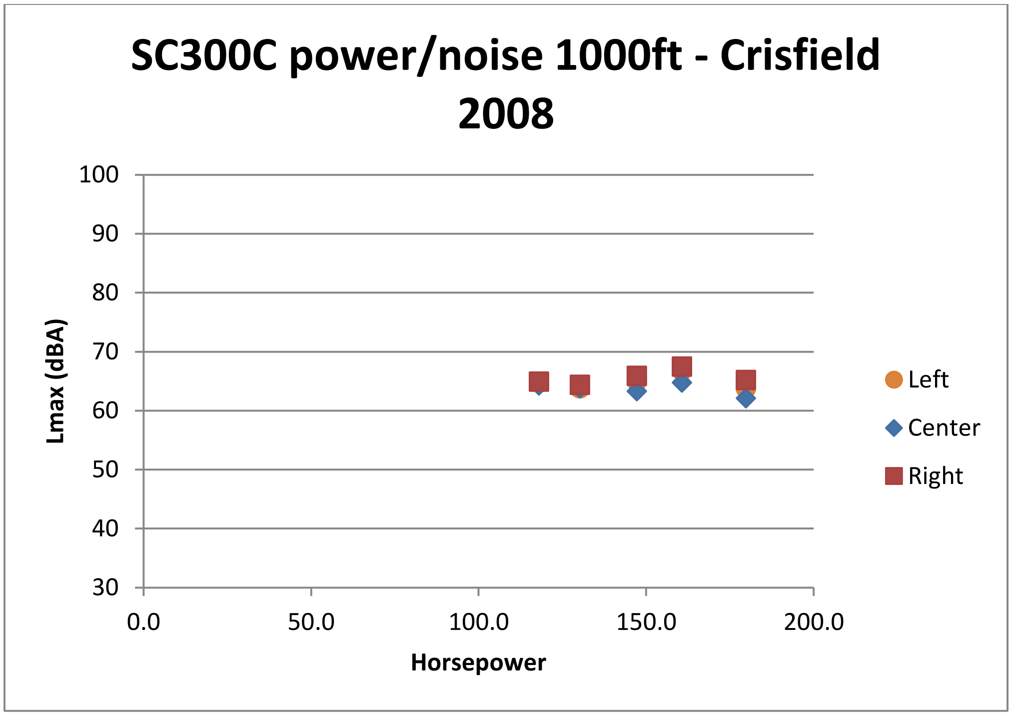

Figure 12, S-300C noise as a function of engine power, 1000 feet distance

9.2 Bell 407

The Bell 407 noise data was also collected during the Crisfield noise measurement tests. The performance data collected during the test are presented in Appendix B below. The noise data are available in the Crisfield report (Lau, 2010). Note that Bell Helicopters provided Bell 407 NPD data for the INM and AEDT after these data were collected at Crisfield. In this section, we use the data from Crisfield, since that is also the source of the helicopter performance data.

9.2.1 Departure comparison

As with the SC300C, the Bell 407 flew two separate departures series; one series used a constant speed climb, the other used an accelerating climb. The differences in these two series prevent a meaningful analysis of their data, and so are not included here.

9.2.2 Cruise comparison

The Bell 407 flight test included four cruise modes, each run at a different nominal airspeed. We note that 200 series only included a single data point where the speed was recorded. For our analyses, we also include the OGE hover, since that dataset represents the lower boundary of the cruise data. Figure 13 below shows the Bell 407 cruise airspeed and power relationship. We note that the horsepower shown here was calculated from the cockpit measurements; these power data are *not* from the RPM. The definition of the Bell 407 series, and the data for the series, can be found in Appendix B.

