A PROCESS FOR THE QUANTIFICATION OF AIRCRAFT NOISE AND EMISSIONS INTERDEPENDENCIES

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A PROCESS FOR THE QUANTIFICATION OF AIRCRAFT NOISE AND EMISSIONS INTERDEPENDENCIES

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To my family and specially, my wife

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ADP	Aero Design Point
AEDT	Aviation Environmental Design Tool
AHC	Analytic Hierarchy Process
AIA	Aerospace Industries Association
AIM	Aviation Integrated Modelling
ANOPP	Aircraft Noise Prediction Program
APMT	Aviation Portfolio Management Tool
AR	Aspect Ratio
ATA	Air Transport Association
BADA	Base of Aircraft DAta
BPR	Bypass Ratio
CAEE	Committee on Aircraft Engine Emissions
CAEP	Committee on Aviation Environmental Protection
CAN	Committee on Aircraft Noise
CAS	Corrected Airspeed
CD	Drag Coefficient
CD,0	Profile Drag Coefficient
CD,2	Induced Drag Coefficient
CL	Lift Coefficient
CMPGEN	Compressor Generator
CN	Cumulative Noise
CO	Carbon Monoxide
CO2	Carbon Dioxide

δ	deflection
δ	Pressure Ratio
dB	decibel
dBA	A-weighted decibel
DNL	Day Night Level
DoE	Design of Experiments
E	Oswald Efficiency factor
E	Modulus of Elasticity
EDMS	Emissions and Dispersion Modelling System
EDS	Environmental Design Space
EEA	European Environmental Agency
EINOx	Nitrogen Oxides Emissions Index
EPA	Environmental Protection Agency
EPNL	Effective Perceived Noise Level
^{o}F	Fahrenheit Degrees
f	Fuel flow
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
far	Fuel Air Ratio
FESG	Forecasting and Economic Support Group
FLOPS	Flight Optimization System
Fn	Net thrust
FPR	Fan Pressure Ratio
ft	feet
η	TSFC

GA	Genetic Algorithm
GEAE	General Electric Aircraft Engines
gr	gram
h	Altitude
H	Height
HC	Hydrocarbon
HLD	High Lift Devices
HPC	High Pressure Compressor
HPCPR	HPC Pressure Ratio
IATA	International Air Transport Association
Iw	Moment of Inertia based on Width
ICAO	International Civil Aviation Organization
ICCAIA	International Council for the Aerospace Industries Association
INM	Integrated Noise Module
IP	Information Paper
IPCC	Intergovernmental Panel on Climate Change
ISA	International Standard Atmosphere
IWATVP	Integrated Wing Aerospace Technology Validation Programme
kg	kilogram
kN	kilonewton
L	Length
lbs	pounds
LPC	Low Pressure Compressor
LPCPR	LPC Pressure Ratio
LTO	Landing Takeoff cycle

MAD	Multidisciplinary Analysis and Design
MADM	Multi-Attribute Decision Making
MAGENTA	Model for Assessing Global Exposure form Noise of Transport Airplanes
Mmax	Maximum Takeoff Gross Weight
MPD	Multi-Point Design
MSE	Modeling and Simulation Environment
NASA	National Aeronautics and Space Administration
NEPP	NASA Engine Performance Program
NEPCOMP	Navy Engine Performance Computer Program
NIST	National Institute of Standards and Technology
nmi	Nautical Mile
NOx	Nitrogen Oxides
NPD	Noise Power Distance
NPSS	Numerical Propulsion Systems Simulator
O2	Oxygen
O3	Ozone
OEC	Overall Evaluation Criterion
OPEC	Organization of Petroleum Exporting Countries
OPR	Overall Pressure Ratio
P	Load
Pamb	Ambient Pressure
PM	Particular Matter
PNLt	Perceived Noise Level, tone corrected
PO	Pareto Optimal
PR	Pressure Ratio

PREDATER	Preliminary Robust Engine Design Analysis Tool for Evaluating customer Return
Pref	Reference Pressure
psi	pound per square inch
θ	Temperature Ratio
QNEP	Quick Navy Engine Performance Program
RDT&E	Research, Development, Testing and Evaluation
RETIVO	Requirements, Technology Impact, and Value Optimisation
RPK	Revenue per Passenger Kilometer
SAE AIR	Society of Automotive Engineers Aerospace Information Report
SAGE	System for assessing Aviation’s Global Emissions
SEL	Sound Exposure Level
sg	Ground Roll Distance
SO2	Sulfuric Dioxide
Sw	Wing Area
T	Thrust
Tam	Ambient Temperature
TAS	True Airspeed
TL	Technology Level
TO	Takeoff
TOC	Top of Climb
TOGW	Takeoff Gross Weight
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TSFC	Thrust Specific Fuel Consumption
UEET	Ultra Efficient Engine Technology
UNEP	United Nations Environment Programme

UAV	Unmanned Air Vehicle
US	Unites States
V	Volume
V	Velocity
VOC	Volatile Organic Compounds
VSP	Vehicle Systems Program
W	Weight
WATE	Weight Analysis of Turbine Engines
WG	Working Group
Wi	Partial Importance Weight
WP	Working Paper
WPM	Weighted Product Model

SUMMARY

The main purpose of this dissertation is to develop a process to improve actual policy-making procedures in terms of aviation environmental effects. This research work expands current practices with physics based publicly available models. The current method uses solely information provided by industry members, and this information is usually proprietary, and not physically intuitive. The process herein proposed provides information regarding the interdependencies between the environmental effects of aircraft. These interdependencies are also tied to the actual physical parameters of the aircraft and the engine, making it more intuitive for decision-makers to understand the impacts to the vehicle due to different policy scenarios.

These scenarios involve the use of fleet analysis tools in which the existing aircraft are used to predict the environmental effects of imposing new stringency levels. The aircraft used are reduced to a series of coefficients that represent their performance, in terms of flight characteristics, fuel burn, noise, and emissions. These coefficients are then utilized to model flight operations and calculate what the environmental impacts of those aircraft are. If a particular aircraft does not meet the stringency to be analyzed, a technology response is applied to it, in order to meet that stringency. Depending on the level of reduction needed, this technology response can have an effect on the fuel burn characteristic of the aircraft.

Another important point of the current stringency analysis process is that it does not take into account both noise and emissions concurrently, but instead, it considers them separately, one at a time. This assumes that the interdependencies between the two do not exists, which is not realistic. The latest stringency process delineated in 2004 imposed a

2% fuel burn penalty for any required improvements on NOx, no matter the type of aircraft or engine, assuming that no company had the ability to produce a vehicle with similar characteristics. This left all the performance characteristics of the aircraft untouched, except for the fuel burn, including the noise performance.

The proposed alternative is to create a fleet of replacement aircraft to the current fleet that does not meet stringency. These replacement aircraft represent the achievable physical limits for state of the art systems. In this research work, the interdependencies between NOx, noise, and fuel burn are not neglected, and it is in fact necessary to take all three into account, simultaneously, to capture the physical limits that can be attained during a stringency analysis. In addition, the replacement aircraft show the linkage between environmental effects and fundamental aircraft and engine characteristics, something that has been neglected in previous policy making procedures. Another aspect that has been ignored is the creation of the coefficients used for the fleet analyses. In current literature, a defined process for the creation of those coefficients does not exist, but this research work develops a process to do so and demonstrates that the characteristics of the aircraft can be propagated to the coefficients and to the fleet analysis tools.

The implementation of the process proposed shows that, first, the environmental metrics can be linked to the physical attributes of the aircraft using non-proprietary, physics based tools, second, those interdependencies can be propagated to fleet level tools, and third, this propagation provides an improvement in the policy making process, by showing what needs to change in an aircraft to meet different stringency levels.

CHAPTER 1. INTRODUCTION AND MOTIVATION

The objective of policy making is the development of laws and regulations that are intended to improve the functioning of diverse aspects of life in society. In the area of civil aviation environmental protection, these regulations include setting limits in the amount of harmful pollutants that are produced by aircraft. Pollutants are divided in two classes: emissions from the combustion of hydrocarbons and noise. Laws are implemented locally in each particular country by that country's government. But the International Civil Aviation Organization (ICAO) and its environmental wing, the Committee on Aviation Environmental Protection (CAEP) help the individual countries collectively adopt limits that are low enough to protect the environment, while maintaining market feasibility. Historically, these limits have been provided by industry, based on their knowledge and years of experience. Because industry has different companies competing in the same market, the fundamental reasons for selecting these limits are not usually provided. In addition, the complexity of aviation and this lack of transparency have forced policy makers to make assumptions to cover a wide array of different systems. At the same time, the current process focuses on either noise or emissions and the impact that a stringency imposed on either would have on fuel burn characteristics. Advances in computational power have allowed CAEP to produce simulations of different stringency options and calculate the effect that they would have on the environment and on people's lives. Unfortunately, industry is still the sole provider of information regarding capabilities of existing and future systems. This research work will provide a solution to this problem utilizing modern modeling and simulation environments, as well as multi-attribute decision making techniques. This solution will provide CAEP with more insight and transparency to predict the effects of different stringency scenarios, which will provide policy makers with more information to set future regulations. The results of the process proposed in this research will also include the interdependencies that exist between noise and emissions, which have been neglected in the past. The ability to capture these interdependencies and propagate them to the policy making scenario will allow for the right policies to be selected for implementation. This also includes the consideration of the economic repercussions that implementing the policies could have [Ref. 1]. At the beginning of this chapter, the objective of policy making was stated as the improvement of diverse aspects of life. Aviation does not act locally, but rather spans the globe. Therefore, the bettering of its environmental impacts will benefit everyone.

In order to propose this process to improve policy making procedures, this document is structured into chapters that follow the logic of the scientific method. This first chapter includes the motivation for the overall research work. At the end of this chapter a series of research questions are proposed. These questions identify the gaps that were found in the current policy making process. The second chapter is composed of three relevant pieces of information, the metrics used to characterize an aircraft in terms of noise and emissions, the current policy making process, and the effects and production mechanisms of aviation noise and emissions. The understanding of these concepts is necessary for the subsequent comprehension of the rest of the document. The third chapter uses the research questions posed to explore possible alternatives to answering them. These possible solutions are formatted as hypotheses, and proving them true becomes the objective of this research work. The main solution is formulated as a process to quantify and propagate the interdependencies between the environmental metrics in aviation. The next chapter, Chapter 4, details the process proposed for the resolution of the problems identified in the first chapter, with the hypothesis described in the third. In the fifth chapter, the proposed approach is implemented in order to show the validity of the process. The example utilizes a 300 passenger wide body aircraft to show the effects that reducing emissions or noise would have on the other metrics. The results obtained provide the evidence needed to support the hypotheses. Finally, the last chapter draws conclusions based on the results obtained and delineates future work to be performed.

