THE ENVIRONMENTAL DESIGN SPACE

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Abstract

The U.S. Federal Aviation Administration Office of Environment and Energy, in collaboration with Transport Canada and the National Aeronautics and Space Administration, is developing a comprehensive suite of software tools that will allow for thorough assessment of the environmental effects of aviation. The main goal of the effort is to develop a new, critically needed capability to assess the interdependencies among aviation related noise, emissions, and associated environmental impact and cost valuations, including cost-benefit analyses. The building block of this suite of software tools that provides an integrated analysis of noise and emissions at the aircraft level is the Environmental Design Space (EDS). The EDS concept was formally introduced to the sixth meeting of the Committee for Aviation Environmental Protection in February 2004, in Montreal, Canada. This paper will provide an overview of the EDS program and its capabilities for capturing environmental interdependencies.

1.0 Motivation

At the Committee for Aviation Environmental Protection 6th meeting (CAEP/6) in 2004, participants recognized that to achieve effective noise and emissions mitigation requires consideration of interdependencies between noise and emissions and amongst emissions. CAEP/6 recommended, and the International Civil Aviation Organization's (ICAO) 35th Assembly subsequently adopted, three environmental goals: to limit or reduce noise exposure, local air quality emissions, and greenhouse gas emissions. Analytical tools and supporting databases that could account for interdependencies amongst these goals and potentially optimize the environmental benefit of mitigation measures would greatly facilitate and enhance progress toward these goals.

In assessing the scope of future analytical tools, it is important to consider the potential decisions that policy makers are likely to face. The complexity of decisions has increased over time as the remit of CAEP has gone from a primary concentration on standard setting applied to aircraft, to providing policy advice on operational issues and consideration of potential market-based options to reduce the environmental impact of aviation. In seeking to meet the ICAO goals, CAEP may consider in a future work program more stringent environmental standards, new emissions standards, technological advancements, and elements of the balanced approach (which includes identification of noise sources at an airport and methods for mitigation such as land-use planning).

Existing aircraft noise and aviation emissions analytical tools used by CAEP cannot effectively assess interdependencies between noise and emissions, or analyze the cost-benefit of proposed actions. Accordingly, the Federal Aviation Administration's Office of Environment and Energy (FAA/AEE) is developing a comprehensive suite of software tools that will allow for the thorough assessment of the environmental effects of aviation. Transport Canada (TC) and the National Aeronautics and Space Administration (NASA) are collaborating with the FAA in those elements of the development effort undertaken by the Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER) Center of Excellence. The main goal of the effort is to develop a new capability to assess the interdependencies between aviation-related noise, fuel burn, and emissions effects, and to provide comprehensive cost and benefit analyses of aviation environmental policy options in an open, transparent, traceable, and flexible manner. The FAA/NASA/TC tool suite is illustrated below. The building block of this suite of software tools that will provide an integrated analysis of noise and emissions at the aircraft level is the Environmental Design Space (EDS).

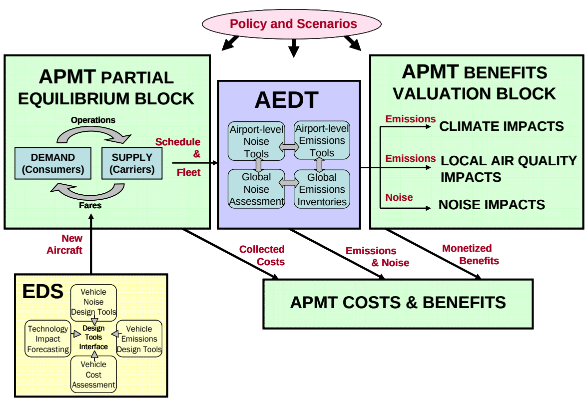

Fig. 1: FAA Tool Suite

EDS provides the capability to estimate source noise, exhaust emissions, performance, and economic parameters for potential future aircraft designs under different policy and technological scenarios. The capability will allow for assessments of interdependencies at the aircraft level. In addition, an integrated tools suite including EDS, the Aviation Environmental Portfolio Management Tool (APMT) and the Aviation Environmental Design Tool (AEDT), will be able to assess operational, policy, and market scenarios of the entire aircraft fleet. While the primary focus of EDS is future aircraft designs (which includes technology modifications to existing aircraft), the tool is capable of analyzing existing aircraft designs (current technology levels) under different scenarios, including the simulation of existing aircraft with higher fidelity than is possible using existing noise and emissions tools and inventories. Capturing high-level technology trends provides a capability for assessment of benefits and impacts for the Next Generation Air Transportation System (NextGen) and long term technology planning and goal assessments for both CAEP and FAA.

