NASA/Final Report for contract NNA08BA47C - 2010

Integration of Advanced Concepts and Vehicles Into the Next Generation Air Transportation System

Volume 1 – Introduction, Key Messages, and Vehicle Attributes

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February 2010

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FOREWORD

The final deliverable for Raytheon contract NNA08BA47C consists of an Executive Summary, eight volumes documenting the work effort and results performed under this contract, and a companion CD that contains the data used for modeling the operation of the new vehicles studied under this contract and the detailed results of our study of the impact the introduction of these vehicles on the NextGen Concept of Operations.

This volume contains an introduction to the final report, our key findings, and the description of vehicle attributes developed under task 1 of this contract. Appendix A identifies the Raytheon team that was assembled to work on this contract.

The key findings were the result of numerous discussions involving our entire team. Task 1 contributors were:

Herbert Resnick, Raytheon; David Bossert, Raytheon; Robbie Cowart, Gulfstream; Jawad Rachami, Wyle; Brian Kim, Wyle; Dan DeLaurentis, Purdue University; Vikram Manikonda, IAI; Yingchuan Zhang, IAI; Kyle Noth, Purdue University; and Megan Smirti Ryerson, University of California Berkley.

Mary Ellen Miller, Herb Resnick, Ed Stevens, and Andres Zellweger contributed to the production of this volume.

Special thanks go to:

Juan Alonso, Herb Schlickenmaier, and Karlin Toner, the Program Directors in the NASA Aeronautics Research Mission Directorate who conceived this NRA;

Phil Arcara, Nancy Mendonca, and Harry Swenson of NASA for their invaluable technical guidance and advice;

Craig Nickol, Jonathan Seidel, Jerry Smith, and Jeff Viken from NASA Langley for their information and insights on the new vehicle classes.

Amy Pritchett, NASA Airspace Safety Program Director, and Jeff Duven, FAA Seattle Aircraft Certification Office Manager, for their support and participation at the 1st Stakeholder Workshop Safety Panel.

Ralph Iovinelli from the FAA Office of Environment and Energy and Christopher Roof and Andrew Hansen of the Volpe National Transportation Systems Center for their insights into environmental analysis and updates of the AEDT model; and

Ed Waggoner of the JPDO for his advice and for making the subject matter expert walkthroughs of our operational scenarios possible.

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1 Introduction

1.1 Overview

Raytheon, in partnership with NASA, is leading the way in ensuring that the future air transportation continues to be a key driver of economic growth and stability and that this system provides an environmentally friendly, safe, and effective means of moving people and goods. A Raytheon-led team of industry and academic experts, under NASA contract NNA08BA47C, looked at the potential issues and impact of introducing four new classes of advanced aircraft into the next generation air transportation system — known as NextGen. The study will help determine where NASA should further invest in research to support the safe introduction of these new air vehicles. Small uncrewed or unmanned aerial systems (SUAS), super heavy transports (SHT) including hybrid wing body versions (HWB), very light jets (VLJ), and supersonic business jets (SSBJ) are the four classes of aircraft that we studied.

Understanding each vehicle's business purpose and strategy is critical to assessing the feasibility of new aircraft operations and their impact on NextGen's architecture. The Raytheon team used scenarios created by aviation experts that depict vehicles in year 2025 operations along with scripts *or use cases* to understand the issues presented by these new types of vehicles. The information was then mapped into the Joint Planning and Development Office's (JPDO's) Enterprise Architecture to show how the vehicles will fit into NextGen's Concept of Operations. The team also identified significant changes to the JPDO's Integrated Work Plan (IWP) to optimize the NextGen vision for these vehicles. Using a proven enterprise architecture approach and the JPDO's Joint Planning Environment (JPE) web site helped make the leap from architecture to planning efficient, manageable and achievable. [1-4]

Very Light Jets flying into busy hub airports … Supersonic Business Jets needing to climb and descend rapidly to achieve the necessary altitude … Super-heavy cargo planes requiring the shortest common flight path … are just a few of the potential new operations in the future National Airspace System.

To assess the impact of these new scenarios on overall national airspace operations, the Raytheon team used the capabilities of a suite of tools such as NASA's Airspace Concepts Evaluation System (ACES), the Flight Optimization System (FLOPS), FAA's Aviation Environmental Design Tool (AEDT), Intelligent Automations Kinematic Trajectory Generator (KTG) and the Aviation Safety Risk Model (ASRM). [5-9] Detailed metroplex modeling, surface delay models for super heavy transports, prioritized routing and corridors for supersonics business jets, and VLJ demand models are some of the models developed by the Raytheon team to study the effect of operating these new vehicles in the future NAS.

Using this suite of models, several trade studies were conducted to evaluate these effects in terms of delays, equity in access, safety, and the environment. Looking at the impact of each vehicle, a number of critical issues were identified. The Raytheon team concluded that strict compliance to NextGen's 4-dimensional trajectory (4DT) management will be required to accommodate these vehicles unique operations and increased number of flights in the future air space system.[1] The next section provides a discussion of this and the other key findings from our study.

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[1] 4D contracts are not rigid – they are renegotiated during a flight as necessary to account for uncertainties in the planning horizon.

1.2 Study Organization

The Raytheon study was divided into 8 tasks. In task 1 we identified the attributes of the four vehicle classes. It was essentially a data gathering and generation task. We identified:

- General specifications for the vehicles in the four classes
- Base of Aircraft Data (BADA) files required for the Airspace Concepts Evaluation System (ACES) tool and the Aviation Environmental Design Tool (AEDT) (for conventional SHT, HWB, SSBJ, and VLJ)
- Environmental data for the AEDT tool set (for conventional SHT, HWB, SSBJ, and VLJ)
- Usage projections for Small UASs

The results of task 1 are documented in chapter 3 of this volume. The detailed data produced in task 1 are in a companion CD.

Under the second task we developed operational scenarios that characterize how these four classes of vehicles would operate in the NextGen environment in 2025 and beyond. They were built from the Next Generation Air Transportation System (NextGen) Concept of Operations and the individual business cases (characterized as business trajectories for the acquisition and use of a super heavy transport, a supersonic business jet, a very light jet, and a civil uncrewed aerial vehicle). All of these vehicles will have entered service in one form or another before that date, but certain capabilities available in 2025 were used to discuss the full range of capabilities of these vehicles. Volume 2 of this final report contains the scenarios and describes how they were developed.

Under task 3 we developed a set of potential metrics that could be used for the trade studies of the impact of operating the new vehicle classes in the 2025 and 2040 time frame. The description of the metrics is broken down into groups defined by ICAO's Key Performance Areas (KPA) and includes a data dictionary (name, definition, and units) for each individual metric [10]. Since a large number of metrics associated with the NAS already exist, the key objective of this task was to identify critical metrics that could be used to effectively assess the NextGen Concept of Operations and the new operational procedures. We also identified how some of the proposed metrics could be measured. In the analysis performed as part of the System Level Assessments (SLAs) described in Volume 7 a subset of the metrics defined in this volume were used. Volume 3 documents the results of task 3.

In task 4 the Raytheon team developed a NextGen Analysis Toolkit that is composed of a library of simulation systems and models. The toolkit served as the analysis framework to examine NextGen technologies associated with introducing new vehicles and procedures into the NAS. It enabled trade studies that evaluate the inter-relationships between key performance metrics and other factors such as aircraft performance, system capacity, efficiency, predictability, systems interoperability, implementation risk, throughput, workload, safety, and environmental considerations (e.g., noise and emissions). The Raytheon team leveraged the extensive library of models and simulation tools that have been developed (or were being developed) by NASA, FAA, the JPDO, and Raytheon team members. Figure 1 shows the models and simulation tools used by the team to support the analysis and assessment.

The goal of Task 5 was to identify the relationships among vehicle characteristics, candidate procedures, and attributes of NextGen in order to determine what the impact of future air vehicles would be on the JPDO's vision of NextGen (as described in the NextGen Enterprise Architecture and realized by the JPDO's Integrated Work Plan). A unique analysis process was developed to objectively perform this assessment. The Raytheon team used an architecture methodology that is similar to what an architect does when adding an addition to your current

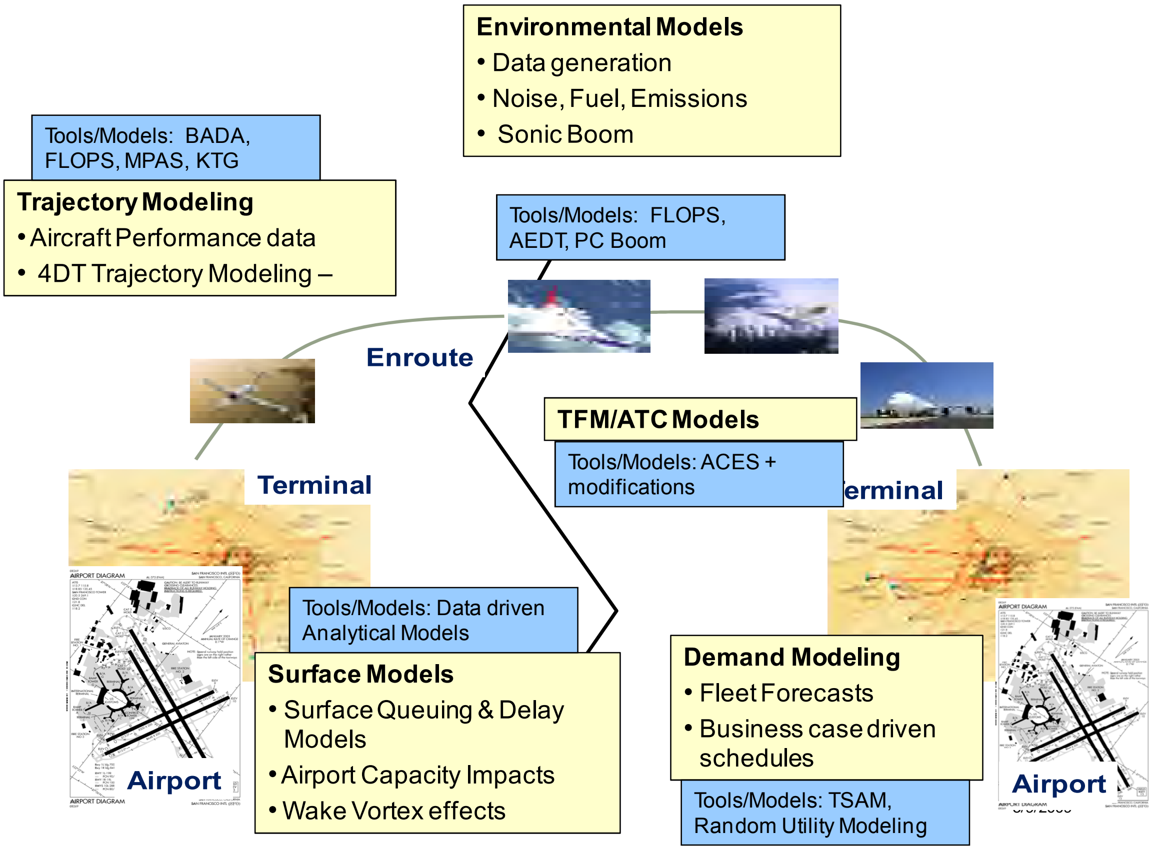

Figure 1. Overview of models and tools that composed the NextGen analysis toolkit