1.1 Policy Making

There are many agencies in the world that recognize that the environment needs to be protected. In the US, the Environmental Protection Agency (EPA) is the part of the government that, according to their mission statement, is in charge of protecting human health and the environment [Ref. 2]. Since the agency was created in 1970, the EPA's mission has included monitoring the quality of the air in and around the United States [Ref. 3]. In Europe, before the creation of the European Environmental Agency (EEA) in 2003, each individual country had its own agency, all with similar mission statements as that of the EPA [Ref. 4]. Now, the EEA is in charge of developing regulations for protecting the environment across the European community. Similarly, almost every industrialized country has an environmental protection agency in charge of creating regulations that will help preserve the environment's delicate equilibrium. In 1972, the United Nations Environment Programme (UNEP) was created to assess global environmental needs [Ref. 5]. The functions of UNEP include, but are not limited to, the promotion of international cooperation to protect the environment, the development of policy guidelines for within the United Nations programs, and the review of these programs' implementation, helping the individual governments promote environmental policies, and promote environmental research. UNEP works closely with the agencies inside countries to develop regulations to be implemented in the respective nations. From an aviation perspective, the United Nations' family of organizations also contains the ICAO, which deals with the civil aviation environment and proposes guidelines and rules for the entire world on aviation management. This organization was created in 1944 during the Convention on International Civil Aviation, also known as the Chicago Convention, with the following purpose:

> *"WHEREAS the future development of international civil aviation can greatly help to create and preserve friendship and understanding among the nations and peoples of the world, yet its abuse can become a threat to the general security; and*
>
> *WHEREAS it is desirable to avoid friction and to promote that co-operation between nations and peoples upon which the peace of the world depends;*
>
> *THEREFORE, the undersigned governments having agreed on certain principles and arrangements in order that international civil aviation may be developed in a safe and orderly manner and that international air transport services may be established on the basis of equality of opportunity and operated soundly and economically;*
>
> *Have accordingly concluded this Convention to that end." [Ref. 6]*

ICAO promotes the setting of regulations and guidelines worldwide, but it is not the organization that is responsible for imposing them. It is up to the individual countries to enforce policies regarding noise and emissions. From a U.S. aviation perspective, the Federal Aviation Administration (FAA) controls noise and emissions created by aircraft during their operations [Ref. 7]. But this was not the purpose of the agency when it was created in 1958. At that time, only safety and effectiveness were evaluated as the major concerns of aviation [Ref. 8]. The FAA is now charged with setting the standards for all aircraft flying inside, and to and from the US. In Europe, each country has its own organization, but a common agency also exists through the European Union Government that regulates the skies. But governments are not the only ones with an agenda to make the skies a cleaner and quieter environment, airports also know that noise and emissions are a big problem for the future. This is why they have begun to propose taxes to carriers that cause more than a specified level of pollutants to try to alleviate the effect of an increased number of flights on the environment [Ref. 9].

The ICAO is composed of many committees, one of which is CAEP. This committee was formed in 1983 by joining the Committee on Aircraft Noise (CAN) and the Committee on Aircraft Engine Emissions (CAEE). This merger took place in order to address the interdependencies of the measures to be taken, ensuring environmental effectiveness. In addition, the union was thought of as a cost reduction method since the work of both committees was very similar and many of the same people were working in the two groups [Ref. 10, 11, 12]. *CAEP's objective is to provide the Council of the ICAO with assistance in the formulation of new policies and standards* [Ref. 13]. The Committee is formed by individuals from various countries and international organizations. There are two participant levels in the committee, members and observers. The role of both is to discuss possible initiatives to be implemented that would reduce the impact of aviation in the environment. The difference between their roles is that observers cannot vote on the decisions being made. Only members can cast a ballot, and each vote has the same weight when casting the results. This means that the representative from the United States has the same decision power as the representative from Tunisia. In 1986 CAEP was formed, and the committee had their first formal meeting that year, called CAEP/1. Since then, they have met approximately every three years; their last reunion was in 2007, CAEP/7. CAEP/1 focused on noise certification procedures and setting noise and emissions standards to be met by newly certified aircraft. CAEP/2, in 1991, agreed on a reduction of NOx limits by 20% [Ref. 12]. CAEP/3 in 1995, ended without a consensus on decreasing the limits of noise but it did propose a NOx reduction of 16% with respect to CAEP/2 limits [Ref. 14]. A reduction in noise was not proposed until CAEP/4 in 1998, which limits were called Chapter III limits [Ref. 15]. CAEP/5, held in 2001, introduced Chapter 4 noise levels, which meant a 10 dB reduction from Chapter 3 [Ref. 16]. CAEP/6 in 2004, proposed a 12% reduction in NOx below CAEP/4 levels [Ref. 17]. The main objectives of each of the seven meetings with the dates they occurred are listed in Table 1. The regulations established in these reunions are also depicted in Figure 1 and Figure 2.

Table 1: CAEP Meetings Outcomes

Meeting	Date	NOx or Noise Reductions
CAEP/1	1986	Initial Meeting Set NOx and noise standards (Chapter 2)
CAEP/2	1991	New NOx Standard, 20% less than CAEP/1
CAEP/3	1995	No noise reductions decided on in meeting.. NOx reduced 16% from CAEP/2
CAEP/4	1998	New noise standard (Chapter 3)
CAEP/5	2001	New noise standard , called Chapter 4, 10 EPNdB less than Chapter 3
CAEP/6	2004	New NOx Standard, 12% reduction from CAEP/3
CAEP/7	2007	No reductions decided on meeting

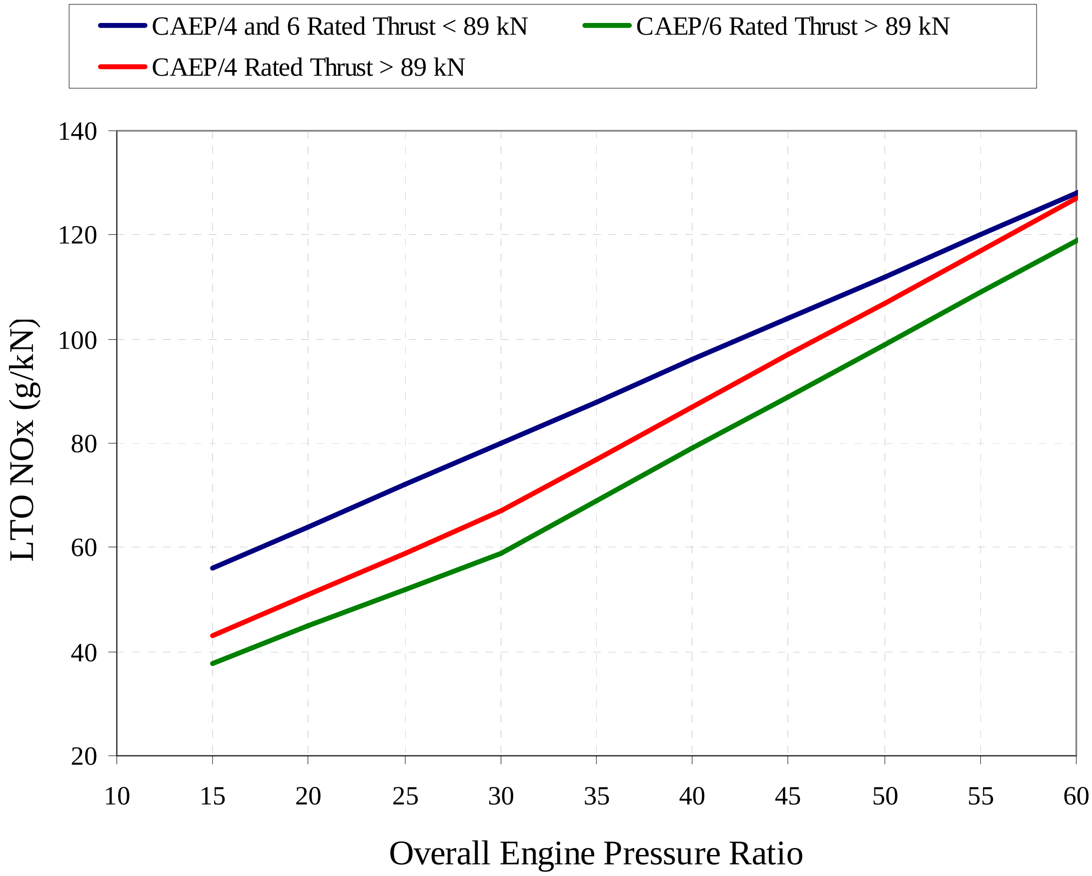

Figure 1: ICAO NOx Emission Limits

It is worth mentioning that *the common practice of CAEP is to propose new standards for either noise or NOx, not both at the same time*. This was established due to the lack of information about the interdependencies that exist between noise and NOx emissions. In addition, traditional aircraft and engine design has been done discipline-independent. This means that the different disciplines, like propulsion, aerodynamics, or structures, work independently from each other and only communicate sporadically. Following this same rationale, the CAEP process was also discipline-independent.

The metric used for nitrogen oxides is the LTO NOx . This metric is the amount of NOx emitted during a Landing Takeoff cycle (LTO), divided by the net sea level static thrust of the engine. The NOx limits depend on the overall engine pressure ratio, with a positive slope. The sea level static thrust of the engine is also part of the equation, allowing larger NOx emissions for comparatively smaller engines.