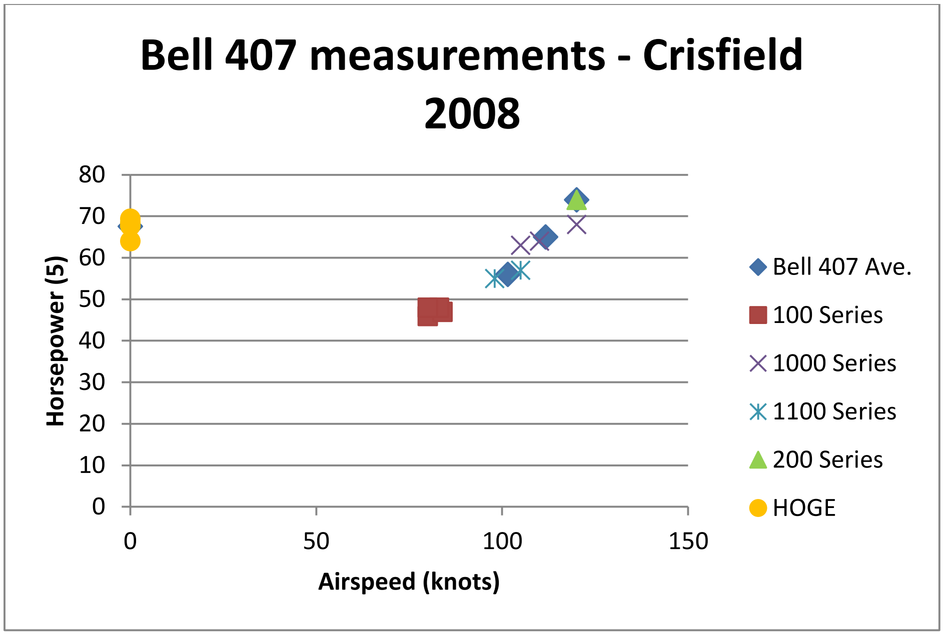

Figure 13, Bell 407 cruise airspeed and power

Figure 14 below shows the noise, unlike that of the SC300C, shows a slight trend of increasing noise with increasing cruise airspeed. That is, the noise levels for the non-hover series appear influenced by how fast the helicopter is flying. We note that the B407 is a faster helicopter than the SC300C, so the increase in the blade tip Mach number may be more influenced by the helicopter's forward speed. The SAE Mach factor for this helicopter is about 4.8 at high forward speed – significantly higher than the SC300C's 2.0. The predicted changed in L_{MAX} from the increase in cruise speed from 80 to 120 knots using the methods of SAE-ARP-1989 is 1.9 dB. Also unlike the SC300C, the Bell 407 noise data show variation from the left, center, and right side of the helicopter. This lateral variation may also correlate with the advancing and retreating blades exhibiting greater acoustic differences due to the forward speed of the helicopter.

Figure 15 below shows the same data as Figure 14, but the noise data are plotted as a function of the engine power. For the B407, the hover condition does not demand the greatest required power. The correlation of increasing power generating increasing noise (even if a slight correlation) is not significantly affected by the hover series. For this helicopter, either airspeed or engine power appears to provide a reasonable predictor of cruise noise.