2.0 EDS Objectives

The primary objective is to design, develop, implement, and assess an Environmental Design Space (EDS) — a numerical simulation based on physics rather than expert opinion or inventory analysis that is capable of estimating source noise, exhaust emissions, performance and economic parameters for potential future aircraft designs under different technological, operational, policy, and market scenarios. EDS development is a five year effort, initiated in 2005, that could provide both NextGen and CAEP analysis support, while training the next generation engineers.

NextGen Support. Given a projected two- to three-fold increase in demand on the air transportation system by 2025, a need exists to assess changing requirements, potential fundamental changes in the nature of the system, and an increased importance of environmental quality. Expanded airport capacities will lead to more aircraft/engine sales for industry, which must be developed in accordance with more stringent future noise and emissions standards. The FAA tool suite could provide the vehicle, fleet and portfolio assessment capability necessary to address the environmental factors and potential system constraints in an integrated transparent manner for NextGen analysis. Specifically, EDS can be utilized in this process to help predict the characteristics of the 2025 fleet, which will include the impacts of technologies in development today and potential new vehicles that may enter into service within that time frame. Industry and the appropriate Joint Planning and Development Office (JPDO) committees' involvement will ensure that specific technologies and general trends of technology metrics are modeled accurately and reflect a reasonable timeframe, cost, risk, and difficulty level.

CAEP Stringency Analysis. It is envisaged that CAEP will evaluate the EDS concept, among others, to determine what capability could support CAEP in the assessment of the prospects for further reductions of airplane noise levels and exhaust emissions standards, taking into account technological feasibility, economic reasonableness, and environmental effectiveness, noting also environmental interrelationships and tradeoffs.

Educating the Next Generation Engineer. During the EDS program, the development team will identify and address significant research challenges, make intellectual contributions and educate students for success and leadership in the conception, design, implementation, and operation of aerospace and related engineering systems.

3.0 Evolution and Requirements Definition

As a result of the CAEP/6 acknowledgement of interdependencies, a committee was formed by the Transportation Research Board (TRB) of the National Academies to gather input from all relevant stakeholders regarding the FAA's initiative to develop a comprehensive tool suite for an integrated assessment of noise and emissions impacts associated with aviation. An outcome of the workshops included the functional requirements of each tool (EDS, AEDT, and AMPT) [1, 2, 3]. The committee recommended that physics drive the environmental trade-offs and associated interdependencies and there was a need to understand interdependencies in EDS for existing and future classes of vehicles. Emphasis was not on designing aircraft and engines, but on trends and correlations. Also, the analysis tools need to move beyond frozen technology inventories currently being used within CAEP. Thus, the primary recommendations to the EDS program were:

- Transparency: EDS should be open, available, and transparent in concept and execution
- Flexibility: EDS should have flexibility to adapt to and accept future modifications, be able to respond to changing future needs, and be able to access future technologies and new functionalities. It should also be modular and flexible, to allow users to incorporate other tools.
- Uncertainty: EDS should be able to manage uncertainties within its modeling capacity.
- Predictive: EDS should have a predictive capability as part of its functionality.
- Availability: EDS inputs must be nonproprietary.
- Coordination: EDS must be able to interface with the other FAA tools (AEDT and AMPT).
- Interaction: EDS should be developed with active stakeholder involvement
- Validation: EDS development process should include a validation plan that involves input from a variety of stakeholders by promoting industry collaboration and incorporating industry feedback

Subsequent to the TRB recommendations, the FAA initiated requirements and architecture studies to formulate a multi-year development program as depicted in Fig. 2. The trade-offs of the desired EDS functionality were considered in terms of transparency vs. complexity, practicality vs. thoroughness (spiral development), new methods vs. existing practices, and restrictions vs. accessibility of codes. In addition, consideration was given to leveraging work performed by FAA, NASA, and various universities that had a history of tool validation and assessment and were state of the art within the government.