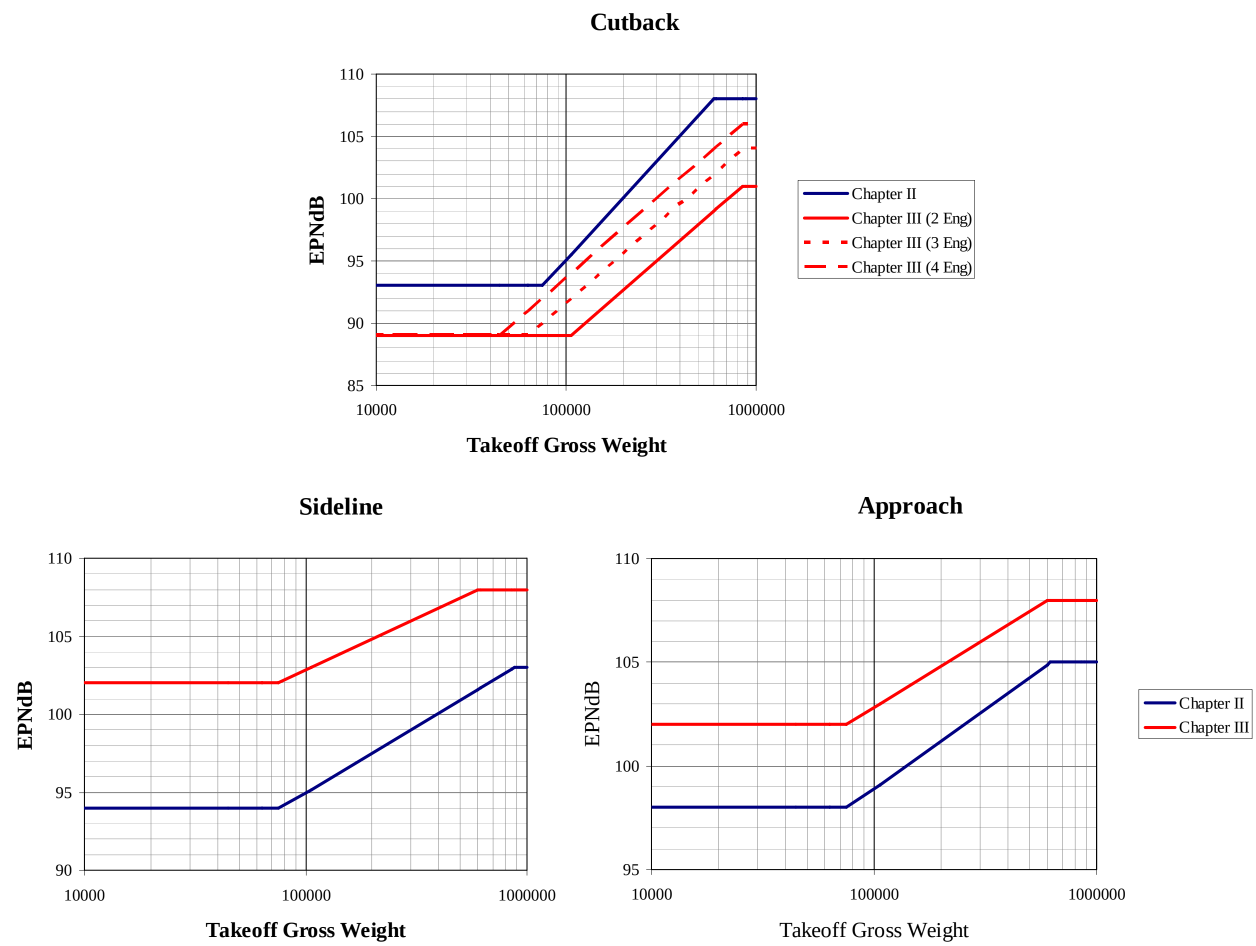

Figure 2: ICAO Noise Limits

The noise limits depicted in Figure 2 are based on the takeoff gross weight of the aircraft. There are three levels used in certification of aircraft: cutback, sideline, and approach. The first two are related to the noise that an aircraft produces during takeoff, while the third deals with the noise during landing. The main difference between cutback and sideline, other than where the observer is located, is the fact that for cutback, the flight profile includes a thrust reduction, or cutback, in order to reduce the overall noise of the aircraft. The metric used is the Effective Perceived Noise Level (EPNL), in decibels (dB). The EPNL was developed by the FAA to measure the subjective effect of aircraft noise on humans. This metric is calculated by using instantaneous noise measurements at an observer location, and then applying a correcting factor for tones and duration [Ref. 18]. In the graphs, only Chapter II and III are shown because Chapter IV limits are based on the cumulative noise, which is the addition of the three certification noise levels.

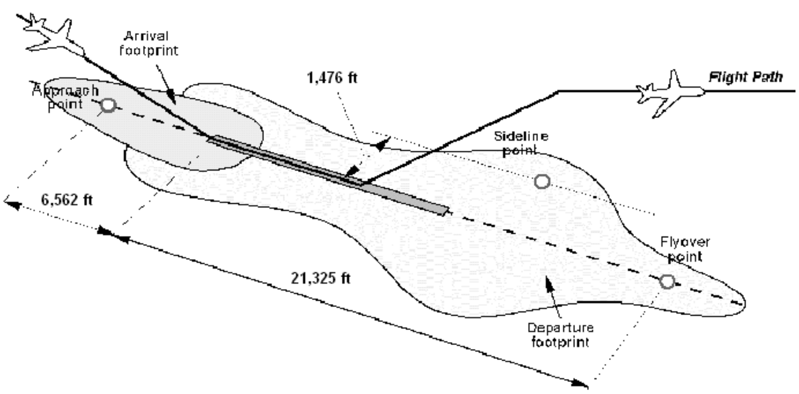

Figure 3: Noise Certification Procedure [Ref. 19]

The limits start at a level and increase constantly with the logarithm of the takeoff weight until a plateau is reached for very large takeoff gross weights. For cutback, the limit depends on the number of engines, whereas sideline and approach are not dependent on it. There is also a measurement called the cumulative noise margin, which is the addition of the differences between each noise point and its limit. The procedure to calculate the three certification points used for noise, as well as the NOx levels, will be explained in detail in CHAPTER 2. A schematic of the trajectory of the aircraft and the position of the observers for this purpose is depicted in Figure 3 [Ref. 19].

1.2 Recent Stringency Process

In September 1999, CAEP supported a workshop in which emissions were the main issue [Ref. 20]. In this workshop, a study developed by the Aerospace Industries Association (AIA) and the Air Transport Association (ATA) was unveiled in which it was stated that interdependencies between noise, NOx, and fuel burn are due to fundamental physical principles and should be considered when setting future stringency. This report also declared that more detailed studies would be needed to understand fully the interdependencies between the three measures: noise, NOx, and fuel burn. Although this information was provided to CAEP members, interdependency assessments to develop new stringency were not fully explored after the workshop.

A very important paper that came out of CAEP/6 was the Information Paper number 13 (IP13). This paper explains in detail the process by which the analysis of NOx stringency is performed [Ref. 21]. The main idea of Information Paper 13 of CAEP/6 is to determine how to study the impact of introducing a NOx stringency in the future that some of the current aircraft cannot meet. An important assumption from IP13, for this research, is that each aircraft engine combination is reduced to a series of coefficients that represent its performance, in terms of noise, fuel burn, and emissions. These coefficients are used in equations defined in the Base of Aircraft Data (BADA, for in route performance calculations, and the Society of Automotive Engineers Aerospace Information Report 1845 (SAE AIR 1845) for terminal area performance calculations, and they are compiled in a series of databases [Ref. 22,23]. *All of this data is used to determine the impact of introducing a new stringency, giving a dollar value to the effects that noise and emissions have on the population and the environment.* Different scenarios are studied, which represent stringency levels implemented at different points in time. The aircraft models are used to calculate the overall emissions, fuel burn, and noise produced with and without the new stringencies being imposed. The comparison of the results of the baseline case, that is where no stringency is imposed, to the other cases, is used to determine which stringency level is more appropriate to pursue. Given a new stringency, not all the aircraft in the database would be able to meet this new level. The assumption made by IP13 is that it would be possible for aircraft/engine combinations that do not meet the new stringency to achieve it by implementing a specific level of technology. This implementation is what is called applying a technology response, and it exemplifies what could be achieved by industry were a stringency level imposed. Specifically, there were five levels of technology that could be used. These technology levels, as well as their economic impacts and the related information, were provided by the International Council for the Aerospace Industries Association (ICCAIA). For the first level of technology, TL1, it is assumed that a reduction of up to 5% can be achieved with no fuel burn penalty, and a figure of $10 million is provided for the cost of implementing such technology. This technology can be implemented the year preceding the introduction of the new stringency. The second level of technology, TL2, would be implemented if more reduction is needed, and the same company has proven in another family of engines the necessary reduction. This assumes that the technology can be scaled up or down to the required family, and it would not have any impact on the fuel burn. This technology level has an associated cost of $50 million, and it would require four years to be implemented. If the company has no proven technology that can achieve the required levels of NOx emissions, but a rival company can, it is assumed that the reduction can be achieved with no impact on the fuel burn, but at a cost of $75 to $150 million. This technology is known as TL5A and it would also require four years before the technology is ready for introduction. TL5B, the last technology level, implies that no company has been able to achieve the required reduction in NOx emissions, and the implementation of the technology would degrade the fuel burn by 2%. A TL5B technology would have a cost of $500 to $1,000 million. Figure 4 represents the minimum NOx levels below CAEP/4 that could be achieved by each family of engines, with an associated fuel burn penalty. What this figure represents is that for the first four families of engines, the AE3007, and the CF34-3, -8, and -10, a reduction of up to 30% can be achieved without incurring any fuel burn penalty. For the following six families, from the BR700 to the RB211-524, the 30 % reduction can be achieved, but with a 2% increase in fuel burn.

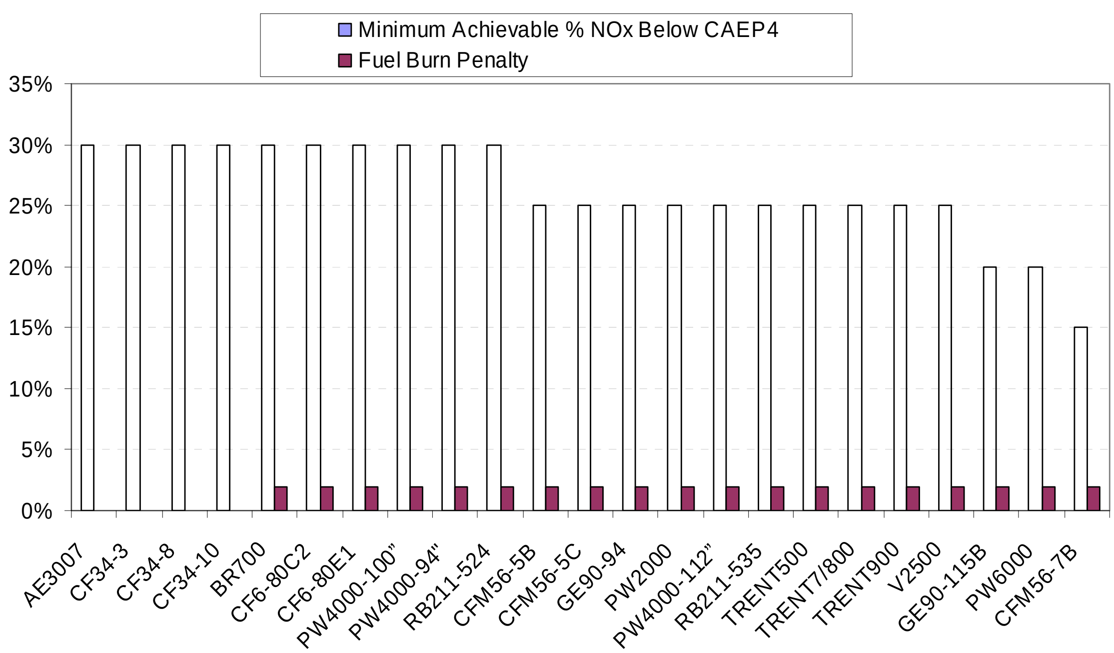

Figure 4: Fuel Burn Penalty vs. NOx Below CAEP/4 Achieved

With the next families of engines, from the CFM56-5B to the V2500, the plot explains that in order to achieve a level 25% below CAEP/4 or higher, a 2% fuel burn penalty will happen. The next two families, the GE90-94 and the PW6000, will incur the 2% fuel burn penalty when the levels need to be below 20% of CAEP/4, and for the last family, the CFM56-7B, the fuel burn penalty will start from a reduction of 15% on.

The first observation to be made from the current stringency process, denoted as Observation A, is that there is no physical correlation between the NOx and the fuel burn, and that, for TL5B implementation, the fuel burn penalty is constant at 2%, no matter how much NOx reduction is needed. *These assumptions are based on industry input*, which has historical data to predict these trends, analysis tools, calibrated with real performance information, and years of expertise in designing and manufacturing engines. But all these attributes are the basis of each company, and thus, they are protected as “family jewels”. No company will provide any of them voluntarily because of the risk of losing a competitive edge. The protection of the proprietary information is done by the use of the database of coefficients mentioned above, which represent each vehicle by a series of coefficients. This lack of transparency makes the *physical relationships that may exist between NOx and fuel burn not intuitively obvious*, from the information provided by ICCAIA. In addition, there is no information about how the NOx and fuel burn relate to the characteristics of the aircraft. This is useful for considering what has to be made in order to achieve the required stringency levels. This observation leads the reader to two questions. The answering of these questions would assure that the data used for policy making has a physical basis, and it is,at the same time, transparent in nature.

What are the physical aircraft and engine characteristics that contribute to the environmental key measures?

Can these physical attributes be determined utilizing non-proprietary, public domain data and tools?

Observation B addresses the assumption that no matter what *reduction of NOx is required, the fuel burn increase associated is always constant*. Along the lines of this observation, another one exists regarding the limits that could be obtained, in terms of reduction of NOx. Right now there is no limit stated, so the assumption is that any reduction is possible. These two observations lead to two questions that should be answered.

Is this constant technology response assumption appropriate? And if not, how can it be improved?