home. Essentially the design of your addition must accommodate how you will be using it. The operational scenarios developed under task 2 told us how the new vehicles use NextGen. The scenarios are then translated into step-by-step scripts or use cases that allow the analyst to map the actions to the Operational Activities in the Next Gen Enterprise Architecture. The JPDO has constructed its Integrated Work Plan using building blocks that are necessary to create the Enterprise Architecture. This provides a direct mapping of the IWP to the architectural elements, hence to the use case steps, and finally to the scenarios. It then becomes a straightforward effort to assess the ability of NextGen to support the future vehicle operations and at the same time review the adequacy of the IWP to provide the necessary capabilities. The output of this enabled us to suggest, to the JPDO, changes to the overall NextGen capabilities as currently defined in the Integrated Work Plan. Volume 5 describes the methodology used and shows examples of the results. The complete results of task 5 are included on a companion CD.

Task 6 dealt with the safety of the new vehicles, in terms of their design and in terms of their operation in the future NAS. We asked:

- Are there potential vehicle failures that cannot be mitigated by failure response systems or procedures?
- Can these vehicles safely operate, as required by their business case, in the future NAS?

Subject matter experts identified the most critical vehicle and operational safety concerns and then we performed a “deep dive” safety assessment for one of the critical operational issues for each vehicle class using the Aviation Safety Risk Model (ASRM). Volume 6 documents the results of our safety analysis and describes the safety methodology that was used.

In task 7 (System Level Assessments), the Raytheon team conducted a series of analyses using the tool box described in Volume 4 and the safety model described in Volume 6. These tools allowed investigations into a wide range of future vehicle operations and performance issues. Volumes 7A and 7B summarize the results of these analyses and provide insight into a number of issues that must be resolved to allow full integration of the new vehicle classes into NextGen. The basis for our analyses continues to reflect the focus on optimizing the future vehicles business case. In Task 5 we identified how NextGen's current planning and enterprise architecture must change to accommodate efficient operations for all four future air vehicles. Under task 7 we continued that approach by selecting specific operations that were essential to meeting a vehicles business case. We extended the "deep dive" safety analysis for the SUAS of task 6 to look at the safety of three, increasingly complex, SUAS missions. Finally, we conducted in depth environmental impact analysis for our vehicles that looked at NAS wide emissions, noise impacts in a metroplex region, and sonic booms (Volume 7B).

During the conduct of tasks 1 through 7 the Raytheon team identified and documented potential issues for further research. In task 8 these research issues were organized, clarified, expanded as necessary, and subsequently vetted with the team's subject matter experts. Volume 8 documents the results. It makes suggestions about research specific to the new vehicles classes, to their operation in the future NAS, to safety, to the environment, and to models and data. The final section of volume 8 discusses R&D strategies to deal with predicting the future aviation environment in the face of uncertainty due to foundational shifts in demand drivers.

2 Key Messages

The 2007 National Plan for Aeronautics R&D stated that the NAS must be designed to accommodate all vehicles and that future vehicles must be designed to operate in the NAS. [11] We believe that vehicles must operate in the NAS to optimize their return on investment, their "business case". Therefore vehicles must be designed with advanced technologies and aligned with their business model and the NAS must be open and flexible, designed to accommodate a range of vehicle operations. This section contains the conclusions we reached on the basis of our analyses of these new vehicles and their operation in the context of their business case.

2.1 New Vehicle Findings

The uniqueness of the aircraft's performance must be accepted - not all aircraft performance is the same and not all operators of the same aircraft fly the same, thus one set of procedures does not fit all. To realize the business case and business trajectory, it will be necessary to segregate trajectories within the airspace. To get the 4D trajectory you need for your flight, you have to know what is possible - the user proposes, the Air Navigation Service Provider (ANSP) approves or identifies feasible alternatives, and the user selects the best alternative. Our analysis showed that to support multiple trajectories in metroplex areas, the airspace design should be done in the context of all airports in the metroplex. The design should provide dynamically for segregated arrival and departure paths that accommodate the aircraft's performance with multiple paths that merge close to the airport for arrivals or diverge close to the airport for departures.

The NextGen Trajectory Based Operation (TBO) system that is part of the JPDO's NextGen concept is based on 4D trajectory contracts. In TBO, aircraft movements in the airspace are described with the aircraft's intended surface and flight trajectories. The set of trajectories represent the "master plan" for TBO. To generate, exchange, negotiate, and re-negotiate 4D trajectories among individual aircraft, and between aircraft and ground stations (ANSP facilities, flight operation centers, and UAS pilots) requires further study, especially with relation to the four new vehicles that were explored in this NRA. Due to the high performance flight management systems expected in 2025, more emphasis should be placed on 4D trajectory relationships than trajectory prediction. Research is needed on 4D trajectories to optimize operations:

- To deliver merging and spacing
- To define the separation distances (times) on the basis of the relationships between aircraft, for example:
  - Cruise-climb
  - Converging and diverging
  - Multiple aircraft on the same flight track
  - Significant differences in speed/overtake
- To support separation assurance and therefore “build in” safety
- To manage different business uses of the same class of aircraft
- To extend the net-centric infrastructure and its critical information to flight operation centers (FOCs) and owner operators in order to enable full integration of VLJs into a 4DT NextGen system.

2.2 New Vehicle – Super Heavy Transport (SHT)

While these vehicles are a reality today, their market uptake is unpredictable. In the longer term, Hybrid Wing Bodies (HWBs) may be introduced, first for cargo, but the HWB business case is uncertain. While it is not NASA’s charter to study these business cases and project possible uses of the SHT, NASA researchers must remain cognizant of SHT market projections. Concept research should ensure that the NAS is open and robust to accommodate a diverse market-based SHT fleet.

We found that surface issues far outweigh effects of larger arrival/departure separations. Figure 2 shows the increase in delay due to SHT surface issues. They create significant delays and costs for other users, especially at airports designed to Group V standards[2]. When feasible, new airports likely to have SHT demand must be designed to meet Group VI standards; similarly, existing airports with such demand must be partially re-designed for this purpose. Nevertheless, there is a need to safely and efficiently deal with wake vortex effects, particularly if traffic optimization research finds ways to improve surface operations when SHTs are arriving and departing.

Innovative technologies like the HWB can provide unprecedented performance improvement and open new markets. It is recommended that HWB aircraft be designed in context with their business use. Designers should, based on operational scenarios, define such characteristics as surface movement (e.g. sideways taxiing), cargo and passenger handling, and environmental improvements (e.g. deicing).

The SHT represents a twin-edged challenge. Today, they make more passengers per operation possible but at the expense of increasing delay to other operators. For example, today, as an A-380 moves on the airport surface, at some airports certain taxiways and intersections must be closed to other traffic until the aircraft clears the space. Research should be undertaken to develop mitigation measures by stakeholders for externalities that the SHT

[2] Group V and group VI airport design standards include specification of runway width (150 and 200 ft respectively), taxiway width (75 and 100 ft respectively), and taxiway separation (267 and 324 ft respectively). [12]

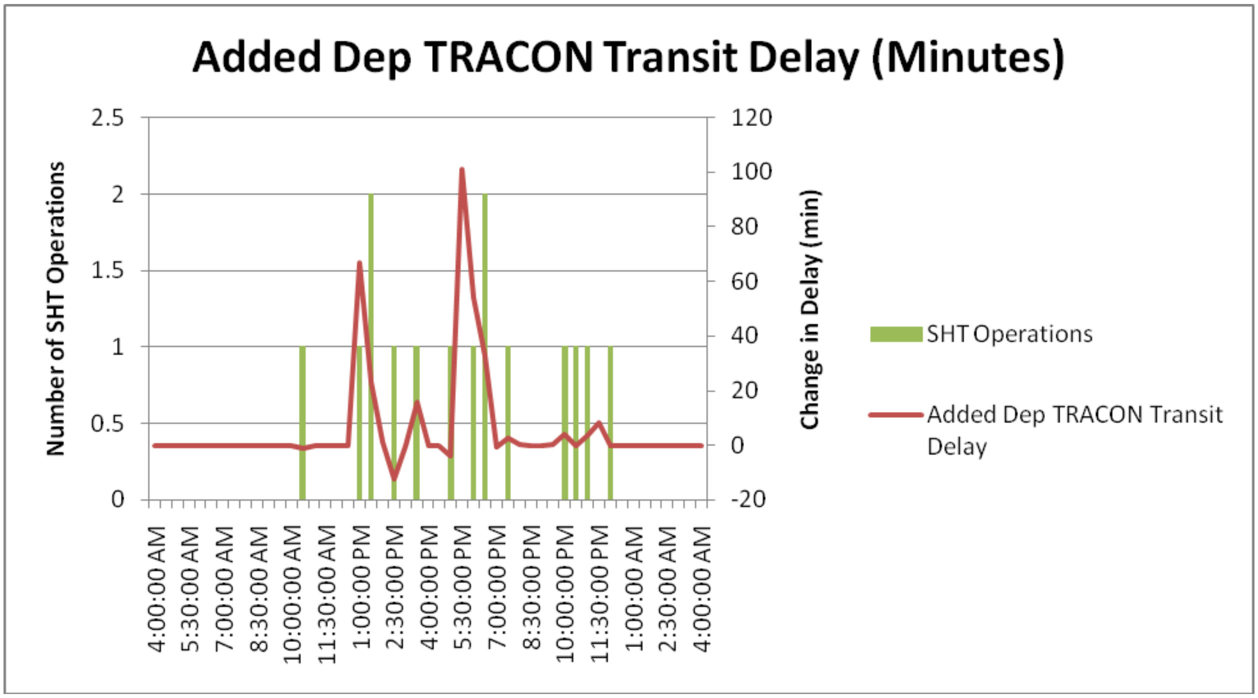

Figure 2. Delays due to SHT surface operations problems

creates. This might be accomplished through such measures as schedule adjustments, different airport design considerations, segregation of the airspace for wake vortex avoidance (as simple as changing the glide path thru aircraft design), and decision support and on-board tools that expedite surface movement.