Year	CAEP Cycle	EDS Deliverable
2005		EDS Requirements and Architecture Defined
2006		EDS v1 Capability Demonstration
2007	CAEP/7 Begin CAEP/8 Work Program	Update EDS Architecture to Multiple Point Design Complete 300 Pax Vehicle Support CAEP Sample Problem
2008		Complete 100-210 Pax and 50-99 Pax Vehicles Support NOx Stringency Analysis Begin Technology Forecasting
2009		Continue Development of Vehicle Library Continue Technology Forecasting
2010	CAEP/8	Complete Vehicle Library

Fig. 2: EDS Program Overview

3.0 EDS Program Overview

The EDS program has been focused on four themes to accomplish the desired capabilities and include development, assessment, application, and technology impact assessments; each of which will be described in more detail. To support NextGen and CAEP analysis, the expected products of EDS are a series of physics-based trade spaces which account for the interdependencies at the vehicle level across the eight CAEP/FAA seat classes. An example trade space is depicted in Fig. 3. In this context, a trade space is a surrogate model of a given engine/airframe architecture that will allow for a parametric exploration of the vehicle interdependencies. The surrogate models of noise, emissions, and performance, and the connectivity to APMT and AEDT will provide the "currency of communication" to the international community and the FAA stakeholders.

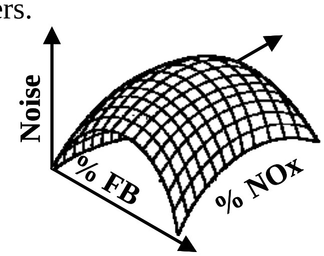

Fig. 3: Example EDS trade space

The manner in which a surrogate model is created within a vehicle class falls into three trade space categories. The first is a model of existing aircraft with the ability to apply current technology modifications, such as a combustor change. The second category is a current technology trade space that allows for changes to engine cycle parameters that are bounded by the limits of current technology (Technology Readiness Levels, TRL, of 8/9). Potential aircraft produced from the current technology trade space would be considered "new aircraft", but with current certified technology. Application of category 1 and 2 trade spaces could include CAEP stringency analysis. The third category trade space would produce potential future vehicles defined within trade spaces estimated assuming potential future technology with a mid- to long-term development focus (TRL3-7). Application of category 3 could include mid- to long-term goal setting and NextGen analysis support.

3.1 Theme 1: Development

The development of EDS has been focused on providing a common, transparent integrated capability of generating interrelationships between noise and emissions and amongst emissions at the vehicle level with the objective of providing technical information to support aviation environmental policy.

At the beginning of the program, functional analysis, architecture and data requirements studies were conducted. The two main drivers identified from the studies shaped the development efforts, specifically; the methods and assumptions must be non-proprietary and public domain and the data generated must be accessible to the international community to increase transparency and acceptance. In addition, the FAA did not want to create a tool from scratch, thus, research was leveraged from previous NASA systems studies conducted at Georgia Tech for the Vehicle Systems Program (VSP). The integrated analysis tools used for VSP were based on a number of different NASA tools and include the following.

Compressor Map Generation – Parametric Compressor Generator (CMPGEN) uses a handful of component design point inputs to develop appropriate maps of fans, boosters, and compressors with a backbone map of each component embedded into the program [4, 5].

Engine Cycle – Numerical Propulsion System Simulation (NPSS v1.6.4) models an engine cycle by analyzing the flow conditions through the engine components and balancing work requirements component-based object-oriented engine cycle simulator which performs cycle design and off-design performance analysis [6, 7].

Engine Flowpath – Weight Analysis of Turbine Engines (WATE++) is used to estimate the weight and dimensions of a gas turbine engine calculates the weight of engine components using physics-based calculations and semi-empirical curves for specific component elements [8, 9].

Aircraft Mission Analysis – FLight OPtimization System (FLOPS v 6.1.2) is a synthesis and sizing tool that evaluates an aircraft concept performance by flying the vehicle through a specified mission.

Noise – Aircraft Noise Prediction Program (ANOPP L25, version 3) predict the noise levels of aircraft by analyzing various noise sources of the engine and airframe. Engine cycle data may be imported so the program can adjust noise levels for different operating conditions noise sources may be flown on user-prescribed trajectories and propagated through an atmospheric model to evaluate the impact to observers [10, 11].