What are the physical limits in terms of NOx, noise, and fuel burn; and how do they affect each other?

A final observation was made regarding the key measures being sought. The study proposed in IP13 only related NOx and fuel burn, leaving noise unaffected. This assumption will be noted as Observation C. The reader should ask whether there are relationships between the three. If the response to this question is affirmative, a logical follow-up question would be whether the interdependencies can be established using physics based modeling tools.

In regards to the BADA and SAE AIR 1845 databases, the manner in which the coefficients are used to predict or approximate the performance of any given aircraft is described, but *how the coefficients are to be calculated is not specified*. Extensive research was performed, but no clear indication was found as to how the different aircraft and engine manufacturers provide those coefficients, only a few scattered documents exist, but they do not cover the entire database. *These coefficients are fundamental to the stringency analysis process since they are used to model the effects of aviation.* The validity of the coefficients with respect to the physical world is necessary if the results from the analysis are to be relevant. There is a logical question that comes up based on this observation.

How could a process to create these coefficients be created?

A summary of the observations described above, as well as the questions that arise from them, is shown in the following section for clarity.

1.3 Research Questions

The research questions presented above form the basis of this research work. These questions are summarized here for the reader's convenience. They are divided into four groups, based on the observation they were produced from. All the observations have to do with the current technology response used by policy makers to represent the interdependencies that exist between the environmental metrics. The nature of the technology response is such that it represents the achievable limits on these metrics and the relationships that exist between them.

- Observation A. Current technology response does not provide physical relations between NOx and fuel burn, due to competitive issues between companies.

  Research Question A.1. What are the physical aircraft and engine characteristics that contribute to the environmental key measures?

Research Question A.2. Can these physical attributes be determined utilizing non-proprietary, public domain data and tools?

Research Question A.3. How can the traceability of the data be assured?

- Observation B. Current technology response assumes a constant fuel burn penalty for any NOx reduction.

Research Question B.1. Is the assumption of constant fuel burn penalty appropriate for the technology response?

Research Question B.2. If not, how can it be improved?

- Observation C. Current technology response only connects NOx emissions and fuel burn, leaving noise outside of the area of study.

Research Question C.1. Can the physical interdependencies of NOx, fuel burn, and noise be established using physics based modeling tools?

Research Question C.2. What assumptions can be made or have to be made?

- Observation D. A clear process for the calculation of BADA and SAE AIR 1845 coefficients does not exist.

Research Question D.1. Can a process be created to delineate the calculation of the coefficients to populate the BADA and AIR 1845 databases?

CHAPTER 2. BACKGROUND

The previous chapter, CHAPTER 1, defined the problems that are to be tackled in this research work. The main objective is to answer the research questions that were established. But there are some important concepts that need to be explained before any further progress is made. These concepts include the metrics used in the certification of aircraft, in terms of noise and emissions, as well as the importance of reducing the noise and emissions, along with the fundamental processes that create them in aircraft operations.

2.1 Noise and NOx Emissions Certification Levels

The noise characteristics used to certify an aircraft are defined in the Code of Federal Regulations Title 14, Part 36 [Ref. 24]. They are the noise levels at three specific observer points from the trajectory of the aircraft: two of them are for takeoff, cutback and sideline, and the third is for landing. Figure 5 shows a notional trajectory along with the location of the three observers [Ref. 25]. The ambient conditions for the certification procedure have to be 2,116 psf of ambient pressure, 77^{o}F of temperature, and a relative humidity of 70%. The runway must not have any inclination and there should not be any wind. As shown in the figure, the observer for the approach noise level has to be 6,562 ft behind the beginning of the runway, in the centerline. The beginning of the runway is assumed to be at the point where the aircraft is 50 ft above ground. The community reference observer, also called cutback or simply takeoff, is situated in the centerline, but 21,325 ft from the brake release point. The sideline observer is located at either side of the runway, 1,476 ft from the centerline. The location on that line is at the point where the aircraft produces the most noise.

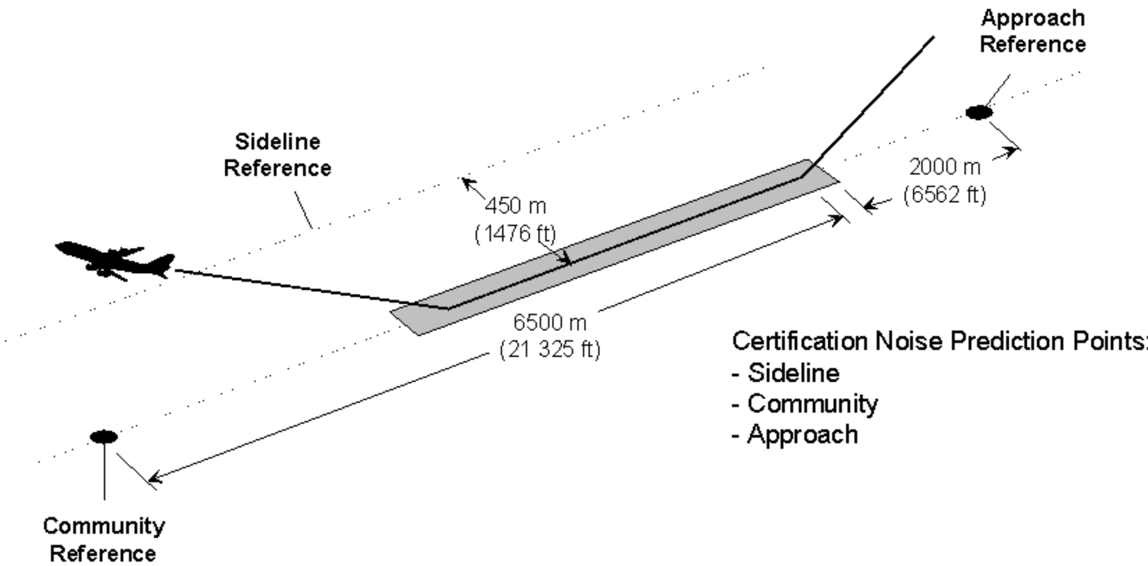

Figure 5: Noise Certification Procedure [Ref. 25]

In terms of the actual procedure for the aircraft, for the landing, the aircraft configuration has to be that of loudest noise, the velocity of the aircraft is set to 1.3 times the stall speed plus 10 knots, gliding at a descent angle of 3^o. The weight of the aircraft has to be the maximum weight for which it is being certified. For the cutback procedure, the configuration of the flaps has to be the maximum allowable for takeoff, and has to be kept throughout the procedure. The weight has to be the maximum takeoff gross weight. The velocity of the aircraft is to be kept constant after takeoff, varying only the climb angle after cutback. This cutback has to be performed after the aircraft reaches 984 ft, and the power has to be reduced to the greater power of that that would allow a climb angle of 4^o, or level flight with one engine out. The sideline noise limit is calculated without performing the power cutback, so the full power is used throughout.

The metric used for noise certification is the EPNL, as mentioned in CHAPTER 1. This unit was developed by the FAA and it consists of a compilation of instantaneous noise measurements corrected for tones and duration. The procedure to calculate this

EPNL is complex, but it is explained in detail in the Code of Federal Regulations, Title 14, in Section 4 of Appendix A to Part 36 [Ref. 24].

The NOx level used to certify an aircraft is defined in the ICAO Annex 16 to the Convention on International Civil Aviation [Ref. 26]. It represents the NOx emissions that an engine would emit in a landing-takeoff cycle, commonly known as LTO NOx, and represented in Equation 1. It is composed of the addition of four overall emissions, for four different power settings, over a determined amount of time. The power settings and times are 100% for 0.7 minutes, 85% for 2.2 minutes, 30% for 4 minutes, and 7% for 24 minutes. All of them are a percentage of the maximum static thrust.

Equation 1: LTO NOx Calculation

$$LTO\ NOx = \frac{EINOx_{100\%} \cdot f_{100\%} \cdot 0.7 + EINOx_{85\%} \cdot f_{85\%} \cdot 2.2 + EINOx_{30\%} \cdot f_{30\%} \cdot 4 + EINOx_{7\%} \cdot f_{7\%} \cdot 24}{Fn_{SLS}}$$

The calculation has to be performed with the engine on its test bed and with the ambient conditions defined as ISA at sea level, with the exception that the humidity has to be 0.00629 kg water/kg dry air. The amount of NOx in grams has to be divided by the maximum thrust in kN, so that the units of the measurement are gr/kN.

Now that the metrics used to quantify the effects of airraft in terms of noise and emissions has been explained, it is time to describe the process by which specific limits are set. The following section describes this process, as proposed by CAEP/6.

2.2 Aviation Policy Making Process

It is important to anchor any research work to show its relevance. In the case of this research, the main area to which it is connected to is policy making with respect to aviation environmental protection. The process that is described in this section is the one outlined in the CAEP Information Paper number 13 [Ref. 21].

The policy making process proposed in IP13 is performed by selecting among different stringency levels, which one is the most economically viable. This viability depends on the economic impacts that would be incurred by implementing said stringency levels. The cost of each policy is compared to that of a baseline case, where no stringency is utilized. In order to calculate these economic effects, information has to be propagated from the aircraft level to the fleet and the environment levels. Figure 6 shows all the modules used in this procedure [Refs. 27, 28, 29]. For each policy stringency level being studied, a scenario is produced and defined. This scenario includes the level of stringency and the timeframe of implementation. The ICCAIA (International Council on Aerospace Industries Association) provides information regarding the effect that achieving a required stringency would have on noise and fuel burn at the aircraft level. In addition, performance characteristics of the different aircraft are also provided by this association. Using available data from real flights, economic models decide on the number of flights and the schedules to be used in the analysis. These flights are then modeled by the AEDT to predict the emissions in terms of fuel burn and other pollutants, and noise, from all the aircraft in the current fleet.