The surface operation issues for large-span SHT aircraft that were indentified in our study are a precursor for the surface issues for ultra-high L/D aircraft that could have much longer spans. NASA's research to develop future, environmentally friendly, generations of SHT/HWB should include consideration of how such aircraft would be operated at airports in the future.

2.3 New Vehicle – Super Sonic Business Jet (SSBJ)

The SSBJ business case is predicated on the value of passenger time savings, but this business case is debatable and the future of the SSBJ is highly uncertain. Most SSBJs will be used for long haul international flights, but Continental US (CONUS) supersonic flight is necessary to close the business case.

While analysis of the business case and associated demand projection for the SSBJ is not part of the NASA charter, we recommend that NASA concept research ensure that the NAS remain open and flexible to accommodate alternative futures. In any case, we recommend that NextGen concepts be designed to accommodate operations that minimize delays for SSBJs while in US airspace.

Our analysis pointed to the need for segregated trajectories for SSBJs. These aircraft will come off the production line with NextGen avionics and thus will be ready for early 4DT operations.

The SSBJ assessment showed that 4DT "Best-Equipped, Best-Served" will cause delay for the less equipped, and the impact will be greater during congested times. The transition from "No 4DTs" to "All 4DTs" will involve several years of mixed equipage. To better understand this, a much more in-depth sensitivity analysis should be conducted to determine the impact of adding a single flight with 4DT contract to an airport with various levels of mixed equipage aircraft and at various levels of demand/capacity. This could answer a question such as: "If Teterboro (KTEB) were running at 60% demand/capacity with 20% of its flights on 4DT contracts, what would be the delay impact of adding another flight with a 4DT contract?"

Our safety study showed that safety at smaller airports is a concern. The study concluded that these concerns can be alleviated if avionics for taxiing at airports where infrastructure is limiting are developed and if there is proper training for controllers and pilots (see Figure 3).

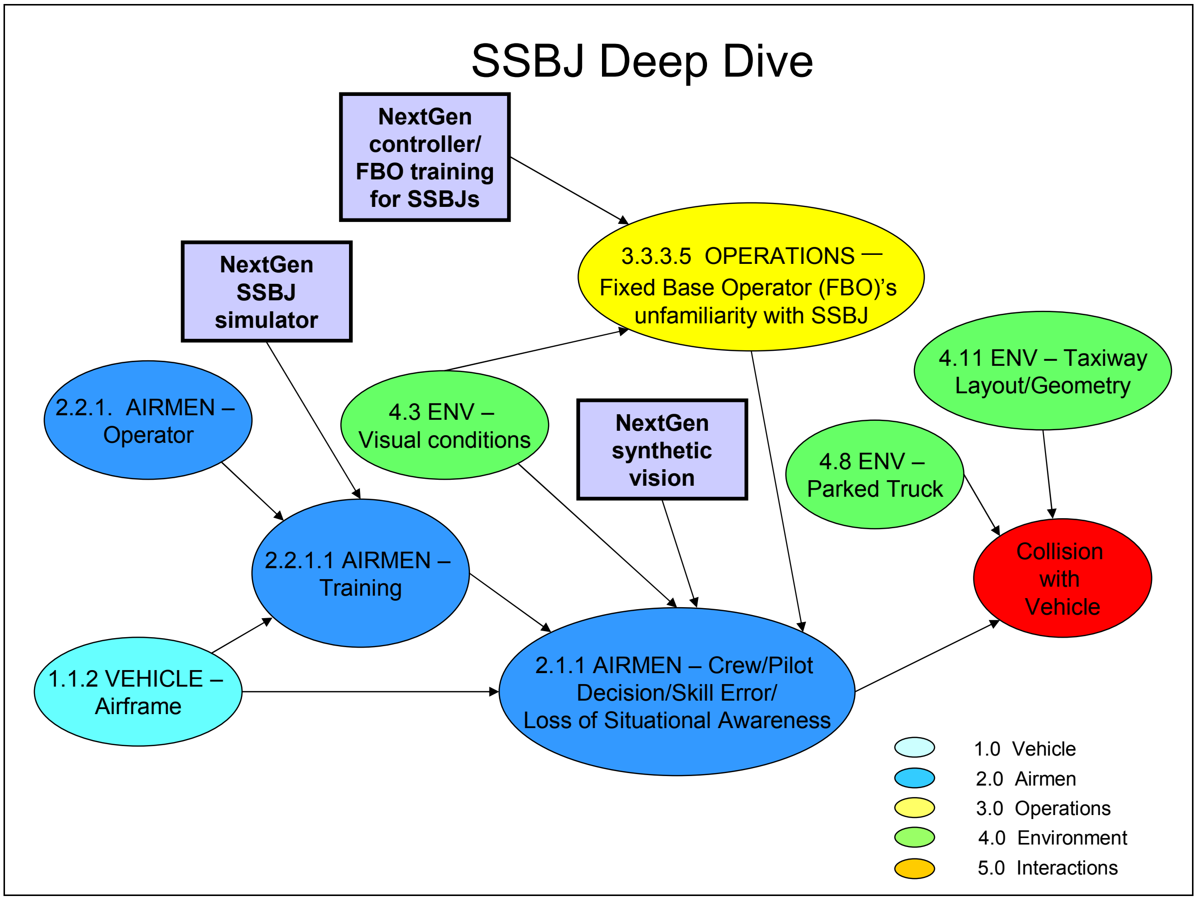

Figure 3. ASRM Influence Diagram with Insertion of Potential Mitigations for SSBJ Operation at a Small Airport[3]

2.4 New Vehicle – Very Light Jet (VLJ)

Despite recent economic setbacks to the general aviation industry, the business model for entry-level jets remains sound. Our subject matter experts expect that VLJs will operate primarily at smaller airports. VLJs could also be a viable alternative for connecting on-demand to scheduled air carrier services, as well as for connecting regional and generation aviation airports more efficiently to hubs. The distribution of activity at hub airports will be substantially different from scheduled operations.

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[3] The ovals in the legend refer to the Hazard Classifications from the Hazard Classification and Analysis System (see volume 6). The red oval is the potentially unsafe final outcome. The rectangles reflect the mitigations introduced to reduce risk.

At smaller airports, traditional CAT II/III landing systems will be too costly, but emerging on-board avionics (including enhanced and synthetic vision systems) can give very low minima with minimal, less costly, ground infrastructure.

Our analysis showed that to make VLJs a viable choice for connecting to long haul flights at hub airports, these hub airports will need segregated approach and departure trajectories (see Figure 4), runway use designed for VLJ operations, and, in some cases, may require capacity expansion.

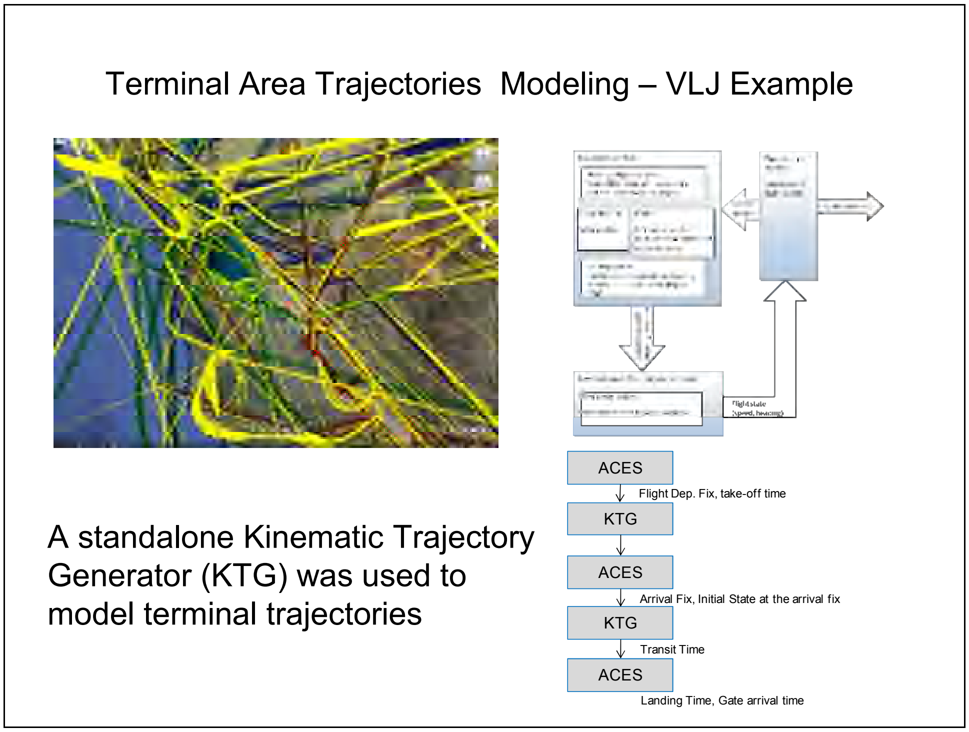

Figure 4. VLJ Terminal Area Trajectory Modeling

To fully integrate VLJs with 4DT capability into NextGen the net-centric infrastructure and its critical information must be extended to flight operation centers and owner operators.

The economic performance of on-demand air carrier industry experiences (both jet and propeller aircraft) are relevant to understanding the characteristics of this emergent market. NASA should consider utilizing the data from these experiences in projecting future modal preference demand.

2.5 New Vehicle – Unmanned Aerial System (UAS)

Small UAS (SUAS) operations represent a potential growth sector for the aerospace industry and, more generally, the US economy. They merit special attention due to their large numbers - driven by the market potential for commercial, law enforcement, and military training applications, the way they are operated (often well below the altitude of other aircraft), and their expected extensive use in the airspace above major metropolitan areas and near major airports. We must integrate them in our skies. Rather than restrict their flight with arduous and constraining approval processes inherited from manned aviation, processes should be customized for the SUAS itself.

The barrier to pervasive SUAS operations is safety. The SUAS must not impact other aircraft, and it must not pose appreciable risk to people or property on the ground. Rather than restrict operations to rural areas unoccupied by other traffic, we must understand the safety hazards imposed by the SUAS and expedite the development and deployment of technologies that will mitigate these risks.