Emissions – Nitrous oxides are modeled with an empirical approach that relates the ICAO emissions databank to the compressor discharge pressure and temperature in the terminal area.

Environment Integration - The EDS environment is structured using the object-oriented coding base used to power NPSS. With this configuration, information can be passed between the component codes and the modules executed in an automated fashion. Since the original code on which EDS is based was created in a scripting language, EDS is formulated in a way which executes commands in an exact order and is depicted below.

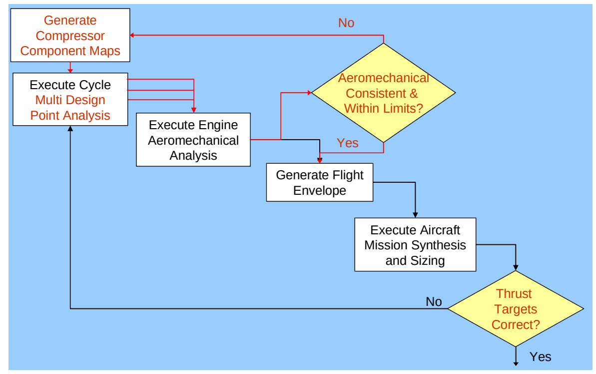

Fig. 4: Fundamental EDS Architecture

A major intellectual contribution of the EDS development has been a public version of the multi design point (MDP) approach for engine and airframe sizing. For most aerospace engineers during their education, a single deign point for sea level static conditions and fuel balance is taught with consideration given to off-design conditions as a constraint. This was also the approach taken by EDS in the first years of development. However, in the last two years of the EDS program, industry guidance through collaborative studies has pushed the design approach away from the single point design to the MDP approach. The MDP approach concurrently designs for thrust requirements at takeoff, top of climb, and a cruise condition of the vehicle, which results in more realistic engine and airframe designs and is indicative of manufacturers approach to design. A doctoral thesis describing this approach in detail is expected at the end of 2008. No other public entity is known to have this capability.

3.2 Theme 2: Assessment

An important part of the EDS program is assessment of the tools, architecture, and technology forecasting process. This assessment is critical for defining the appropriate level of fidelity as well as ensuring that EDS has that level of fidelity. The assessment is also critical for achieving the goal of international acceptance of the final EDS product. The assessment spans the five-year program and targets modeling assumptions, accuracy, and input assumptions. The key questions to be addressed are:

- What assessment metrics are appropriate for EDS, at both the module and the system level?
- What are the uncertainties associated with EDS?
- In terms of the assessment metrics, what are the program requirements in the near- and long-term, (i.e., what level of fidelity must be achieved?).
- What is an appropriate process to engage the broader community in assessment efforts?
- What is an appropriate process to communicate assessment outcomes to the broader community?

In addition, the assessment also has an important role to play throughout the EDS development theme, by providing detailed, quantitative guidance regarding EDS development needs. On an ongoing basis over the program duration, assessment efforts must also address the following questions:

- How good is EDS with respect to the assessment metrics, and what additional capability do they provide to the other FAA tools?
- What improvements are required in order for EDS to meet program requirements?

The primary focus of the assessment is to develop an understanding of the impact of input parameters on output response through a sensitivity analysis. The sensitivity analysis is essential in identifying uncertainties and errors that exist within the process, it will also aid in determining how the uncertainties and errors will impact other tools within the FAA suite. The identification of error and uncertainty defines the fidelity of the model and allows for the opportunity of recognizing areas of deficiency which must be improved upon.

The overarching assessment plan for the FAA/NASA/TC tool suite is centered on six specific questions formulated to capture all aspects of the tool analysis. These questions address the issues of uncertainty categorization and quantification, propagation of model inputs and the effect of model limits and assumptions on the module results. To address these issues a three step process was created consisting of the calibration process, sensitivity analysis and trade space exploration. The three steps allow for the calibration of existing systems, the determination and quantification of input and assumption sensitivities, and the exploration of environmental trades through the selection of potential vehicle designs. This process is described in detail by Barros et.al. [12].