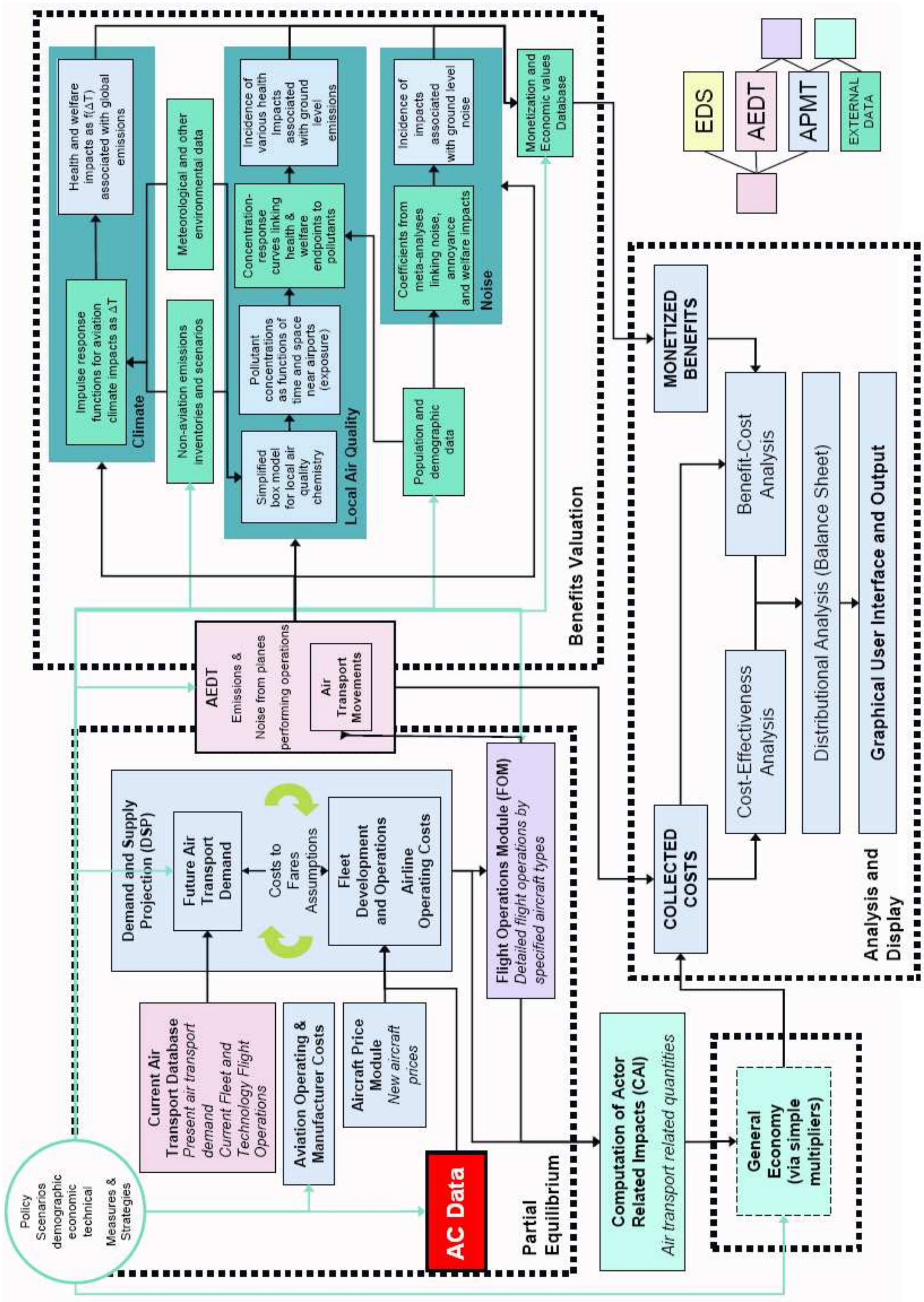

Figure 6: CAEP Tool Connectivity and Logic Flow [Ref. 29]

The way in which the AEDT models these flights is by utilizing the BADA and SAE AIR 1845 coefficients, already mentioned in the previous chapter. These coefficients represent the performance of each aircraft/engine combination in terms of fuel burn, noise, emissions, and flight characteristics. The emissions from all the aircraft in the fleet are added up, and so are the noise contours from their takeoffs and landings. A series of monetizations are made to assign a dollar value to each of these emissions, in terms of the climate impacts, local air quality, and noise impacts. This process is performed for the baseline case, where no stringency is being proposed, and then repeated for the different stringency levels being studied. For each scenario, there would be a number of aircraft that could not meet the studied stringency, and to those the technology response would be applied to. The technology response was defined before as a fuel burn penalty of 2% for any required NOx reduction. The different scenarios would have a different level of emissions in each case, thus resulting in different costs of implementation. These different costs are the ones used to determine which stringency level is more viable.

As it was stated at the beginning of this document, there exists a need in the information passed by ICCAIA, the technology response, to be more physics based, so that it properly captures the interdependencies between the environmental measures being studied. The information actually being provided lacks in transparency, and traceability to physical characteristics of the aircraft and engine. This is the area where the focus of this research work is placed. The importance of this information is due to the effect that inaccurate information provided at this early stage could have. A simple example is provided in Figure 7 to show how the relationship between the environmental measures at the aircraft level impact the policy making decisions. In this example two NOx reduction policies are being studied, and compared to the baseline case.

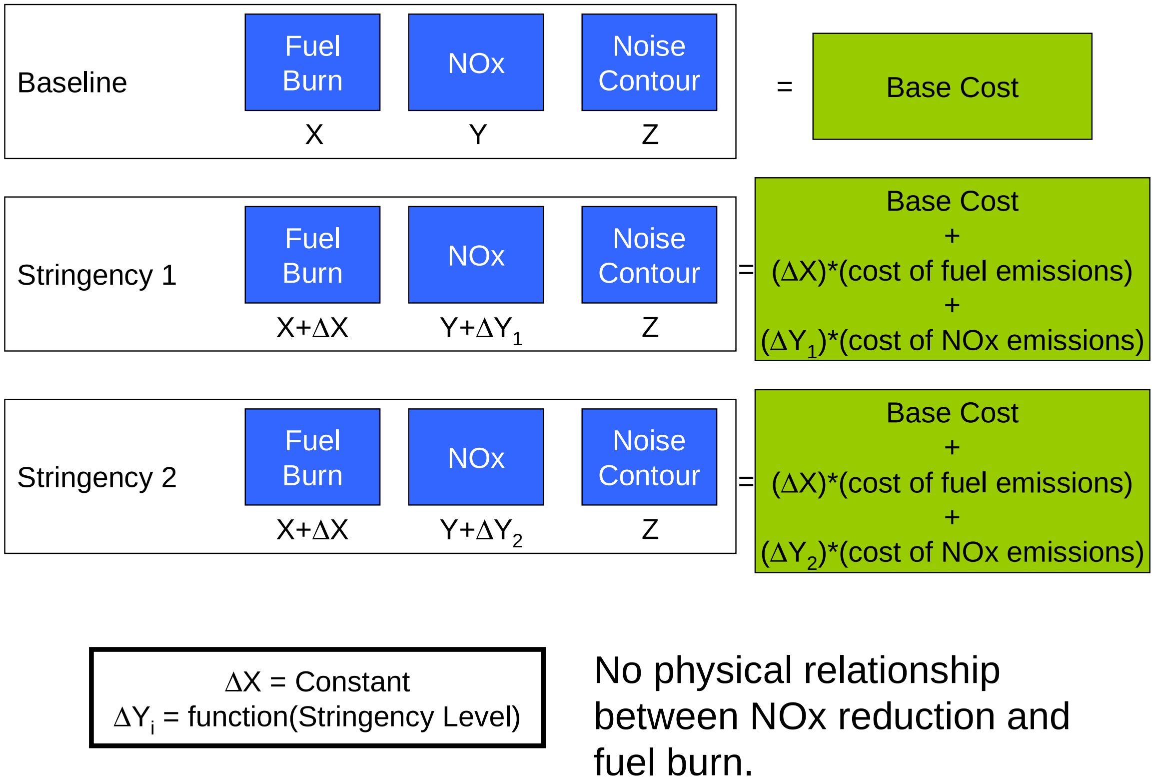

Figure 7: Example on Impact of Aircraft Interdependencies on Policy Making

The effect on fuel burn is shown as what is provided currently by ICCAIA for any NOx reduction required. Using simple algebra it is observed that the difference between the cost of stringency 1 and stringency 2 is only the cost of reduced NOx emissions. This is as to say that a bigger reduction is always better and, based on the relationship provided by industry, there is no limit in how much that reduction can be. If instead of the currently used relationships between NOx and fuel burn, physically tied ones were used, the process would be more similar to the one shown in Figure 8. In this case, depending on what the interdependencies between NOx, noise, and fuel burn are, the differences between the stringencies would have physical meaning, and would provide a true representation of the differences of implementation of the two stringencies.

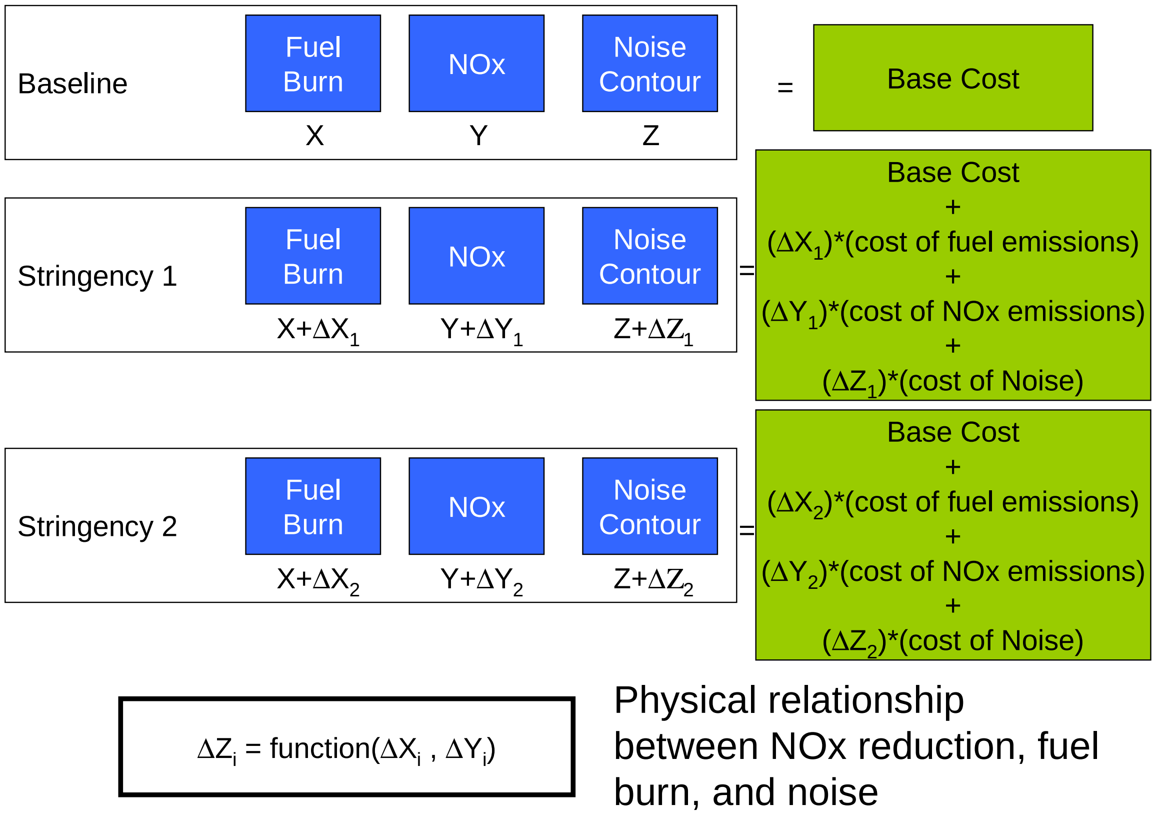

Figure 8: Example Using Physics Based Interdependencies Information

After understanding the process by which aviation environmental effects are regulated, it is important to understand why these two characteristics of aviation are significant. In the next section the effect that both noise and emissions have on the environment and humans are explained. At the same time, the process by which they are produced during the regular operations of aircraft is also described.

2.3 Aviation Environmental Impacts

Although natural occurrences, like wild fires and volcano eruptions, produce damaging effects to the atmosphere, most of the harm inflicted on earth is air pollution, caused by humans and daily life activities. The utilization of fossil fuels for energy production is the greatest contributor to air pollution [Ref. 30]. The effects of air pollution are well known and vastly documented throughout the world, and include not only respiratory problems, but also damage to the cardiovascular system and skin [Refs. 31, 32, 33]. While air pollution is the most talked about and commonly known form of contamination, noise pollution also produces a significant reduction in the quality of life and can even create health issues, specifically hearing problems that can be permanent [Refs. 34, 35]. Other indirect effects of noise contamination include increased blood pressure, elevated cholesterol levels and heart rate, and damaged digestive and respiratory systems. Also, stress and depression can be caused by this air contamination, leading to more extreme consequences, like suicide [Refs. 36, 37].