"See and avoid" has been one of the operational safety "rules of the road" since the early days of flight. The term "sense & avoid" is the adaptation of those rules to UAS. Defining and developing sense and avoid technologies is essential to the safe and full integration of SUAS operations in the civil airspace. Our safety analysis of increasingly complex missions suggests that this goal can be realized most effectively in a four-phased approach by migrating from existing ground-based capabilities to an architecture that includes small, autonomous collision avoidance capabilities completely on board the vehicle (see Figure 5). The very smallest "micro" vehicles in this class make this a difficult problem. A possible novel approach would be to see whether one could develop a frangible micro (<5lb) UAS that would not cause harm in a collision.

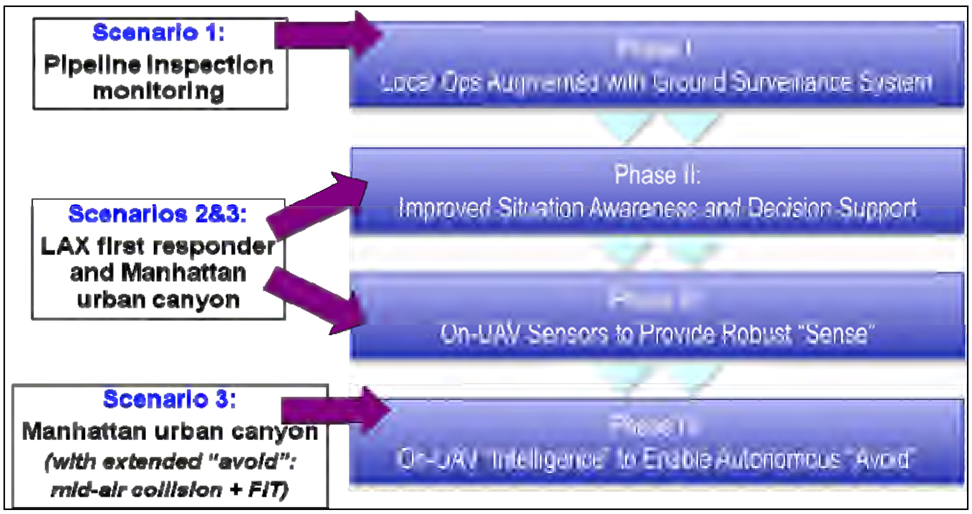

Figure 5. Sense and Avoid: Phasing it in to meet the Future

One size regulation doesn't fit all. For example, small UAS can operate safely even if the platform is not reliable. They are expendable: airframe loss does *not* necessarily imply risk of harm to persons or of appreciable damage to property. They could, for example, be "ditched" if there is the possibility of a safety compromise.

Our safety study concluded that safe SUAS operation in the NAS must be based on a type of 4D trajectory operation. All activities are coordinated between SUAS operators and ANSP via 4DT-like negotiation and net centric connectivity. For Visual Flight Rules (VFR) operations, this mission profile will be made available to other operators who will be responsible for avoiding the profile. Connectivity between air vehicle and ground operations is required - loss of link will require emergency response.

2.6 Safety

Given the assumption of a fundamentally safe NextGen baseline, we found no obvious "show stoppers" to safe operations of the four vehicle classes in the future NAS.[4] While a number of significant safety-related issues have emerged from our analysis using the ASRM (Figure 6), we concluded that these can be adequately addressed on the way to NextGen and

[4] Our underlying assumption was that the NextGen system that is in place when the four new vehicle classes are introduced is inherently safe.

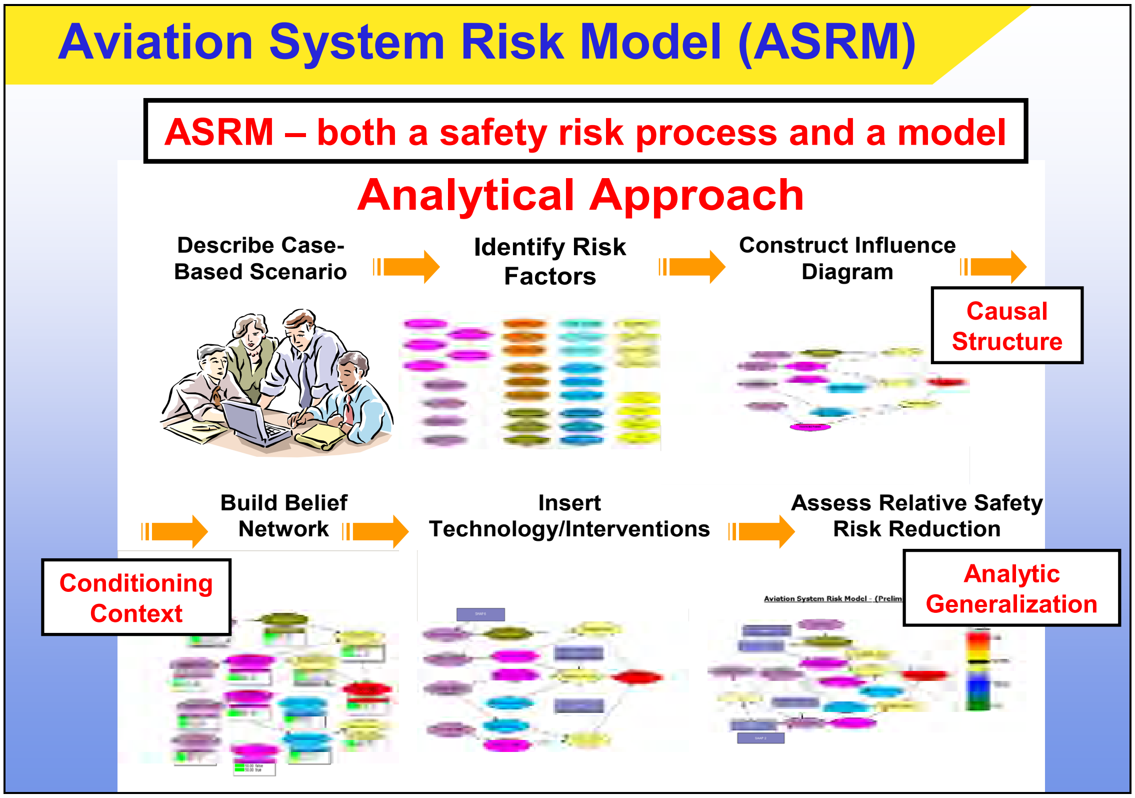

Figure 6. The Aviation Safety Risk Model (ASRM)

will not eventually pose a threat to safe incorporation of the four vehicle classes in the future NAS.

The unique characteristics and operations of these classes of vehicles will require:

- New operational procedures (ex - de-icing of an HWB aircraft)
- Special attention during the certification process
  - All four classes of vehicles studied require modification to the airworthiness standards for certification
  - Possible new Special Conditions or equivalent safety level findings may need to be evaluated (ex - new models for SHT crashworthiness substantiation)
- It is important to gain a thorough understanding of the *complex interactions* of these vehicles in the airspace and their inherent uncertainties that affect safety.

Better safety models are needed to allow safety analysis of NAS enhancements during *early stages* of concept/system definition. As technology matures in sophistication, so too must the associated analytic methods for system safety and probabilistic risk modeling of NextGen concepts. There is a need to extend real-time predictive system safety modeling to the four vehicle classes to provide advanced warnings emergent events to both ATC and pilots.

2.7 Environment

Analysis of environmental impacts of specific vehicles can not be divorced from the business case those vehicles serve. Tradeoff metrics and modeling are critical to understand the overall value served by each vehicle in the NAS. Figure 7 is an example of the results possible with such modeling.

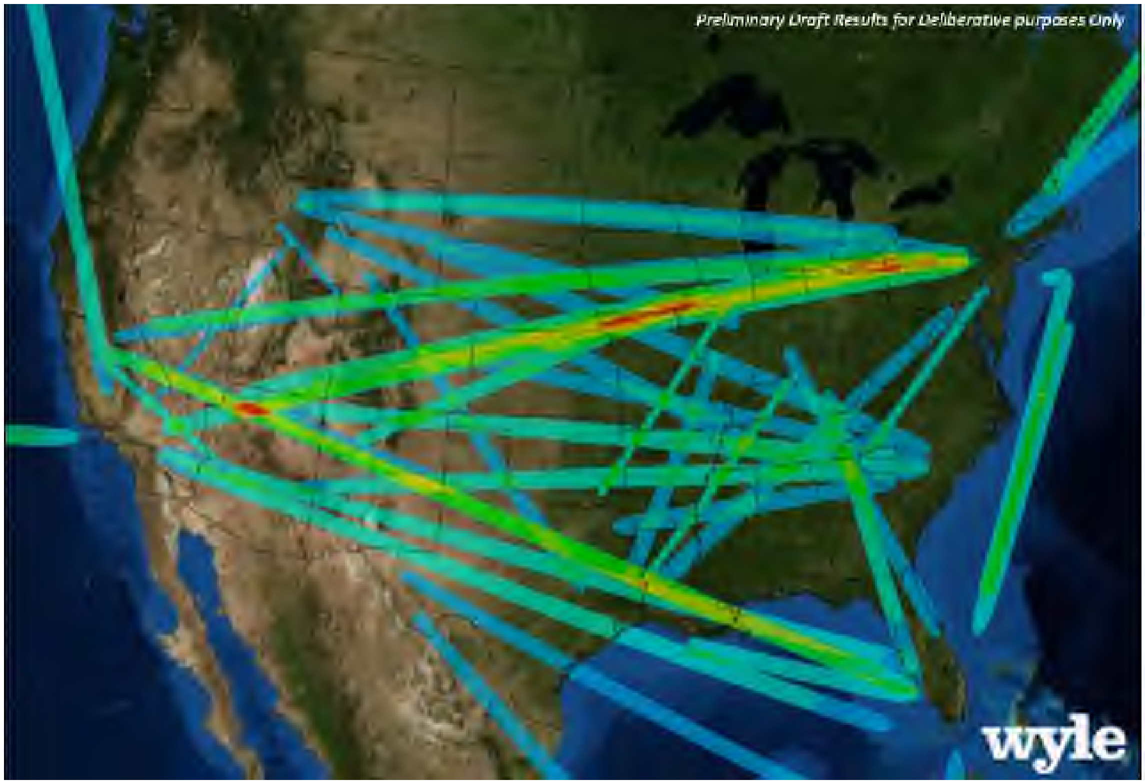

Figure 7. NAS-Wide SSBJ Analysis: Projected Number of Booms for NextGen 2025

The biggest return on investment with regard to lowering aviation's overall environmental footprint through technology lies in the development and accelerated adoption of advanced single-aisle and twin-aisle vehicles (the large jet and heavy jet categories in Figure 8).