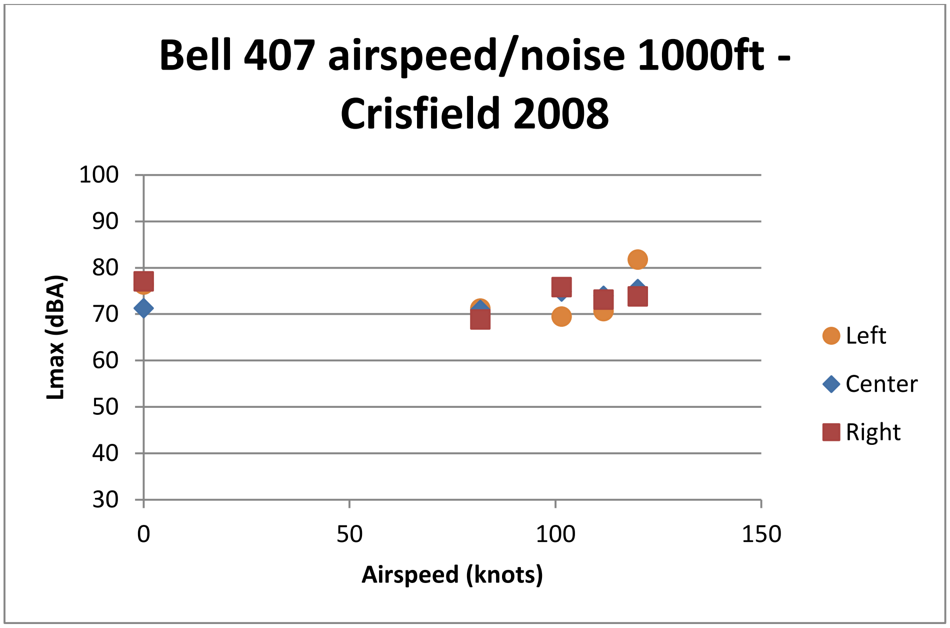

Figure 14, Bell 407 noise as a function of airspeed, 1000 feet distance

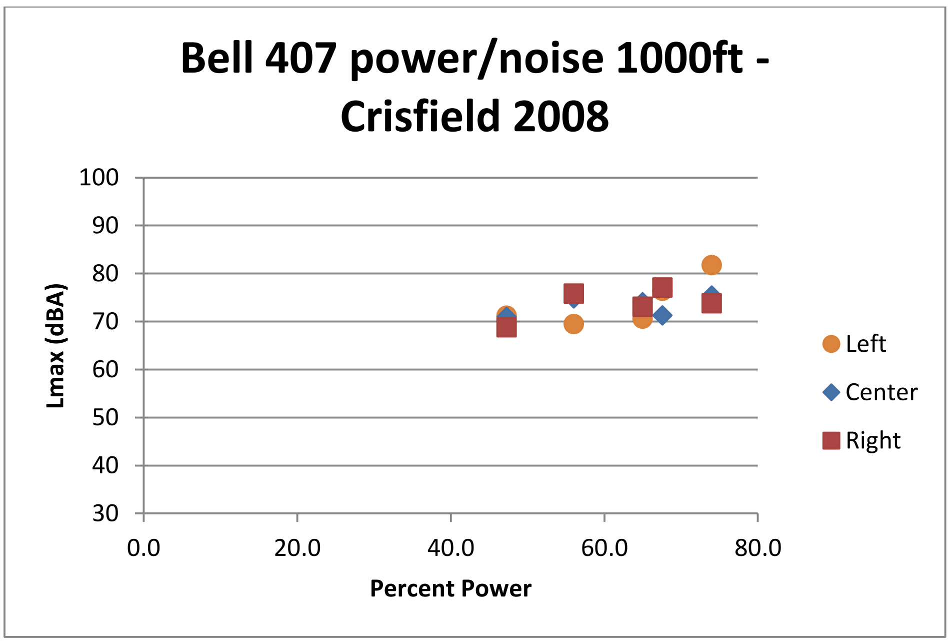

Figure 15, Bell 407 noise as a function of engine power, 1000 feet distance

10. Trajectory modeling

Trajectory modeling is the process of modeling an aircraft operation from the helipad departure, through cruise flight, then back down to the arrival helipad. Trajectory modeling is a requirement when modeling complete operations within a metroplex area, as opposed to the terminal operation modeling which is sufficient when modeling a single heliport. An example of the need for this type of modeling ability is the Long Island, New York airspace, where terminal operations occur in the New York City area, those operations then over-fly Long Island, and the other terminal operations may potentially occur at heliports or airports on the east end of Long Island. We note that this functionality is not available in AEDT 2b for helicopters, though overflights themselves can be modeled (Volpe Center, 2012).

The RPM trajectories are assumed to contain the departure and the arrival helipad. The airspeed and altitude information in the trajectory are ignored for the individual trajectory points; only the maximum altitude and maximum airspeed used from the trajectory file to define the cruise altitude and airspeed of the trajectory modeling. Note that the method of using the full position vector is discussed in section 11 below

10.1 Terminal departure procedures

The terminal departures used in the trajectory model are identical to the standard departure profiles in AEDT as discussed in section 8, with the exception that the final level segment is removed. In terminal modeling, this final level segment serves to move the helicopter far enough away from the heliport that the noise of the helicopter is no longer a concern. In trajectory modeling, every track segment has equal impact, so we drop this 'fudge-factor' final segment and replace it with an en-route climb procedure as discussed below.

10.2 En-route climb procedures

The en-route climb procedure is the transition between the standard terminal departure and the cruise segment. The departure climb is a two-step process: the first step is a constant airspeed climb to the final cruise altitude, followed by a level segment acceleration to the final cruise speed. The current implementation assumes fixed distances for these two segments, this can be changed in the AEDT implementation version to distances which are calculated from the power available.