The total amount of harmful pollutants emitted by aircraft is less than 3% of the overall hydrocarbon combustion emissions [Ref. 47]. However, since most of these emissions take place in the upper layers of the atmosphere, their effects are particularly damaging [Ref. 38]. A 3% contribution may not seem significant to life on the Earth's surface, but these emissions can damage the ozone layer, decreasing the protection it provides from the Sun. In addition, the noise produced from aircraft operations is also very significant around airports, which are usually located close to densely populated areas. The noise produced by aircraft can reduce the quality of life of those living around airports: it is known to decrease the amount of sleep, along with many other physical and mental health problems, like unbalanced blood chemistry or depression [Ref. 39].

2.3.1 Emissions

During the last century, the amount of emissions from fossil carbon related materials has gone from almost insignificant to over sixty-five hundred millions of metric tons a year [Ref. 40]. In the early 1800' to the 1900's the usage of carbon was mostly coal, used in the early development of the industrial revolution, as depicted in Figure 9.

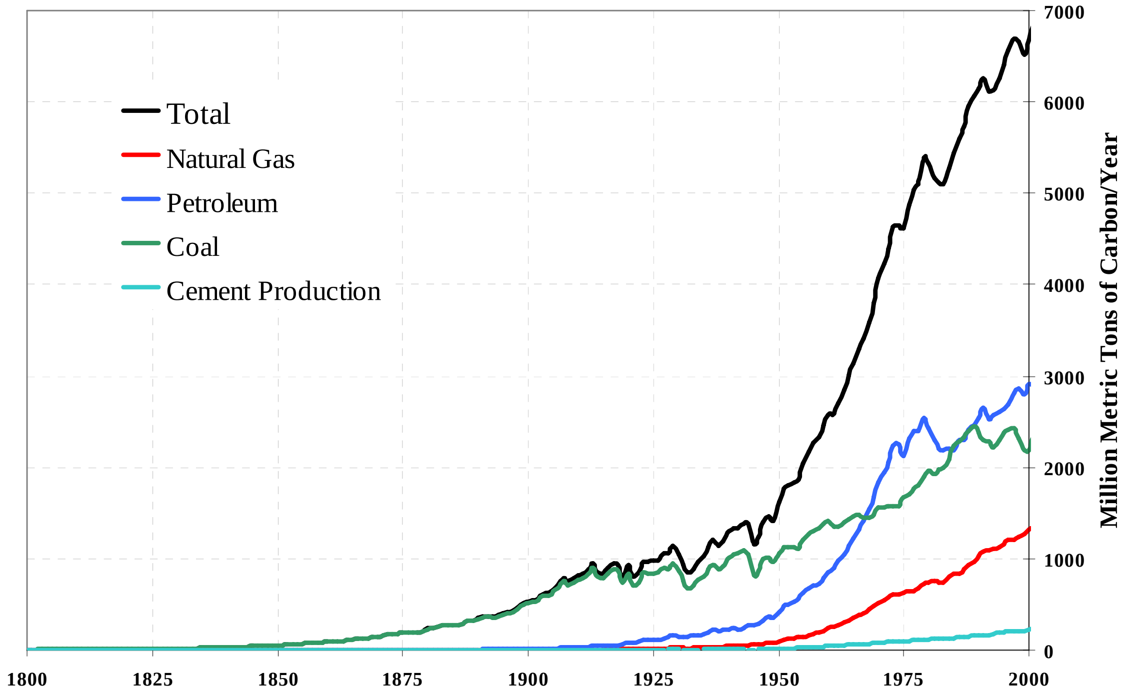

Figure 9: Global Fossil Carbon Emissions [Ref. 40]

Another significant milestone from this time period is the widespread use of electricity, starting with the invention by Edison of the incandescent light bulb in 1879 [Ref. 41]. After 1900, oil and petroleum becomes part of this energy usage, thus decreasing the growth in the emissions rate due to a cleaner burn. From 1950 on, a rapid increase in petroleum usage starts, which corresponds with the drastic increase in population that happens after World War II [Ref. 42]. In the 1970's we see a decrease in the emissions, mostly due to the oil embargo from the Organization of Petroleum Exporting Countries to the west [Refs. 43, 44]. After the embargo was lifted, oil usage was reduced mostly by two reasons: the price of crude increased, and also the western governments realized that oil should not be the only energy source [Ref. 45]. In the last 50 years, fossil fuel usage has jumped by more than 300 percent. If this trend continues for the next 50 years, the global impact could be devastating since one of the major players in global warming is thought to be CO_2 emitted from carbon emissions [Ref. 46]. According to the Intergovernmental Panel on Climate Change (IPCC), the demand for aviation will increase by 250% from 1996 to 2015 and exacerbate the issue [Ref. 47].

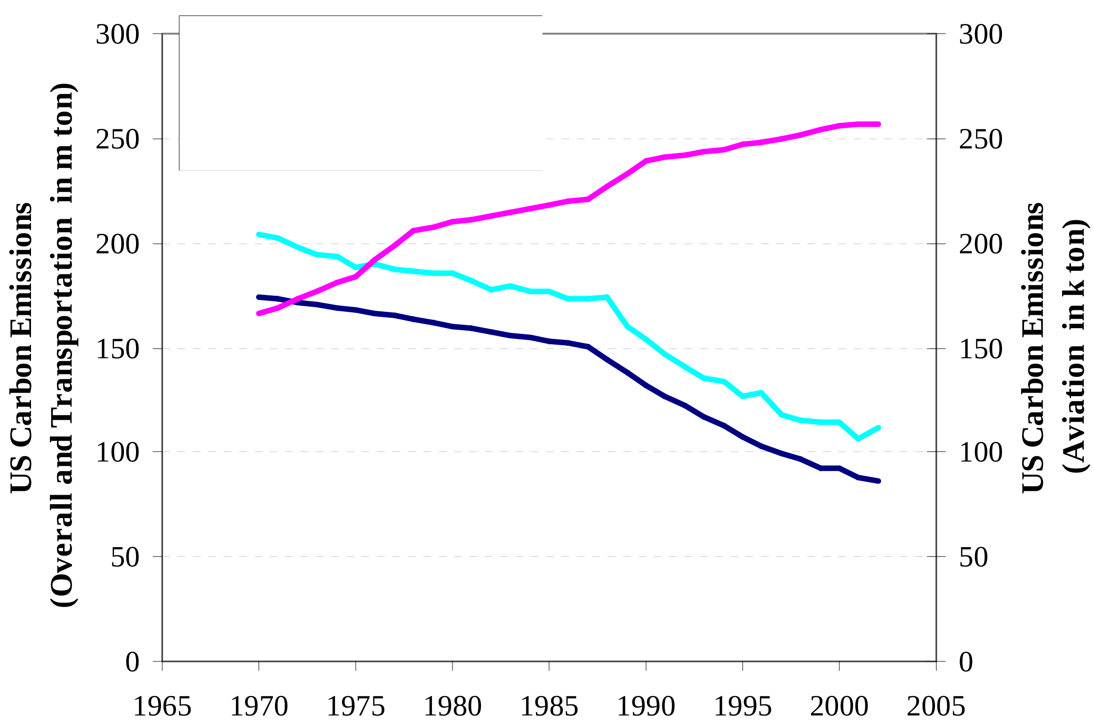

Figure 10: Emissions of Carbon in the US

In the US, most of the emissions of carbon due to liquid fuel come from transportation sources, as depicted in Figure 10, although fuel burn for energy production, industrial processes, residential fireplaces, and other fires, like forest wildfires, also contribute [Ref. 48]. Transportation emissions of carbon account for more than 70% of the overall emissions and aviation is a significant contributor.

The amounts of carbon emissions for transportation and also the overall emissions are in millions of tons, while the aviation emissions are in thousands of tons. While overall emissions and those due to transportation have decreased, the emissions due to aviation have increased over time. Aviation Carbon related emissions are directly proportional to the cruise thrust specific fuel consumption (TSFC). Since 1970, TSFC has been improving due to more efficient turbofan engines, as shown in Figure 12 [Refs 49, 50, 51, 52, 53]. However, the total demand for aircraft related travel has been increasing and is expected to continue in terms of revenue per passenger-kilometer (RPK) as shown in Figure 11 [Ref. 54].

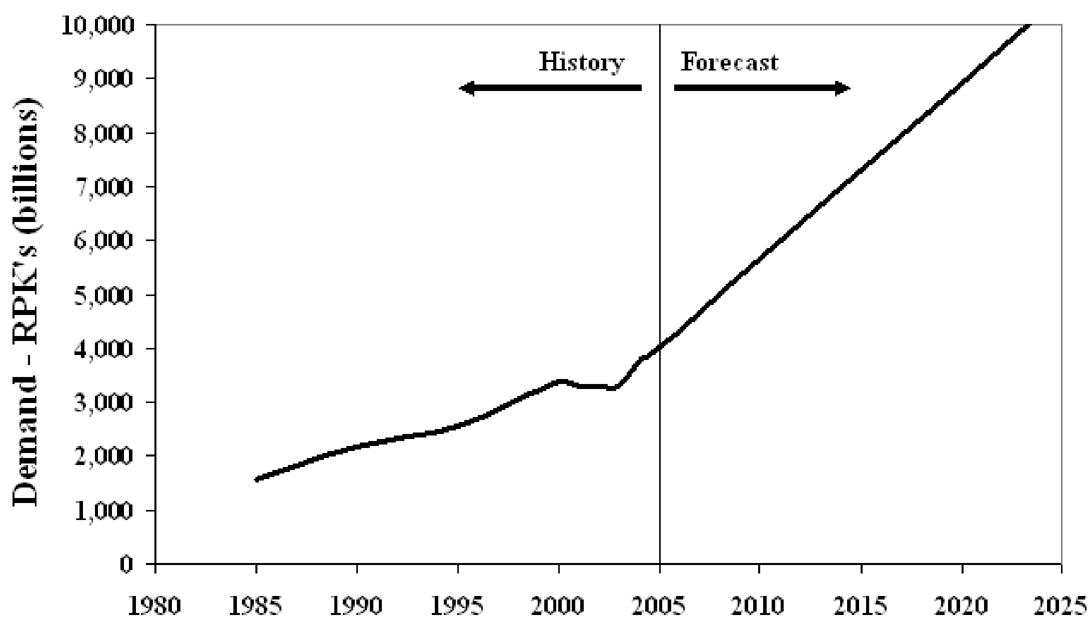

Figure 11: Trends in Aviation Demand [Ref. 54]