One should note that the EDS assessment process is influenced by the framework and architecture of the system being modeled. The framework describes the engine/airframe relationships within a passenger seat class. For example, one framework might contain a single fixed airframe with multiple engines, while another might consist of two unique vehicles with no common qualities. The architecture describes the features of the analysis tools that are required to model a given engine or airframe. For example, the modeling of a dual-spool versus a triple-spool represents an architecture change. Due to differences between architectures and frameworks there is a need to maintain some area of distinction when describing the process and rules. The generic assessment process and set of design rules will be applicable across all passenger classes for which EDS generates vehicles; however, differences in frameworks and architectures will require slight modifications to the process and will be incorporated as needed.

The assessment process has been conducted for the 300 passenger design space, which contains a single airframe with two potential engine designs. A Boeing 777-200ER was modeled with both Pratt and Whitney 4090 and GE90-94B engines. The EDS representation of the GE90 family on the B777-200 ER is depicted in Fig. 5 for the current CAEP nitrous oxides (NOx) and noise standards.

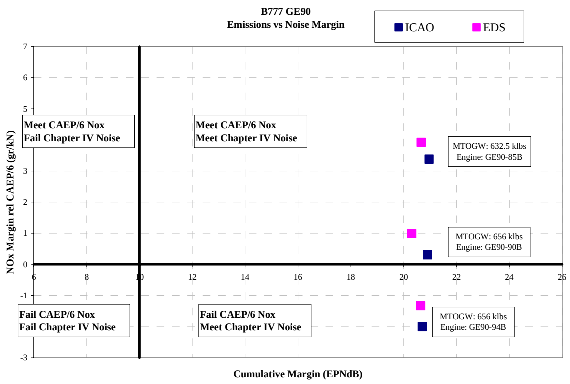

Fig. 5. EDS Predictive Capabilities Example (Preliminary for Illustration)

The main goal of the EDS assessment is to create a structured, repeatable process for benchmarking existing vehicles, and determining associated environmental trades for use within the framework of the FAA/NASA/TC tools suite while categorizing model fidelity through an error and uncertainty analysis. Towards this goal, the international community, including manufacturers, and operators, has been actively engaged through the creation of an Independent Review Group (IRG) that reviews the assumptions, design rules, and products of EDS trade spaces.

The EDS Development Team, led by the Georgia Institute of Technology and supported by the Massachusetts Institute of Technology and NASA, is working extensively with the IRG to develop a current technology trade space for a 300 passenger class vehicle. The IRG was formed from the EDS Technical Advisory Board (industry experts) and independent reviewers identified by different CAEP working groups. The EDS Team is working with the IRG to assess and validate the assumptions, methods, and data used to develop the 300 passenger trade space. At the last meeting of the IRG in December 2007, the IRG agreed that the trends produced by the EDS 300 passenger trade space were reasonable and representative of industry results. An example of the trends produced for the 300 passenger class vehicle is provided in Fig. 6 for a fan pressure ratio (FPR) and overall pressure ratio (OPR) investigation. Note that these trends are preliminary and are for illustrative purposes only.

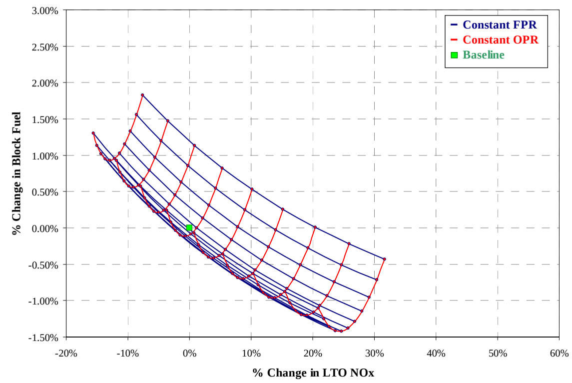

Fig. 6. Example of EDS-Generated Trends (Preliminary for Illustration)

3.3 Theme 3: Application

Throughout the EDS program, sample CAEP exercise problems progressing from simple problems to more complete policy analyses will be performed. Within the five-year program, the EDS tool will have the ability to fully support and address CAEP analysis goals. The development strategy is to demonstrate EDS capability via a phased approach of successively higher-fidelity integration with other aspects of the AEDT and APMT framework. The objectives of the EDS sample problems are:

- Provide a demonstration of the EDS toolset to the FAA and to the broader community (FAA, ICAO/CAEP, JPDO, and potentially others),
- Provide an assessment of the effectiveness of the EDS, AEDT, and APMT system at addressing policy questions and scenarios, and
- Establish EDS, AEDT, and APMT connectivity

At present, EDS has participated in two CAEP exercises. First, a capability demonstrator was conducted by the entire FAA tool suite in 2006. The focus of the demonstrator was to exercise connectivity amongst the tools; specifically, data passing, coordination, and results evaluation. Second, EDS participated in a CAEP NOx stringency sample problem in 2007. The focus of the problem was for CAEP to evaluate capabilities of the various international tools available for the CAEP/8 analysis. The approach and results were presented to working groups of CAEP in October 2007. At present, EDS is continuing the development of current technology trade spaces to support the U.S. position at CAEP/8 in 2010. The international use of EDS is still under evaluation by CAEP and will be determined in the coming years.