10.3 Cruise procedures

The trajectory cruise procedures are based on the level segments which begin and end the standard arrival and departure terminal procedures. A major difference from the terminal procedures is that the cruise segment distance must include a known length and can't overshoot the given trajectory. To do this, the lengths of the en-route descent procedure and the terminal arrival procedure must be known so that distance can be subtracted from the distance remaining to end of the trajectory file. In practice, this means the arrival procedure distances are calculated before the cruise segment begins.

10.4 En-route descent procedures

The en-route descent currently assumes a known descent angle, which is passed to the program through an input file. The known descent angle and the known distance between the cruise altitude and the final altitude allows for the calculation of a distance over which this change will occur. RPM use the decelerating descent procedures for the en-route descent so that any speed change is also picked up correctly.

10.5 Terminal arrival procedures

As with the terminal departure procedures, the trajectory terminal arrival procedures are similar to the AEDT standard arrival procedures with the exception that the initial level segment is removed and replaced with the en-route arrival procedure discussed above.

10.5.1 New flight path procedure steps

Two new procedure steps are required for improved noise modeling. One is a constant airspeed approach at a defined angle; the other is a decelerating approach at a constant angle. These proposed procedure steps are defined by their descent angle. The assumption is that AEDT should force these procedure step angles to match the NPD data through a limited set of angles provided by the program. With this enforcement, AEDT will have no need to interpolate the NPD approach data. We could relax this enforcement if a method of added BVI approach noise could be added to the existing NPD data.

11. Sensor path modeling

We define sensor path modeling as the ability to generate helicopter power required data (and the associated fuel flow data) from the full state vector of the helicopter via the TEM equation presented in section 5. That is, given the change in the potential and kinetic energies between any two points in a trajectory, if we know the weight of the helicopter and the time required to move between the two points, we can find the power required to make the change between the points.

The current version of RPM has the capability to model sensor path trajectories. This was the method used in section 8.3 above to model the fuel consumption for the two helicopter types for which we have FDR data. While the general methods of using the TEM equation work well for the en-route parts of the flights, the terminal regions may require use of the standard methods to transition from the ground to the en-route segments when full flight path information is not known (e.g. radar data where the first radar return is when the helicopter is already in flight). These sensor path terminal transition methods are discussed below.

11.1 Sensor path translation

The sensor path format for the helicopter validation was the FDR information collected from each of 100 flights for the two helicopters. These data were given to the Volpe Center in text format. This text format included latitude-longitude position data, indicated airspeed, pressure altitude, engine torque percentage, and fuel flow as the primary state data. Note that the data did not include vehicle weight, ambient temperature, or ambient pressure data.

We translated the proprietary FDR data into a more generic data format which contains all the state vector information required for the TEM equation. This included using an assumption of ISA weather conditions for the ambient temperature and pressure, and MTOW less the difference between the maximum fuel weight of the helicopter and the FDR reported fuel on board for the take-off weight. Note that we used the reported fuel on board for each flight at the point prior to takeoff when the torque setting was advanced to flight idle; we did this because long idle pre-flight times (and hence significant ground operation fuel consumption) for some helicopter operations produced errors when the initial fuel weight at the start of engines was used.

In addition to noting when the engines where advanced to flight idle torque settings, we also added true airspeed and ground speed to the sensor path vector using the ISA and no wind assumptions. We also flagged each node as being on the ground or in the air, and, if in the air, the helicopter’s change in true airspeed and altitude from the prior sensor path node. These in-the-air state changes were used as input into the TEM equation.

12. Next steps

This section discusses the next steps in implementing the RPM in AEDT and further improving the helicopter performance methods discussed in this document.

12.1 Inclusion in AEDT

The authors believe the helicopter performance methods discussed in this documents have sufficient technical merit to begin the process of including the methods in AEDT.

12.1.1 Code Translation

Implementation of RPM will involve translating the current Fortran 90 version of RPM used for development into C#. Note that for those helicopters which did not have flight manual performance data available, the current methods of modeling performance with mode-based methods will need to be retained. This issue is discussed in more detail in section 12.2 below. Validation of the code translation can be done with the existing FDR data.