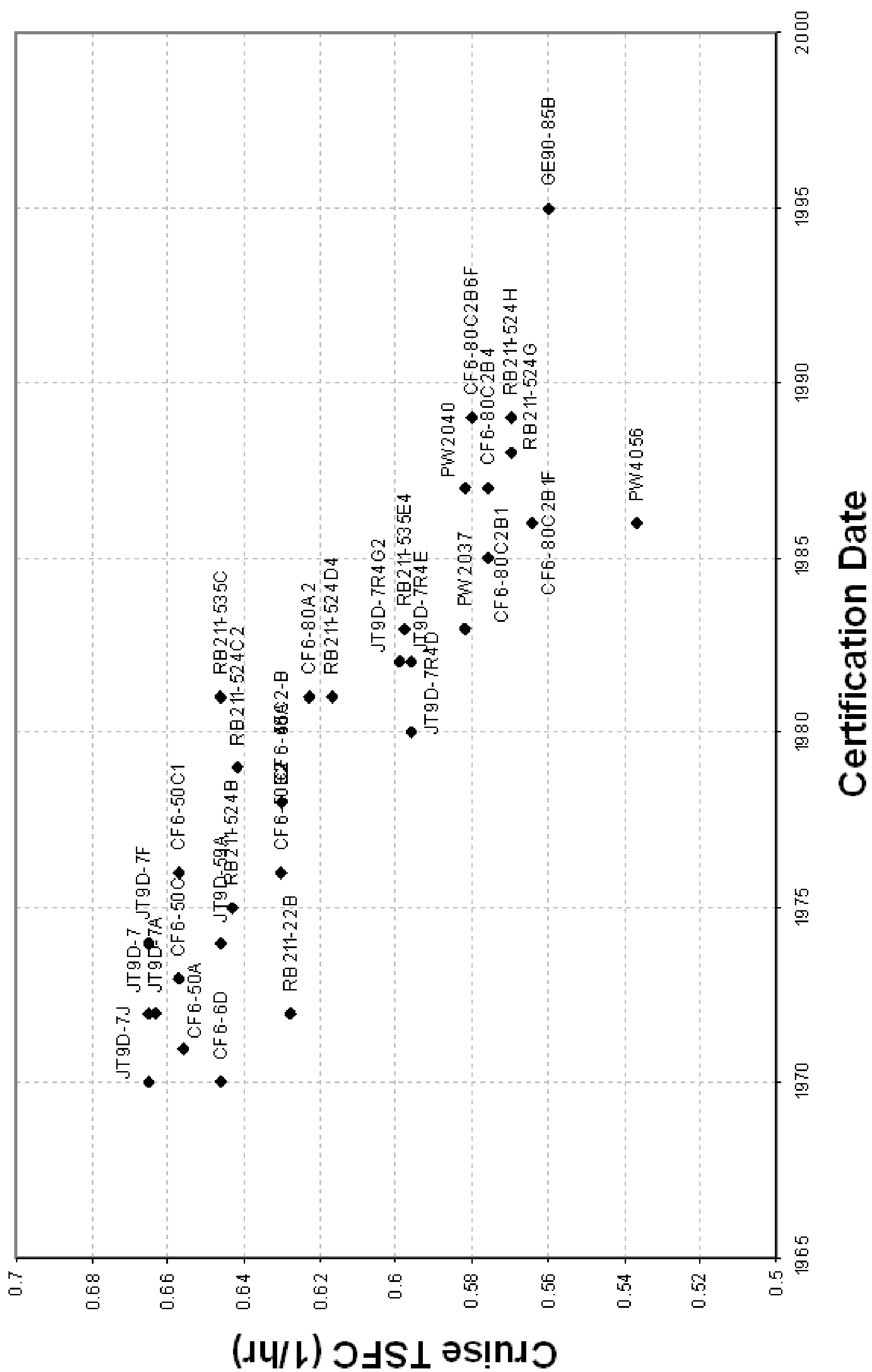

Figure 12: Historical Trend of Cruise TSFC

A spike in demand directly affects the number, type, and distance of aircraft being flown on a given day. Although demand reduced after the World Trade Center attacks in 2001, an increasing trend has resumed, with an even higher growth rate than before, and it is expected to double by 2025. Although fuel efficiency has been improving over the last few years, the benefit of the reduced emissions has been offset by the increased demand in the number of flights per day; thus making it imperative to implement policies that reduce the amount of harmful emissions to the atmosphere through aircraft related operations.

2.3.1.1 Creation of Emissions

The main purpose of the combustor in an aircraft engine is to mix air and fuel and burn the mixture. Combustion increases the temperature of the flow through the engine, thus increasing the energy that the air flow possesses [Ref. 55]. This energy is later extracted from the flow in the turbines to power the compressors and after that to produce thrust. In an ideal combustor, only oxygen would form the air coming in and only a hydrocarbon would be the fuel, and the combustion process could be written as in Equation 2. The amounts of both the hydrocarbon and the oxygen would also have to be regulated for a complete combustion. If there is any unbalance, there would be remains of one or both of the reactants. For this reaction to occur, specific temperature and pressure conditions must be met, or the process would not be complete.

Equation 2: Ideal Hydrocarbon Combustion

$$C_nH_m + \left(n + \frac{m}{4}\right) \cdot O_2 \rightarrow n \cdot CO_2 + \frac{m}{2} \cdot H_2O$$

In reality, this reaction is not valid. The air coming in is composed mostly of nitrogen and some oxygen, and the fuel also has other additives, including sulfur. The reactions that take place inside the combustor resemble Equation 3 more than Equation 2. In this reaction not only is the combustion incomplete, as there are remains of both fuel and air afterwards, but there are other reactions taking place, including the formation of carbon monoxide and nitrogen and sulfur oxides.

Equation 3: Realistic Hydrocarbon Combustion with Air

$$[C_nH_m + S] + [N_2 + O_2] \rightarrow$$
$$\rightarrow CO_2 + H_2O + CO + NO_X + SO_X + [C_nH_m + S] + [N_2 + O_2]$$

2.3.1.2 Effects of Emissions

Living in an environment with low air quality reduces quality of life significantly. The combustion of fossil fuels produces different components in addition to the main products of carbon dioxide (CO_2) and water vapor. These two gases are not harmful to human life directly, although excessive amounts of CO_2 in the atmosphere is cited as a primary contributor to global warming [Ref. 56]. Along with these two gases a number of other byproducts are formed during the combustion process, and each one has a different impact on human health. The main 5 byproducts are [Ref. 2]:

- Carbon Monoxide (CO)
- Nitrogen Oxides (NOx)
- Particulate matter, divided into
  - PM10, below 10 micrometers in diameter
  - PM2.5, below 2.5 micrometers in diameter
- Sulfur Dioxide (SO_2)
- Volatile Organic Compounds (VOC)

Carbon monoxide is the pollutant that is emitted in the largest amounts to the atmosphere, and its effects vary widely. CO is emitted every time a carbon compound is combusted incompletely, or in a thermodynamically imperfect manner. Most fossil fuels produce CO at the same time that they produce energy because no process can be done with an efficiency of 100%. Processes that produce CO include the combustion of fuel in most internal combustion engines, the combustion of coal for electric energy generation, and most types of fires. The effects of CO poisoning can range from faint cardiovascular and neurobehavioral problems when the concentrations of CO are low in the body, to unconsciousness and death after prolonged or severe exposure to higher concentrations. The early symptoms of CO poisoning include headache, dizziness, weakness, nausea, confusion, and visual disturbances. After that, if the person remains in a CO rich environment, more problems arise, like difficulty breathing, chest pains, and most likely death, due to heart failure. CO can also cause disorientation and in higher concentrations even coma. Not seen immediately after poisoning, CO has the capability of affecting the brain function within 2 to 28 days after exposure. In pregnant women, CO poisoning can cause developmental disorders, brain damage to the fetus, or even pre-birth death [Ref. 57]. CO is a very harmful substance that is emitted to the atmosphere everyday in large quantities and its effects can be devastating to human health.

Nitrogen Oxides, also known as NOx, are composed of a group of compounds, all containing Nitrogen and Oxygen in different concentrations, which are highly reactive and highly detrimental to human health. These oxides are formed when fuel is combusted at high temperatures, usually above 1800^{o}F, mostly in motor vehicle engines and industrial processes that burn fuel [Ref. 58]. The main effects of NOx depend on what other compounds are in the atmosphere at the same time. NOx have a highly reactive nature, so the effects are very varied. When they interact with the volatile organic compounds (VOC) and the compound reacts with solar light, they create ground level Ozone, also known as smog. When NOx interacts with sulfur dioxide, it creates acid rain, and with ammonia and water, nitric acid and other harmful compounds are created. All these particles help in the deterioration of water quality. At the same time, NOx is also known as a greenhouse gas, potentially aiding in global warming.

The effects of NOx on human health and on the environment vary widely due to the high number of ways in which Nitrogen Oxides appear on the atmosphere. When smog is created, the main effect is respiratory problems to people, animals, and plants exposed to it. These problems can be temporary or permanent, depending on the exposure time and concentrations. Acid rain causes damage to lakes and rivers, making them inhospitable for aquatic life and also hurting the agricultural lands that use that water. Nitrogen Oxides can also cause genetic mutations [Ref. 58].

Sulfur Dioxide is produced when fossil fuels are burned, especially in producing electricity. It is a very irritating substance that causes respiratory problems and can aggravate cardiovascular disease when exposure occurs over long periods of time [Ref. 4].

Particulate matter is the name of small solid particles or liquid droplets that float in the atmosphere. They can be emitted directly to the atmosphere, like in the combustion of carbon compounds, or dust from roads, or formed in the atmosphere from gas emissions, like Nitrogen or Sulfur Oxides. Particulate matter can cause respiratory problems, aggravate existing ones, like asthma and bronchitis, and can also damage animals and plants, decreasing their life-span [Ref. 4].

Although the five emissions mentioned here are important for human health and the environment, only NOx and fuel burn will be used in the scope of this research work. These two are the most important aspects of pollution for policy makers, along with the noise produced by aircraft.

2.3.2 Noise

Noise is, by definition, any sound that is unpleasant, undesired, or produces interference in the hearing of something else [Ref. 59]. Humans and most living creatures obtain information from their surroundings in different ways: visual, tactile, acoustic, and so on. The acoustic impressions are the sounds, and are received by the human auditory system. Slight perturbations in pressure cause the eardrum to vibrate and these vibrations are translated into electrical stimuli at the cochlea, which in turn transmits them to the brain, which translates them into the feelings of sound.

In response to the increasing emphasis on the environmental impacts of aircraft operation, one of the goals under the National Aeronautics and Space Administration (NASA) plan for Success in Aeronautics and Space Transportation is the reduction of aircraft noise by the year 2017. In particular, the aim is to have a reduction of perceived noise levels for future aircraft in comparison to that of the current ones by a factor of two and four, within the next 10 and 20 years, respectively. This further corresponds to about 10 effective perceived noise decibels (EPNdB) reduction by the year 2007 and 20 EPNdB by the year 2017 with respect to levels from 1997 [Ref. 60].