3.4 Theme 4: Technology Impact Assessment

The final theme in the EDS program is to serve as a mechanism for collecting, incorporating and quantifying long-term technology forecasts, which will be an expert-driven process drawing on industry advice and guidance. The technology impact assessments were phased into the program to focus the development efforts to CAEP applications and gaining international acceptance. Presently, EDS is engaging the NextGen's Joint Planning and Development Office (JPDO) to support technology and new vehicles concept assessments and the associated noise and emissions interdependencies.

There exist two avenues by which technologies may be infused into a system as depicted in Fig. 7. One is to look forward and ask the question: *With the specific technologies that are being developed, how will the end product compare to the design specifications of the future or compete with future systems?* This approach is an exploratory forecasting technique that considers current technology development trends and extrapolates into the future to predict what may happen [13]. An approach of this nature was created for specific technology assessments in aerospace systems and is called the Technology Metrics Assessment and Tracking (TMAT) process [14]. This approach may be leveraged with the current NASA Fundamental Aeronautics program to assess the impact of farther term technologies under development by NASA.

The other avenue is to look back in time from the future and ask the question: *What technology developments should be pursued to meet or exceed the design specifications or system requirements of the future?* This approach is a normative forecasting method that begins with future goals and works backward to identify the levels of performance or economics needed to obtain the desired goals, if at all achievable with the resources available. This approach was also formalized into a method for aerospace applications and is called the Strategic Technology Planning (STeP) process [15].

Both of these processes have been applied to various NASA Aeronautics programs in the last decade in addition to being adopted by industrial partners.

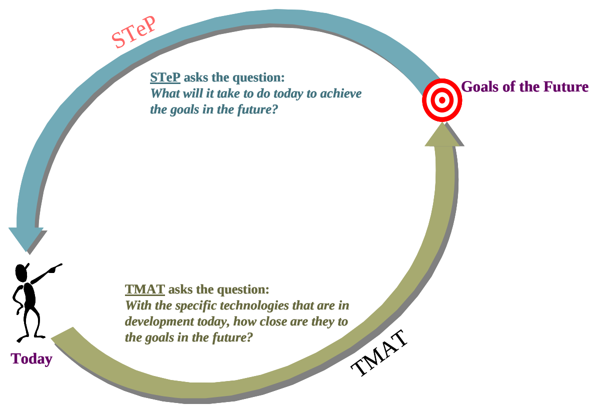

Fig. 7. Approaches for Technology Impact Assessments

EDS will focus the technology impact assessments to support NextGen analysis. Currently, the development team is coordinating with various JPDO committees, specifically, the Technology and Tools Standing Committees of the Environmental Working Group and the Systems Modeling and Analysis Division. Technology assessments have just been initiated and the specific support that EDS will provide is evolving.

4.0 Summary

FAA has made a commitment to use EDS to help establish trades among noise and emissions impacts in order to better quantify and manage the impacts associated with NextGen operations and CAEP. Significant advancements have been made in the last few years that produce results that are more representative of industry analysis tools, but provide an open and transparent means to communicate the impact of aviation. Industrial studies and benchmarking assessments through the Independent Review Group are ongoing and are viewed as essential to the success of this project.

As a result of the FAA initiative, the EDS Program may allow for more effective assessment and communication of environmental effects, interrelationships, and economic consequences in support of CAEP and NextGen. EDS may also serve as a platform for round table discussions with manufacturers about future technologies for both NextGen and CAEP which could lead to harmonization of methods, i.e., industry standard, for quantifying noise and emissions interrelationships. Ultimately, the program will provide a more 'transparent' process in model development leading to wide 'buy-in' from the international community.

6.0 Acknowledgements

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