12.1.2 Database development

The input data for RPM currently exists as ASCII text files. These data files will need to be translated to SQL tables for inclusion in the AEDT FLEET database. While some of these translations will be straightforward, others, such as the C_TC_P tabular data, will not. As mentioned in the report previously, the μ data in the C_TC_P tabular data will vary by helicopter type, so the SQL tables need to be designed to handle different levels of detail in the C_TC_P tabular data.

12.2 Expansion of database

The methods used in this document have been developed for five helicopters. Concurrent with the effort to include the RPM in AEDT, we believe an expansion of the database to include helicopters of primary value to the AEDT user community is warranted. For example, the Robinson R-44 is the most popular helicopter in the world by current registration numbers, but can't be modeled with these methods since the required performance data are not available in the flight manual. While performance data associated with all helicopters in the AEDT database would be optimal, we believe focusing on those helicopters of most value to the AEDT user community should receive the initial effort.

12.2.1 Use of NDARC to expand the fleet

Volpe staff have access to NDARC, the high fidelity helicopter performance tool developed by NASA (Johnson, 2009). This program can potentially be used develop performance data for those helicopters for which the required performance data either does not exist or can't be located.

12.3 Improvements to the methods

The RPM methods have been showed in the validation effort to produce reasonable results compared to the FDR data. While the results are reasonable, they are not perfect: the modeled power trends show slight differences at low and high speeds, and the calculated fuel consumption for one of the helicopters with FDR data shows more variance than we expect (though much of this difference is explainable). FAA and Volpe should continue efforts to improve the method through both improved methods and access to higher quality data.

12.3.1 Use of NDARC to improve RPM methods

As with the use of NDARC to expand the helicopter fleet, we can also use NDARC as a tool to vet aspects of RPM which we know have weakness, such as the simplistic assumption of no losses in the engine power-to-thrust translation. RPM also uses a simplistic turboshaft engine performance model. Both these and other issues can potentially be quantified, and possibly corrected, with a high fidelity performance tool, such as NDARC.

12.4 Incorporation of ACRP 02-44 findings

The RPM methods meet the soft requirement stated at the beginning of this document to provide the same fidelity of noise modeling as the current AEDT methods. That requirement is met by using the same mode-based look-up into the existing NPD tables as the current AEDT methods. These methods could potentially be improved by using the helicopter state information provided by RPM. In particular, the engine power and trajectory information provided by RPM could potentially be inputs to the improvements to noise helicopter noise proposed in ACRP 02-44.

12.5 Expansion of procedure methods

As discussed in section 8, all the current standard procedures in AEDT use the same parameters for acceleration/deceleration and climb/descent distance. These procedures should be replaced with procedures that are a function of the actual environmental conditions at the time of the operation, the physically characteristics of the helicopter, and the piloting methods used. This would align helicopter modeling with the fixed-wing methods, and would provide users with the ability to adjudicate the environmental consequences of different operational procedures

12.6 Expansion of methods to different rotorcraft

The RPM methods have been developed to work with conventional helicopters. The methods are based on an energy balance which is not constrained by the vehicle type (i.e. the method is used for both fixed and rotary wing aircraft), but the data and methods to apply this energy balance to new vehicle types do not currently exist.

13. References

A-21 Committee. (1986). *Procedure for the calculation of airplane noise in the vicinity of airports.* Warrendale, PA: SAE.

A-21 Committee. (1989). *Helicopter External Noise Estimation.* Warrendale, PA: SAE.

Bailey, F. (1941). *A simplified theoretical method of determining the characteristics of a lifting rotor in forward flight.* Langley, Virginia: National Advisory Committee for Aeronautics.

EUROCONTROL Experimental Centre. (2011). *User manual for the Base of Aircraft Data.* Sur de Orge: European Organisatoin for the Safety of Air Navigation.

FAA. (2007). *Integrated Noise Model (INM) Version 7.0 User's Guide.* Washington, DC.

Fleming, G. e. (1994). *Heliport Noise Model Version 2.2.* Washington, D.C.: Federal Aviation Administration.

Gessow, A. a. (1985). *Aerodynamics of the Helicopter.* New York: Fredrick Ungar Publishing Co.