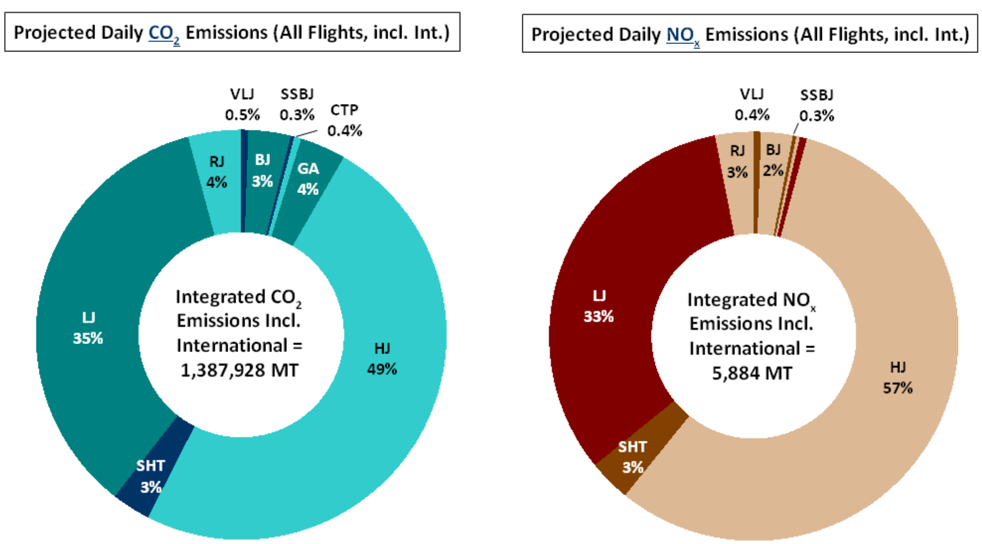

Figure 8. CO_2 and NOx Emissions for All Flights (including International) by Aircraft Category and Advanced Vehicle Class[5]

[5] LJ –large jet; RJ – regional jet; VLJ – very light jet; BJ – business jet; SSBJ – super sonic business jet; CTP – commercial turboprop; GA – general aviation aircraft; HJ – heavy jet; SHT – super heavy transport.

To optimize environmental performance of fleets:

- Create market incentives that encourage operators to accelerate adoption of new technology;
- Introduce mechanisms/procedures that discourage system inefficiencies and induce true stakeholder collaboration on system performance optimization.

More research is needed to model climate forcing effects of aircraft operations (including stratospheric operations), to optimize advanced supersonic vehicle designs and operations, and to continue the development of integrated environmental performance metrics and models.

2.8 Models and Data

The system level assessments were conducted largely through ACES, a fast-time computer simulation capable of analyzing thousands of aircraft traveling from gate-to-gate through the NAS, interacting with each other, with weather, and with national control strategies. As described in Volume 7, ACES models were updated based on the new vehicle performance and business cases, and various operational scenarios were analyzed to determine NAS-wide and vehicle specific impact.

ACES/AEDT provides an integrated gate-to-gate environmental modeling toolkit and ACES and PCBoom [13] provides sonic boom modeling capability, but:

- Further development and integration of modeling & simulation platforms is needed to assess tradeoffs and design optimized solutions in complex operational environments
- More research is needed to assess environmental impacts at altitude, including stratosphere operations
- More research needed to assess acceleration and focused booms

While ACES provides a robust modeling environment, current modeling and simulation tools are somewhat limited to current NAS operations. It is recommended that airspace configurations and operations be updated to provide a correct reflection of the future NAS. It is desirable to enhance ACES and other tools to model additional "future" concepts such as trajectory based operations that may include 4DT contracts, new airspace design concepts such as the Dynamic Airspace Concept [14], higher levels of ATC automation with significantly changed human roles, and more functionality on the flight deck.

Analysis revealed impact to less-equipped vehicles on the transition to a system with 4D Trajectory Based Operations. We recommend development of model enhancements to study this as well as research into the business case and policy issues to develop a viable and equitable path to TBO.

Better projections of demand and of capacity for 2025 and 2040 time frame are required. Our analysis revealed 14 major hub airports where the demand/capacity ration exceeded 100%, clearly not representative of a realistic operational state. Traffic demand reduction and/or airport capacity increases need to be modeled to create a realistic baseline from which to analyze the insertion of new vehicles. Also, the current 2025 traffic demand is based on FAA's terminal area forecast (TAF), which varies widely from year to year, and 2040 demand levels are a simple linear extension from 2025 demands. The baseline also had a high incidence of very small segment headways (times between successive departures). There is a need to reduce segment headways that reflect historical schedules. Finally, the existing 2025 Baseline Flight Data Set (FDS) contains aircraft that are unlikely to be in service in 2025 (e.g. DC-9). We recommend that the FDS be updated to represent a credible evolution from current fleet to 2025 fleet that includes new and in-production aircraft. As improvements are made, assumptions and pedigree need to be clearly articulated for both demand and capacity and sensitivity analysis should be done around the projected demand level(s).

2.9 NextGen Enterprise Architecture

We found, in our architecture analysis (Figure 9), that integrating the four new vehicle classes into NextGen will require updates to the current JPDO Integrated Work Plan (IWP) and Enterprise Architecture. Many IWP Enablers do not address the automation tools (both in the cockpit and on the ground) needed to integrate/manage these vehicles in the NAS. Information flows throughout the enterprise architecture are not adequate to allow Trajectory Based Operations for these future “best equipped” aircraft. The research, development, and policy pieces of the IWP need to be updated as well to reflect the expected operation of the new vehicles classes. We had several meetings with the JPDO staff to present our methodology and findings, and, subsequently, the JPDO adopted our methodology for scenario development and architecture analysis and has started to update the specific enabler shortcomings that we identified.

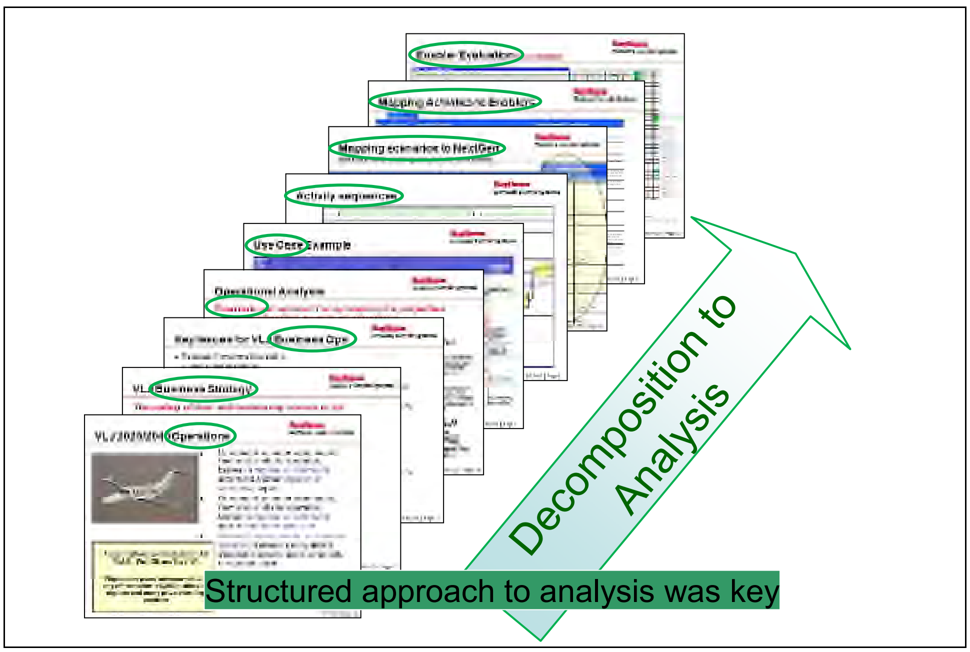

Figure 9. NextGen Architecture Analysis Process Flow

3 Vehicle Attributes

3.1 Objectives

Task 1 dealt with establishing the attributes of the advanced vehicles to be used in all subsequent tasks. The studied vehicles are:

- Super Heavy Transport (SHT)
  - Conventional Body SHT
  - Hybrid Wing Body (HWB)
- Supersonic Business Jet (SSBJ)
- Very Light Jet (VLJ)

- Small Uncrewed Aircraft Systems (UASs under 40 pounds)

Task 1 was essentially a data gathering and generation task. We identified general specifications for the vehicles in the four classes. The rest of the required products of this task fell into the following distinct categories:

- Base of Aircraft Data (BADA) files required for the Airspace Concepts Evaluation System (ACES) tool and the Aviation Environmental Design Tool (AEDT) (for conventional SHT, HWB, SSBJ, and VLJ)[6]
- Environmental data for the AEDT tool set (for conventional SHT, HWB, SSBJ, and VLJ)
- Usage projections for UASs

Task 1 data was generated in a joint effort by Raytheon, Purdue University, Gulfstream Aerospace Corporation, and Wyle Information Systems. In addition, some data specific to the VLJ vehicle was obtained from NASA and the FAA Volpe Center.

3.2 General Vehicle Specifications

The following tables summarize the general specifications of these vehicles:

Super Heavy Transport (SHT) (Passenger Version):

Table 1. Conventional SHT Specifications

Conventional SHT Specifications	
Max Gross Take-off Weight (MGTOW)	1,250,000 lbs
Operating Empty Weight (OEW)	595,000 lbs
Fuel Weight	525,000 lbs
Payload Weight	110,000 lbs
Passengers	525
Wing Span	261.8 ft
Length	238.6 ft
Width	261.8 ft
Height	79.1 ft
Cruise Speed	.82 Mach
Max Speed	.89 Mach
Approach Speed	141 knots
Cruise Altitude	35,000 ft
Ceiling	43,000 ft
Range	8,000 nm
Runway Length (TO)	9,900 ft
Engines	4

[6] Definition of files (such as BADA) and models (such as ACES) can be in Volume 4.

Hybrid Wing Body (HWB) (Cargo Version):

Table 2. HWB Specifications

HWB Specifications	
Max Gross Take-off Weight (MGTOW)	980,000 lbs
Operating Empty Weight (OEW)	415,000 lbs
Fuel Weight	380,000 lbs
Payload Weight	185,000 lbs
Wing Span	250 ft
Length	162.5 ft
Width	250 ft
Cruise Speed	.85 Mach
Max Speed	.9 Mach
Approach Speed	<140 knots
Cruise Altitude	39,000 ft
Ceiling	43,000 ft
Range	7,750 nm
Runway Length (TO)	<11,000 ft
Engines	3

Supersonic Business Jet (SSBJ):

Table 3. SSBJ Specifications

SSBJ Specifications	
Max Gross Take-off Weight (MGTOW)	100,000 lbs
Operating Empty Weight (OEW)	49500 lbs
Fuel Weight	50,500 lbs
Passengers	8 to 14
Wing Span (swing wing)	100 ft (forward); 60 ft (aft)
Length	140 ft
Height	25 ft
Cruise Speed	1.6 -1.8 Mach
Max Speed	> 1.8 Mach
Approach Speed	137 knots
Cruise Altitude	49,000 ft
Ceiling	> 51,000ft
Range	4,800 nm
Runway Length (TO)	9,900 ft
Engines	2

Very Light Jet (VLJ):

Table 4. VLJ Specifications

VLJ Specifications	
Max Gross Take-off Weight (MGTOW)	6,000 lbs
Operating Empty Weight (OEW)	3,600 lbs
Fuel Weight	1,698 lbs
Passengers	3
Wing Span	37.9 ft
Length	33.5 ft
Height	11 ft
Max Cruise Speed	370 knots
Max Cruise Altitude	41,000 ft
Range	1,125 nm
Runway Length (TO)	2,345 ft
Engines	1 or 2

Small Uncrewed Aircraft Systems (SUAS):

Table 5. UAS Specifications

	ScanEagle Class	**Raven Class**
Max Takeoff Weight	37.9 lb	6 lb
Payload	13.2 lb	2 lb
Endurance	20 hours	1.5 hours
Service Ceiling	16400 ft	1,500 ft
Max Level Speed	70 knots	60 knots
Cruise Speed	49 knots	40 knots
Wing Span	10.2 ft	4.4 ft
Fuselage Diameter	7.0 in	6 in
Length	3.9 ft	2.9 ft
Camera Range	100+ km	10 km
Climb Rate	492 ft/min	656 ft/min
Support	Catapult Launch; Sky hook land	Hand launch; Skid land

3.3 BADA Data

Required BADA Files

BADA data files are text files in a format specified by Eurocontrol. They provide data on aircraft performance which can be used by simulation tools such as ACES. The two essential BADA data files are:

- Operation Performance File (OPF): This file holds all the thrust, drag, and fuel coefficients together with information on weights, speeds, maximum altitude, etc.

- Performance Table File (PTF): This file presents the nominal performance of the aircraft model in the form of a look-up table, providing speeds, fuel flows, and climb/descent rates at various flights levels.

BADA files are available from Eurocontrol for most existing aircraft, but no BADA files were available for conventional SHTs, HWBs, SSBJs, or VLJs at the start of this project. Since no BADA files were available for these vehicles, they were generated using aircraft synthesis software. This software utilizes parameters and coefficients specific to an aircraft engine and frame to predict aircraft performance. An example of such a program which was used on Task 1 is the Flight Optimization System (FLOPS). FLOPS is a NASA-developed, multidisciplinary system for conceptual and preliminary design and evaluation of advanced aircraft concepts.

<u>Use of FLOPS</u>

FLOPS input parameters include geometric definition of the aircraft fuselage, wing, and tail surfaces, passenger and cargo payload information, engine model definition, and mission specific performance parameters (cruise altitude, range, speed, etc). Each of the aircraft models was generated from publically available manufacturer data and Jane's Encyclopedia of Aircraft. The FLOPS aircraft sizing module iterates to find aircraft sizing and weight for a given mission profile. During this process, the vehicle's aerodynamic drag polar is computed, engine propulsion is evaluated to obtain thrust and fuel flow, and a component weight buildup and economic analysis is conducted, as shown in Figure 10.

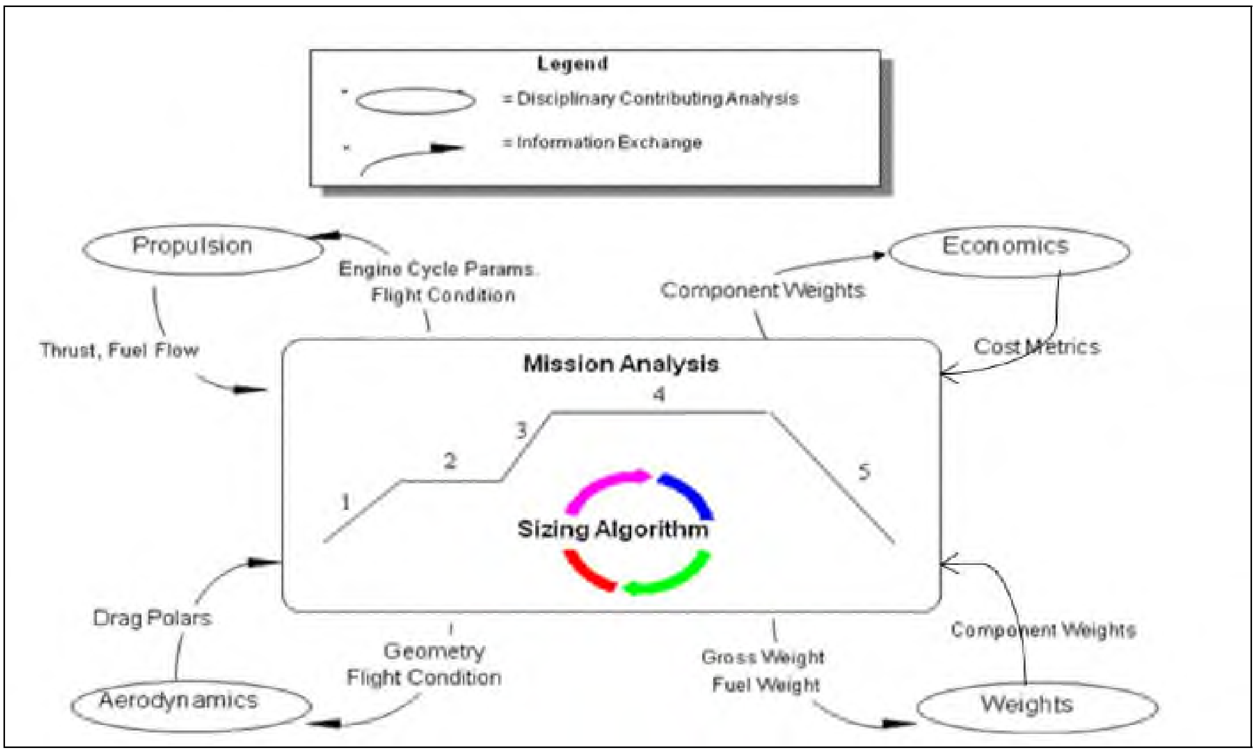

Figure 10. FLOPS (Flight Optimization System) Information Flow in Sizing Loop

Output data from calibrated FLOPS models for each aircraft were translated into BADA format files, which include aircraft operation performance, airline procedures, and a performance table for each aircraft type. The OPF specifies aircraft mass and flight envelope as well as coefficients for the modeling of aircraft thrust, drag, and fuel consumption. These performance parameters are readily deducible from FLOPS mission performance output. For example, the BADA parasite drag and induced drag coefficients can be immediately determined from the FLOPS calculated vehicle drag polar. Likewise, thrust and fuel consumption equations, as a function of altitude, can be calculated from FLOPS output of vehicle flight performance tables during climb, cruise, and descent. The airline procedures file specifies nominal maneuver speeds for the aircraft and the PTF contains a summary of aircraft speeds, climb and descent rates, and fuel consumption for a range of aircraft operating altitudes for climb, cruise, and descent. The BADA performance table can be determined, using some interpolation, from the mission performance tables generated by FLOPS for climb, cruise, and descent.

Vehicle-Specific BADA File Generation

BADA data for super heavy vehicles was generated by Purdue University using the FLOPS tool. This included a BADA data set for an A-380 type vehicle and also for an HWB vehicle. FLOPS v7.01 was used for the development of the conventional SHT aircraft model. FLOPS v7.40, which includes HWB-specific geometric definition and weight and sizing equations based on NASA studies, was used for the development of an HWB aircraft model.

BADA data for the SSBJ was generated by Gulfstream using internal tools similar to FLOPS.

A partially complete set of BADA data for the VLJ was obtained from NASA early in the project. It was, however, missing drag coefficients for flaps deployed and gear down. This data was filled in by Purdue University using the FLOPS tool.[7]

BADA data generated for the new vehicle types during Task 1 was tested and verified using the ACES simulation tool to assure that subsequent modeling would work properly.

The final sets of BADA data for conventional SHT, HWB, SSBJ, and VLJ as generated in Task 1 and used in the ACES modeling are included in the disk of supplementary data.

3.4 Environmental Data

In order to model emissions and noise using AEDT, it was necessary under Task 1 to generate the following sets of AEDT input data for each new vehicle type:

- Detailed vehicle profiles for climb/descent/thrust below 10,000 ft altitude. These profiles provide higher fidelity than BADA PTF files when performing environmental analysis in the terminal area.
- Noise-Power-Distance (NPD) curves.
- Fuel flow and Emissions Indices (EIs) for NOx, CO, and HC at 7%, 30%, 85%, and 100% power.

[7] The drag coefficients for the VLJ were determined by using historical trends, empirical relationships, and back calculation. Reference Wing Area (no flaps deployed) is readily available for all aircraft. The wing area is increased when flaps are deployed, as is the camber of the wing section. These effects, as a function of flap type and deflection, can be estimated based on empirical trends. Once the changes in camber and wing area are determined, the new coefficient of lift can be calculated. Additionally, coefficient of lift can be estimated from aircraft approach velocity and wing area (flapped or clean). Calculation of the coefficient of drag can be directly computed once the coefficient of lift is found. These results can be compared then to published data of similar type. Drag of the gear can be approximated using traditional aircraft sizing routines which include a component drag buildup function.

The following table summarizes the sources of this environmental data for each vehicle type.

Table 6. Environmental Data Summary

Vehicle	Terminal profiles	Noise-Power-Distance (NPD) curves	Fuel Flow and Emissions Indices
conventional SHT	Generated by Purdue University using FLOPS	Generated by Wyle using AAM	Generated by Wyle based on extrapolation from existing engines
HWB	Generated by Purdue University using FLOPS	Generated by Wyle using AAM	Generated by Wyle based on extrapolation from existing engines
SSBJ	Provided by Gulfstream	Generated by Wyle using AAM	Provided by Gulfstream
VLJ	Provided by Eclipse Aerospace	Provided by Eclipse Aerospace	Provided by Pratt & Whitney

The final sets of environmental data for conventional SHT, HWB, SSBJ, and VLJ as generated in Task 1 and used in the AEDT modeling are included in the disk of supplementary data.

The following subparagraphs describe the methodology for generating this environmental data.