Glauert, H. (1926). *A general theory of the Autogiro.* British Aeronautical Research Committee.

Haagsma, A., & van Veggel, E. (2011). *Helicopter Fuel Burn Modeling in AEDT.* U.S. Department of Transporation, Volpe National Transportation Systems Center, Cambridge, MA.

Johnson, W. (1994). *Helicopter Theory.* New York: Dover.

Johnson, W. (2009). *NASA Design and Analysis of Rotorcraft.* Moffett Field: NASA Ames.

Kim, K. C. (1999). *Analytical calculations of helicopter torque coefficient (CQ) and thrust coefficient (CT) values for the Helicopter Performance (HELPE) model.* Aberdeen Proving Ground, Maryland: U.S. Army Research Laboratory.

Kiwan, A. (1994). *Helicopter Performance Evaluation (HELPE) Computer Model.* Aberdeen Proving Ground, Maryland: U.S. Army Reserch Laboratory.

Koopmann, B. A. (2012). *Aviation Environmental Design Tool (AEDT) 2a.* Cambridge, MA: Volpe National Transportation Systems Center.

Koopmann, J., et al. (2015). *Aviation Environmental Design Tool (AEDT) 2b User Guide.* Washington, DC: Federal Aviation Administration.

Lau, S. B. (2010). *Aircraft Source Noise Measurement Studies.* Cambridge, MA: Volpe National Transportation Systems Center.

Newman, J. S., Rickley, E. J., & Ford, D. W. (1981). *Helicopter Noise Definition Report.* Washington, D.C.: U.S. Department of Transportation.

Newman, J. S., Rickley, E. J., Bland, T. L., & Beattie, K. R. (1984). *Noise Measurement Flight Test: Data/Analyses.* Washington, D.C.: U.S. Department of Transportation.

Nuic, A., & Mouillet, V. (2012). *User Manual for the Base of Aircraft Data (BADA) Family 4.* EEC Technical/Scientific Report, EUROCONTROL Experimental Centre, Bretigny-sur-Orge, France.

Patterson, J. N. (2009). Analysis of departure and arrival Profiles using real-time aircraft data. *J. Aircraft*, Vol. 46, Num 4, pp 1094-1103.

Reherman, C. R. (2005). *Fitchburg Municipal Airport Noise Measurement Study: Summary of Measurements, Data, and Analysis.* DOT-VNTSC-FAA-03-09.

Rickley, E. J., Jones, K. E., Keller, A. S., & Fleming, G. G. (1993). *Noise Measuremnt Flight Test of Five Light Helicopters.* Washington, D.C.: U.S. Department of Transportation.

Senzig, D. A., & Cumper, J. (2013). *Fuel Consumption of ADS-B and non-ADS-B Helicopter Operations in the Gulf of Mexico.* Cambridge, MA: Volpe Center.

Senzig, D. A., Fleming, G. G., & Iovinelli, R. J. (2009, July-August). Modeling of Terminal-Area Airplane Fuel Consumption. *Journal of Aircraft, 46*(4), 1089-1093.

Stepniewski, W. K. (1984). *Rotary-Wing Aerodynamics.* New York: Dover.

The New York North Shore Helicopter Route. (2012, July 6). *Federal Register*, pp. Vol. 77, No. 130, pp 39911-339921.

Volpe Center. (2012). *Long Island north shore helicopter route environmental study.* Washington DC: FAA Office of Environment and Energy. Retrieved from http://ntlsearch.bts.gov/tris/record/ntl/51023.html

Appendix A: Schweizer S-300C Flight Test Data

This appendix contains the Schweizer S-300C performance data from the noise flight test conducted at Crisfield airport in 2008. The corresponding noise test data can be found in the original report (Lau, 2010).