3.4.1 Vehicle Profiles

Profiles for conventional SHTs and HWBs were based on the FLOPS analysis performed by Purdue University. Integrated Noise Model (INM) [15] departure and arrival profiles at a fidelity required for noise calcuations can be derived directly from the FLOPS aircraft model. In a similar manner, SSBJ profiles were generated by the Gulfstream vehicles models.

Profiles for the Eclipse VLJ were obtained from Eclipse Aerospace through the FAA Volpe Center.

3.4.2 NPD curves

<u>Process</u>

The process of generating NPD curves for the conventional SHT, SSBJ, and HWB for use in AEDT employed a combination of physics-based modeling and empirical extrapolations. This involved the use of existing noise sphere data to derive new vehicle-specific noise sphere datasets. A Wyle tool called the Advanced Acoustic Model (AAM) was used to generate the acoustic data for the NPDs. [16]

The acoustic modeling to create noise spheres for each new vehicle type utilized the following iterative process:

- Create a set of 1,000-ft radius noise spheres for the various engine operating states based on:
  - Spectral shape
  - Lateral directivity

– Noise level

- Simulate the ICAO certification profiles and predict the Effective Perceived Noise Levels at the ICAO measurement locations using the AAM. The ICAO certification profiles are shown in Figure 11. The vehicle profiles generated by tools such as FLOPS were used for this step.
- Compare AAM predictions with certification values. If certification values are not met, adjust the spheres as needed and repeat step 2.

After the set of noise spheres consistent with targeted certification noise level targets was generated, the calculation of NPD data for the ten standard NPD distances (200, 400, 630, 1000, 2000, 4000, 6300, 10000, 16000, 25000 ft.) was performed using AAM. A simulation of straight and level flight at the 160 knot reference speed for each noise sphere (thrust setting for approach and departure conditions) in AAM was used to predicted the Effective Perceived Noise Level (EPNL), Maximum A-weighted Sound Level (LMaxA) and Sound Exposure Level (SEL) metrics at a receiver located 4 feet above soft ground directly underneath the aircraft flight track.

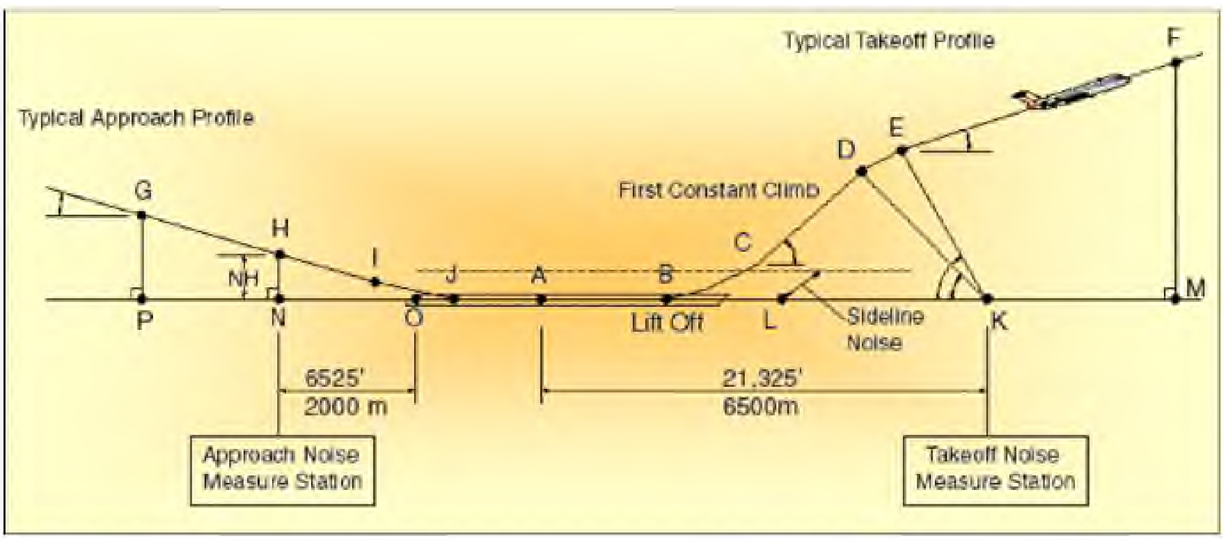

Figure 11. Certification profile and measurement locations

Conventional SHT Noise Sphere Example

The conventional Super Heavy Transport (SHT) vehicle class is modeled with engines in the 75 klb thrust range, an approximate takeoff gross weight of 1,250,000 lbs, and a range of 7,500 nautical miles. Since ground-up predictions of the vehicle acoustic characteristics were not available, a reverse-engineering approach was used beginning with the certification targets for the program.

For the conventional SHT, the AAM three dimensional spectral noise spheres were constructed using the following information:

- Spectra from existing AEDT classes. The AEDT spectral classes are normalized to 70 dB at 1000 Hz and were adjusted linearly to higher or lower levels. AEDT spectral classes #105 (Departure) and #205 (Arrival) were utilized. These spectral classes are a reasonable approximation for a high bypass jet engine in this high thrust class.

- The thrust noise sensitivity (change in source level with change in thrust) was approximated based on existing INM data for high thrust high bypass engines such as the Trent8 and GE90 as found on the Boeing 777 and NASA Aircraft Noise Prediction Program (ANOPP) Aircraft Noise Prediction Program predictions for a flight vehicle with similar twin engines.
- INM lateral directivity source characteristics (SAE AIR 5662) were applied to the noise spheres based on adjustments for aircraft with wing mounted engines. This source directivity correction amounts to a reduction in the sideline directivity of 1.5 dB. No longitudinal directivity was applied to the noise spheres, a simplification consistent with the integrated noise model engine within AEDT.

As an example, the resulting conventional SHT AAM 75,000 lb departure sphere is provided in Figure 12.

SSBJ

Terminal area noise modeling for the SSBJ vehicle class was based on a representative configuration with a takeoff gross weight of 100,000 lbs, which meets an acoustic target of FAA Stage 4 noise standard: -10dB. A process very similar to that described for the conventional SHT was employed in the development of the SSBJ terminal area acoustic parameters.

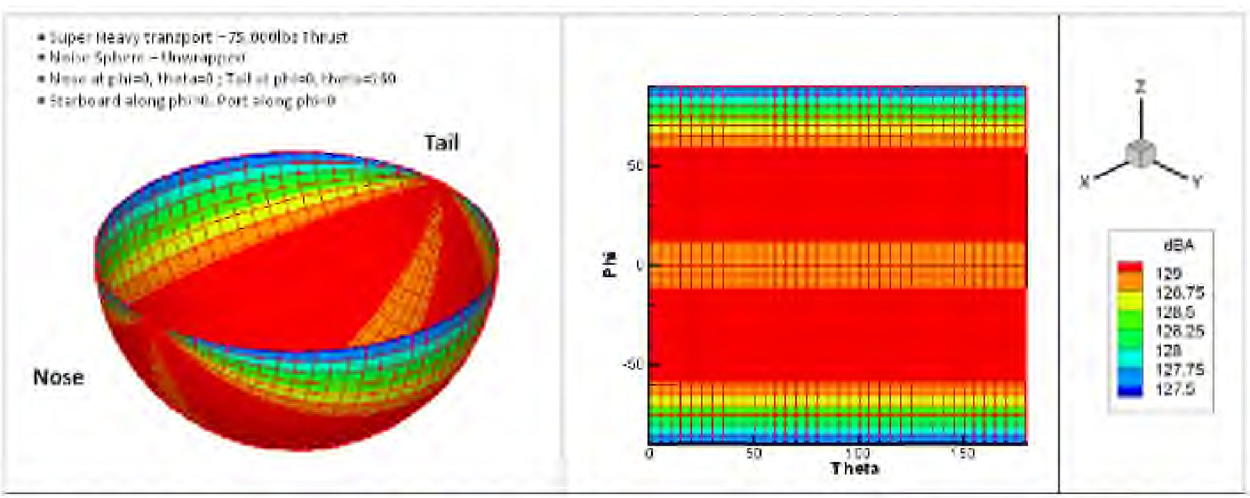

Figure 12. Conventional SHT 75,000 lb Departure Noise Sphere Shown in 3D and Unwrapped

HWB

Noise modeling for the Hybrid Wing Body (HWB) vehicle class was based on a cargo variant with a takeoff gross weight of 980,000 lbs. Again, a process very similar to that described for the conventional SHT was employed in the development of HWB terminal area acoustic parameters. In this case, however, terminal area noise modeling and buildup of the acoustic characteristics covered such aspects as the unique configuration directivity with some high frequency directivity such as the inlet compressor shielding. This was based on the overall prediction of sound pressure shielding from the engine inlets as shown in the NASA-supplied data of Figure 13.

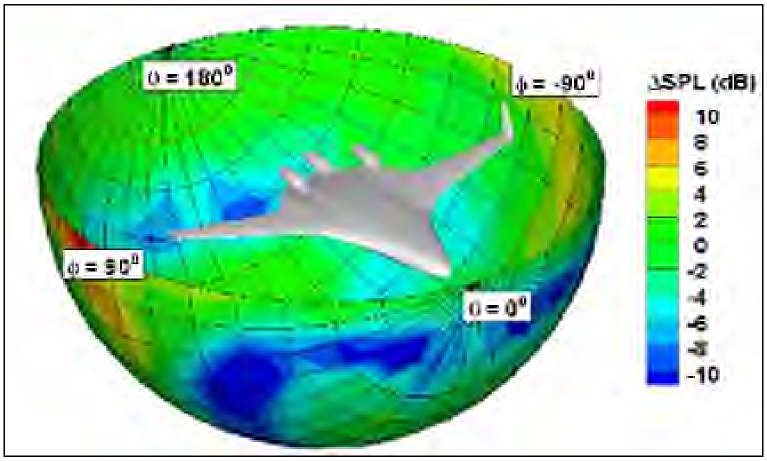

Figure 13. Hybrid Wing Body Inlet / Compressor Shielding Prediction 300 Passenger Variant (courtesy NASA)

3.4.3 Emissions

<u>Process</u>

The core AEDT emissions modeling method is the Boeing Fuel Flow Method 2 (BFFM2), which requires the use of the ICAO standard fuel flows and emissions indices for nitrogen oxides (NOx), carbon monoxide (CO), and hydrocarbons (HC). [17] BFFM2 uses a log-log relationship between emissions indices and fuel flow to interpolate between the four ICAO standard power settings (7%, 30%, 85%, and 100%). Adjustments are also made for atmospheric effects and engine installation effects. Figure 14 shows example plots of the relationships between emissions indices and fuel flow. Because BFFM2 just calculates

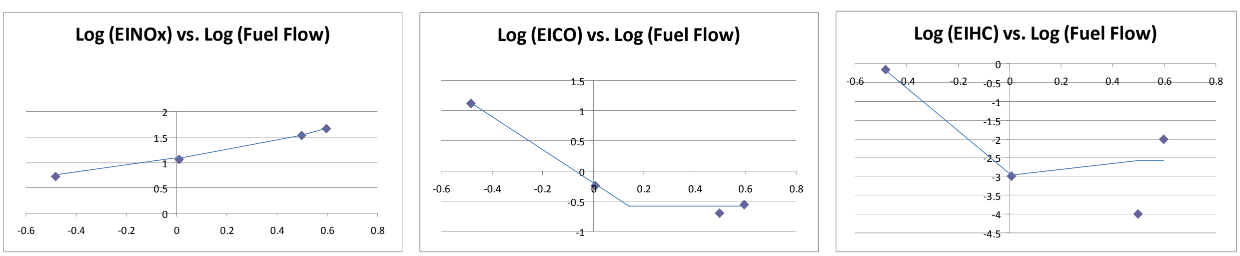

Figure 14. Example Log-Log Relationships between Emissions Indices and Fuel Flows in BFFM2

emissions indices for certain flight conditions, it is generally intended for high resolution (flight segment by flight segment) modeling.

For Particulate Matter (PM) emissions, AEDT also requires the Smoke Numbers (SN), which are obtained through the engine certification process.

The steps required to develop the set of emissions data are:

- Obtain at-flight fuel flow from a model or measurements or engine data
- Develop emissions indices from BFFM2
- Obtain the Smoke Numbers from the engine manufacturer or by extrapolating from similar engines

<u>Derivation of Vehicle Emissions Data</u>

To obtain emissions data for the advanced vehicles of this study, a combination of manufacturer data and existing engine data were used.

For the SSBJ and VLJ, manufacturer data detailing fuel flows and emissions indices for use with BFFM2 were obtained from Gulfstream and Eclipse Aviation, respectively.

For the SHT and the HWB aircraft, existing emissions data were used to derive new datasets for these aircraft. This involved using the ICAO emissions databank to predict fuel flow and emissions indices as functions of rated output and pressure ratio. This appears to provide a good, first-order approximation based on the regression fit criteria, R^2, which was shown to be greater than 0.98 for fuel flow and about 0.7 for NOx emissions indices. These statistics were based on the use of a simple polynomial fit (i.e., $y=a+bx+cx^2$).

In conducting this regression work, most of the certification data in the ICAO databank were used with the exception of engines with dual annular combustors, which are understood to have different emissions characteristics. Using the rated output and pressure ratios of the Trent 970-84 and GP7270 engines for the conventional SHT and HWB, respectively, the fuel flows and nitrogen oxide (NOx) emissions indices were predicted for each of the four ICAO standard power settings (i.e., 7%, 30%, 85%, and 100%). Although it would have been possible to use the fuel flows and emissions indices from these engines directly (i.e., as substitutions), it was desirable to obtain data that would be representative of these vehicle categories rather than any one vehicle in particular (e.g., data for a general conventional SHT rather than specifically for the A380).

Unlike fuel flow and NOx, similar equations for carbon monoxide (CO) and hydrocarbon (HC) emissions as functions of rated output and pressure ratio could not be developed (i.e., R^2 values were very low). This was not surprising since predictions of CO and HC emissions are dubious. This is in large part due to the high uncertainty levels associated with the predictions of emissions, especially under low-power conditions. As such, CO and HC emissions indices were determined by averaging the top 10 largest engines (by rated output) for the conventional SHT and using the GP7270 engine's emissions as a surrogate for the HWB. The A380's engine (Trent 970-84) was included in the averaging for the conventional SHT's CO and HC emissions indices.

For conventional SHT and HWB Particulate Matter emissions, the smoke numbers of similar engines were used as described above for NOx, CO, HC emissions.

With regard to SO2, CO2, H2O emissions, the method and EIs used for this study's advanced vehicles are the same as for other vehicles in AEDT since it is assumed for the purposes of the analysis that these aircrafts will be using the same jet fuel.

3.5 UAS Usage Projections

Since UASs are not modeled in ACES or AEDT, there was no need to generate UAS BADA data or environmental files. Instead, the Raytheon team performed a projection of the UAS usage in a typical city of 1 million people. This data, shown in Table 7, can serve as the basis for further analysis of UAS impacts. For cities with other populations, it is assumed that the numbers in this table scale linearly.

Table 7. Projected UAS Usage in City of 1 Million People

Application	Region	Projected 2025 Flights/day	Projected 2040 Flights/day	Comment (duration, airspace volume, pattern, etc.)
Police Dept/ 1st Responder	Metro	150	250	90 Minutes - 6 hours; Local Orbit, < 500' (Raven)
Perimeter Security	Metro + Border	100	300	24 hours, Elliptical Orbit (20 Mile Range), < 2000' (Scan Eagle)
Wildfire Monitoring	Rural	25	50	25 hours, Elliptical Orbit (20 Mile Range), < 2000' (Scan Eagle)
Commercial Imagery	Metro/ Rural	30	100	90 Minutes - 6 hours; Local Orbit (10 km range), < 500' (Raven)
Crop Monitoring	Rural	25	100	24 hours, Elliptical Orbit (20 Mile Range), < 2000' (Scan Eagle)
Traffic Reporting	Metro	10	25	24 hours, Elliptical Orbit (20 Mile Range), < 2000' (Scan Eagle)
Atmospheric Measurements	Metro/ Rural	10	25	25 hours, Elliptical Orbit (20 Mile Range), < 2000' (Scan Eagle)
Total UASs		350	850	

Appendix A. The Raytheon Team

Team Member - Industry	Key Roles
Raytheon	Use Cases, System Level Assessments, UAS
Intelligent Automation Inc	Models
Booz Allen Hamilton	NextGen and JPE
Wyle labs	Environmental Impacts and Models
SAIC	Safety and Metrics
Aviation Management Associates	NextGen Operational Procedures
Aerospace Computing Inc	ACES support
PDA Associates	System Level assessments
Honeywell	Avionics
Holmes, Consulting	VLJs Operations
Gulfstream	SS Biz Jet
CSC	TFM Procedures and Assessments
Luxhoj Consulting	Safety
Dr. R. John Hansman	System Definition

Team Member - University	Key Roles
University of Michigan	UAS and Safety
University of Illinois	SS Biz Jet Boom Re-routing
Purdue University	FLOP BADA Model, SHT System Level Assessments and Safety
University of Minnesota	Super Heavy Transports and Safety
University of California Berkeley	VLJs and Business Jets Impacts
George Mason University	Safety
University of Maryland	SHT Impacts and Equity Metrics

Advisory Council:

Dr. Andres Zellweger

Dr. Amedeo Odoni

Mr. Don Taylor

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Appendix C. Acronyms

4DT – Four-dimensional trajectory

AAM - Advanced Acoustic Model

ACES - Airspace Concepts Evaluation System

ADS-B – Automatic dependent surveillance broadcast

ADS-B IN – ADS-B input (reception)

ADS-B OUT – ADS-B output (transmission)

AEDT - Aviation Environmental Design Tool

ANOPP - Aircraft Noise Prediction Program

ANSP - Air Navigation Service Provider

ASRM - Aviation Safety Risk Model

ATC – Air traffic control

ATM – Air traffic management

BADA – Base of aircraft data file

BFFM2 - Boeing fuel flow methodology

BJ – Business jet

CAT II/III – Precision instrument approach and landing category II or III

CD – Compact Disc

CO – Carbon monoxide

CO2 – Carbon dioxide

ConOps - Concept of operations

CONUS - Continental United States

CTP – Commercial turboprop

DAC - Dynamic Airspace Concept

dB – Decibels

EA - Enterprise Architecture

EI- Emissions indices

ENV – Environment

EPNL - Effective perceived noise level

Ex - example

FAA- Federal Aviation Administration

FBO – Fixed base operator

FDS - Flight data set

FIT – Flight into terrain

FLOPS - Flight Optimization System

FOC - Flight operation center
Ft - Feet
GA – General aviation or general aviation aircraft
GCS – Ground control system for UAS
GHG – Green House Gas
GPS – Global positioning system
H2O - Water
HC – Hydrocarbon
HF – Human factors
HJ – Heavy jet
HWB - Hybrid wing body
ICAO – International Civil Aviation Organization
INM – Integrated Noise Model
IWP – Integrated Work Plan
JPDO – Joint Planning and Development Office
JPE – Joint Planning Environment
KPA - Key performance area
KTEB – Teterboro Airport
KTG - Kinematic Trajectory Generator
LAX – Los Angeles International Airport
Lbs - pounds
L/D – Lift to drag ratio
LJ - large jet
LMaxA - Maximum A-weighted sound level
LOS – Line of Sight
M - meters
MGTOW - Max gross take-off weight
Min - minutes
MPAS - Mesoscale prediction and analysis system
MT – Metric ton
NAS - National Airspace System
NASA – National Aeronautics and Space Administration
NextGen - Next Generation Air Transportation System
Nm – nautical miles
NorCal – Northern California
NOx – Nitrous oxide

NPD - Noise-power-distance curves

NRA – NASA Research Announcement

OEW - Operating empty weight

OPF - Operation performance file

Ops - Operations

PC Boom – Sonic boom model (originally for personal computers)

PM– Particulate matter

PNT – Positioning/navigation/timing

Prop - Propeller

PTF - Performance table file

R2- Correlation coefficient

R&D – Research and Development

RJ - Regional jet

ROT – Runway occupancy time

SESAR - Single European Sky ATM Research

SEL - Sound exposure level

SFO – San Francisco International Airport

SHT - Super heavy transport aircraft (including hybrid wing body versions)

SLA - System level assessment

SN – Smoke number

SO2 – Sulfur dioxode

SPL - Shielding prediction level (in db)

SSBJ – Super Sonic Business Jet

STI – Scientific and Technical Information

SUAS - Small uncrewed or unmanned aerial systems

TAF – FAA terminal area forecast

TBO - Trajectory based operation

TCAS – Traffic Collision Avoidance System

TFM – Traffic flow management

TO – take-off

TRACON – Terminal Area Control Facility

TSAM – Transportation System Analysis Model

UAS - uncrewed or unmanned aerial systems

UAV –uncrewed or unmanned aerial vehicle

UMD – University of Maryland

US – United States

VEH – Vehicle

VMC – Visual meteorological conditions

VFR – Visual Flight Rules

VLJ – Very Light Jet