Table 15, S-300C Static Operations

Operation	Series	Engine RPM	Engine MAP (in-Hg)
Ground Idle	2400	2000	11.5
Flight Idle	2300	3200	15
HIGE	2100	3200	24.5
HOGE	2200	3200	25.5

Table 16, S-300C Flight Operations - Cruise

Operation	Event ID	Engine RPM	Engine MAP (in-Hg)	KIAS
Cruise	1010	3100	23	67
Cruise	1020	3100	22.5	68
Cruise	1030	3100	23.3	70
Cruise	1110	3100	21.5	55
Cruise	1120	3100	21.5	60
Cruise	1130	3150	21	60
Tour Cruise	110	3120	21	50
Tour Cruise	120	3150	20	50
Tour Cruise	130	3100	20	48
Tour Cruise	140	3100	20	52
High Cruise	210	3150	23.5	71
High Cruise	220	3100	24	75
High Cruise	230	3080	24.7	75
High Cruise	240	3200	25	76

Table 17, S-300C Flight Operations - Approach

Operation	Event ID	Engine RPM	Engine MAP (in-Hg)	KIAS
Approach – 3 deg	710	3130	21.5	60
Approach – 3 deg	720	3100	19.5	64
Approach – 3 deg	730	3100	19	59
Approach – 3 deg	740	3130	21	61
Approach – 9 deg	810	3100	15	62
Approach – 9 deg	820	3100	15	60
Approach – 9 deg	830	3100	15	60
Approach – 9 deg	840	3100	14	60
Approach – 6 deg	520	3200	18.5	61
Approach – 6 deg	530	3200	18.5	62
Approach – 6 deg	540	3200	18.5	61
App-Decel – 6deg	610	3200	18	38
App-Decel – 6deg	620	3180	17	60-35
App-Decel – 6deg	630	3150	15.5	57-40
App-Decel – 6deg	640	3180	16.5	52-39

Table 18, S-300C Flight Operations - Departure

Operation	Event ID	Engine RPM	Engine MAP (in-Hg)	KIAS
Departure	310	3100	21	43
Departure	320	3150	26	40
Departure	330	3100	26	43
Departure	340	3150	25	40
Departure	350	3180	26	-
Departure - Accel	410	3100	25.5	56
Departure - Accel	420	3100	25	55
Departure - Accel	430	3100	25	30-45
Departure - Accel	440	3100	26	27-43
Departure - Accel	450	3100	26	27-41

Appendix B: Bell 407 Flight Test Data

This appendix contains the Bell 407 performance data from the noise flight test conducted at Crisfield airport in 2008. The corresponding noise test can be found in the original report (Lau, 2010).

Table 19, Bell 407 Static Operations

Operation	Series	% Torque	% RPM
Ground Idle	2400	10.3	62.8
Flight Idle	2300	29	84.4
HIGE	2100	69.5	94.5
HOGE	2200	67.7	94.6

Table 20, Bell 407 Flight Operations - Cruise

Operation	Event ID	% Torque	KIAS
Cruise	1010	68	120
Cruise	1020	64	110
Cruise	1030	63	105
Cruise	1110	55	98
Cruise	1120	57	105
Tour Cruise	100	46	80
Tour Cruise	110	47	84
Tour Cruise	120	48	83
Tour Cruise	130	48	80
High Cruise	210	75	-
High Cruise	220	74	120
High Cruise	230	73	-

Table 21, Bell 407 Flight Operations - Approach

Operation	Event ID	% Torque	KIAS
Approach – 3 deg	710	38	60
Approach – 3 deg	720	40	45
Approach – 3 deg	730	33	60
Approach – 3 deg	750	32	65
Approach – 9 deg	810	33	42
Approach – 9 deg	820	38	38
Approach – 9 deg	830	30	39
Approach – 6 deg	510	35	60
Approach – 6 deg	530	47	-
Approach – 6 deg	540	30	-
Approach – 6 deg	550	34	55
Approach – 12 deg	910	47	25
Approach – 12 deg	920	36	28.5

Table 22, Bell 407 Flight Operations - Departure

Operation	Event ID	% Torque	ROC (feet/minute)	KIAS
Departure	310	85	400	-
Departure	320	89	400	69
Departure	330	-	-	-
Departure	340	85	1200	-
Departure - Accel	410	85	1100	-
Departure - Accel	420	87	900	-
Departure - Accel	430	85	1000	-
Departure - Accel	440	83	1300	-

U.S. Department of Transportation
John A. Volpe National Transportation Systems Center
55 Broadway
Cambridge, MA 02142-1093

617-494-2000
www.volpe.dot.gov

DOT- VNTSC-FAA-16-03