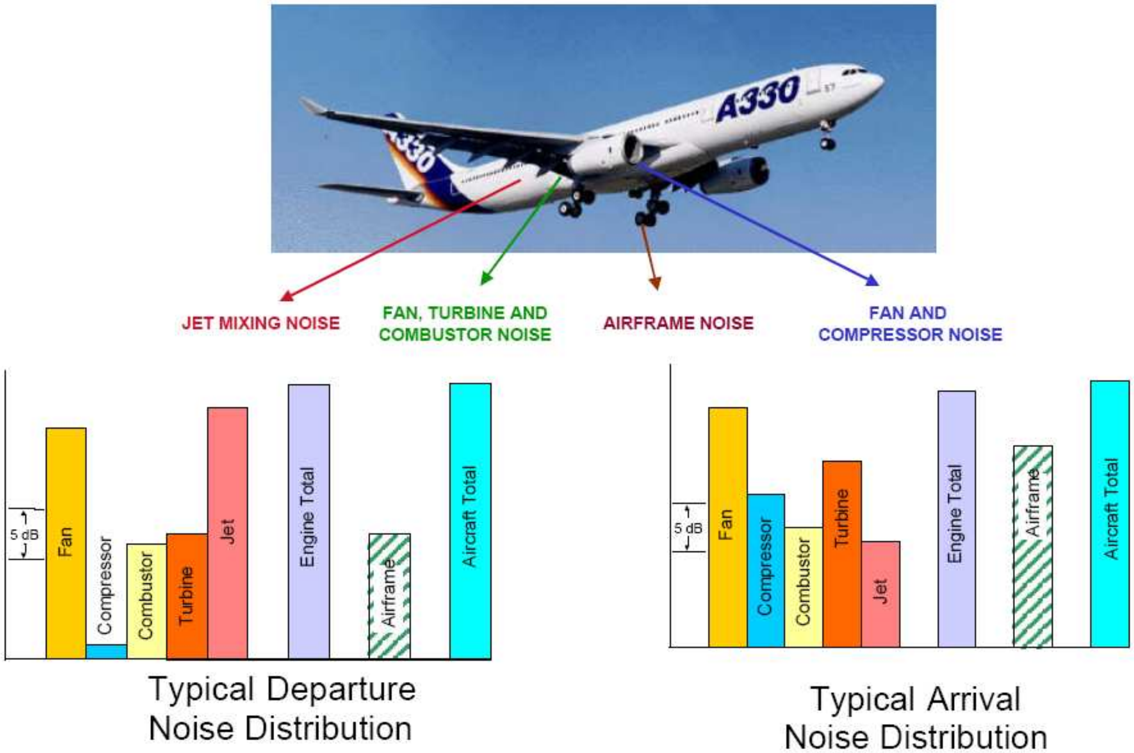

Figure 13: Typical Aircraft Noise Distribution [Ref. 61]

Most of the ongoing efforts to achieve these goals relate to the design optimizations of both the aircraft airframe and engine, which are the two major sources of aircraft noise, as can be inferred from Figure 13 [Ref. 61]. From the noise contribution chart, the engine noise is more dominant than that produced by the airframe in both flight instances. Due to this fact, major research work targets to reduce the noise generated by the engine unit. For typical commercial subsonic aircraft, the improvement in reduction of noise generated by turbofan engines can be seen as the main factor that is driving the trend in the aircraft noise reduction progress, as depicted in Figure 14.

A 20-dB reduction in noise level was achieved within a 20-year period in the past, and this realization actually acts as an indication that the new goals of noise reduction set by NASA may indeed be achieved. In actuality, the noise reduction between the 1st generation and 2nd generation turbofans is mainly due to the evolutionary improvements in reducing the sources of noise, implementation of better noise suppression devices, improvements in aircraft and propulsion efficiency, and adoption of noise abatement procedures.

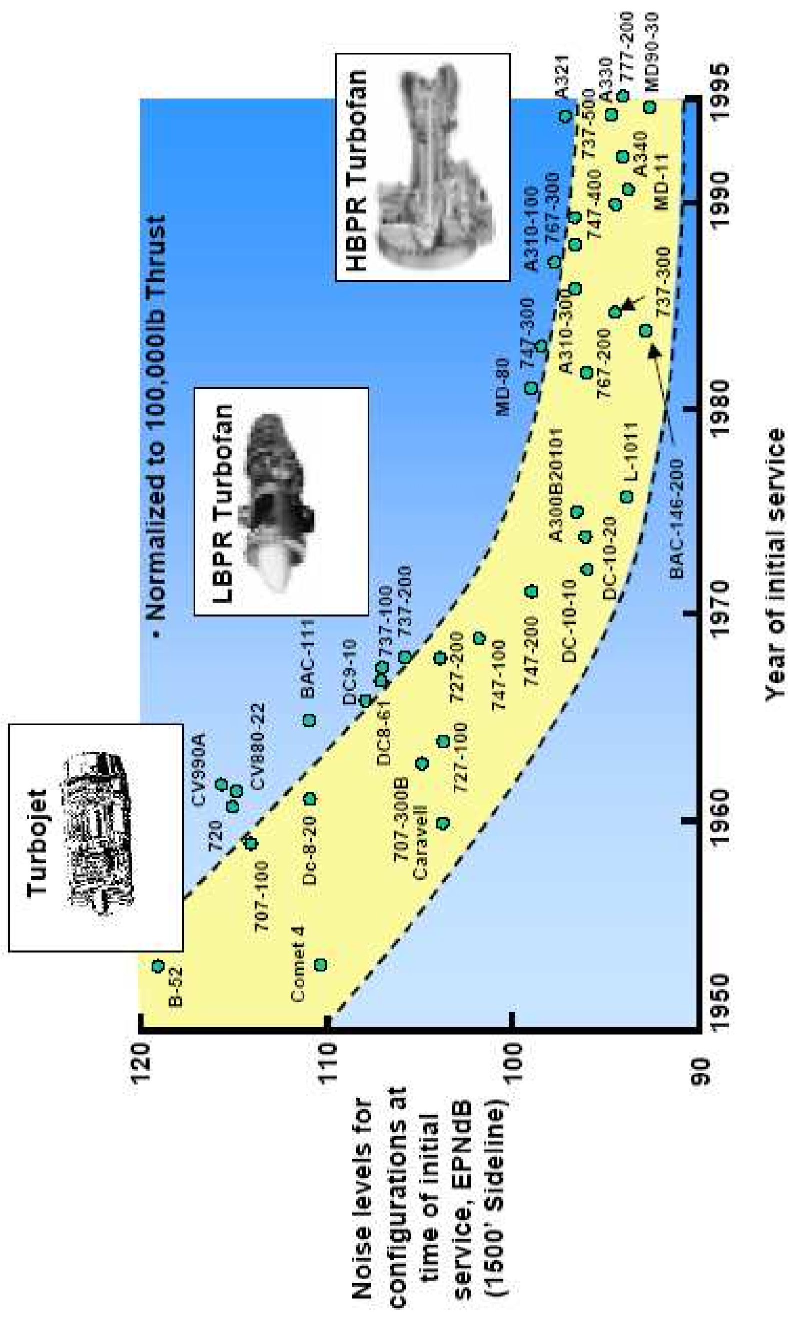

Figure 14: Change in Aircraft Noise due to Evolution of Aero Engines [Ref. 67]

A closer look into this reduction progress can be achieved through the identification of the engine noise sources. As depicted in Figure 15, the main noise source in early jet engines was the jet mixing noise.

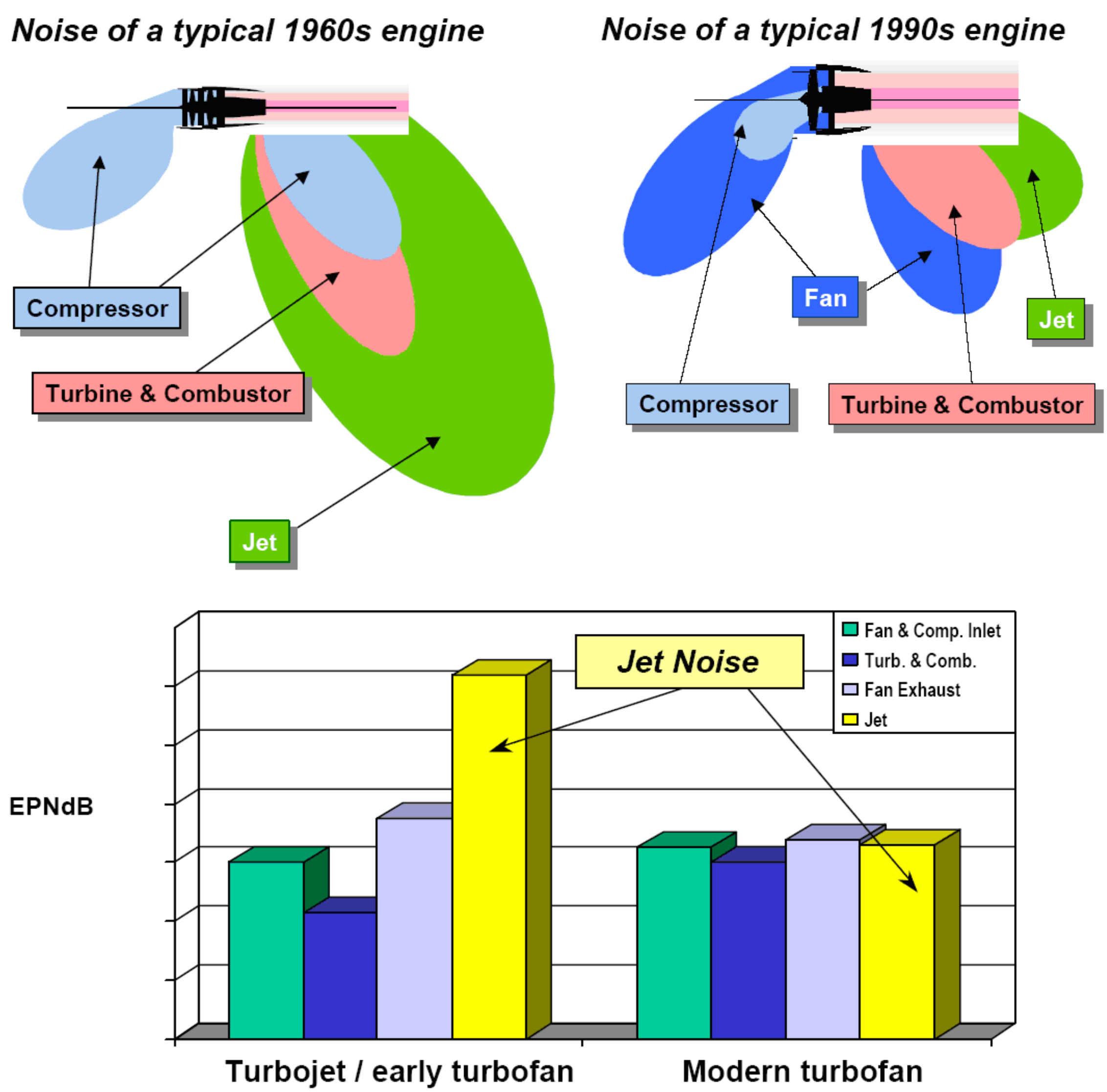

Figure 15: Comparison of Noise Sources between Old and New Aircraft Engines [Ref. 61]

Throughout the years however, jet mixing noise has been successfully reduced with the introduction of the bypass engine concept, which significantly reduces the exhaust speed and therefore, the jet noise emission level. With the current progress of high bypass ratio turbofan, the engine jet noise has become a less dominating noise source and subsequently, the noise emitted by other sources in the engine, such as the fan, compressor and turbine, is becoming more significant. The fan is now the primary source of noise in modern commercial aircraft propulsion, especially when the bypass ratio of the engine goes above ten [Ref. 62].

One way to visualize the effect that aviation noise has on a community is with a noise contour around the airport. A noise contour shows the area where the noise levels are constant. An example is shown in Figure 16 for the San Francisco International Airport area [Ref. 63]. The series of contours depict the areas where the Day Night Level (DNL) in decibels (dB) is above a specific level. According to the FAA, a DNL greater than 65 dB is considered harmful and can modify sleep patterns [Ref. 64]. This means that outdoors a level of 65 dB will produce significant effects on sleep deprivation and can have more serious effects on human health if sustained for long periods of time even with a sound insulation of 20 dB.

The increasing trends of future aviation demand depicted earlier in Figure 11 point towards an increase in the number of flights that will takeoff and land from any given airport, which will have a negative effect on the noise contour around the airports, including a bigger area and affecting more people. These noise contours are one of the most used ways to determine the effect of aviation noise over a population. The contours can be coupled with census data so that the number of people affected by a series of aircraft operations.

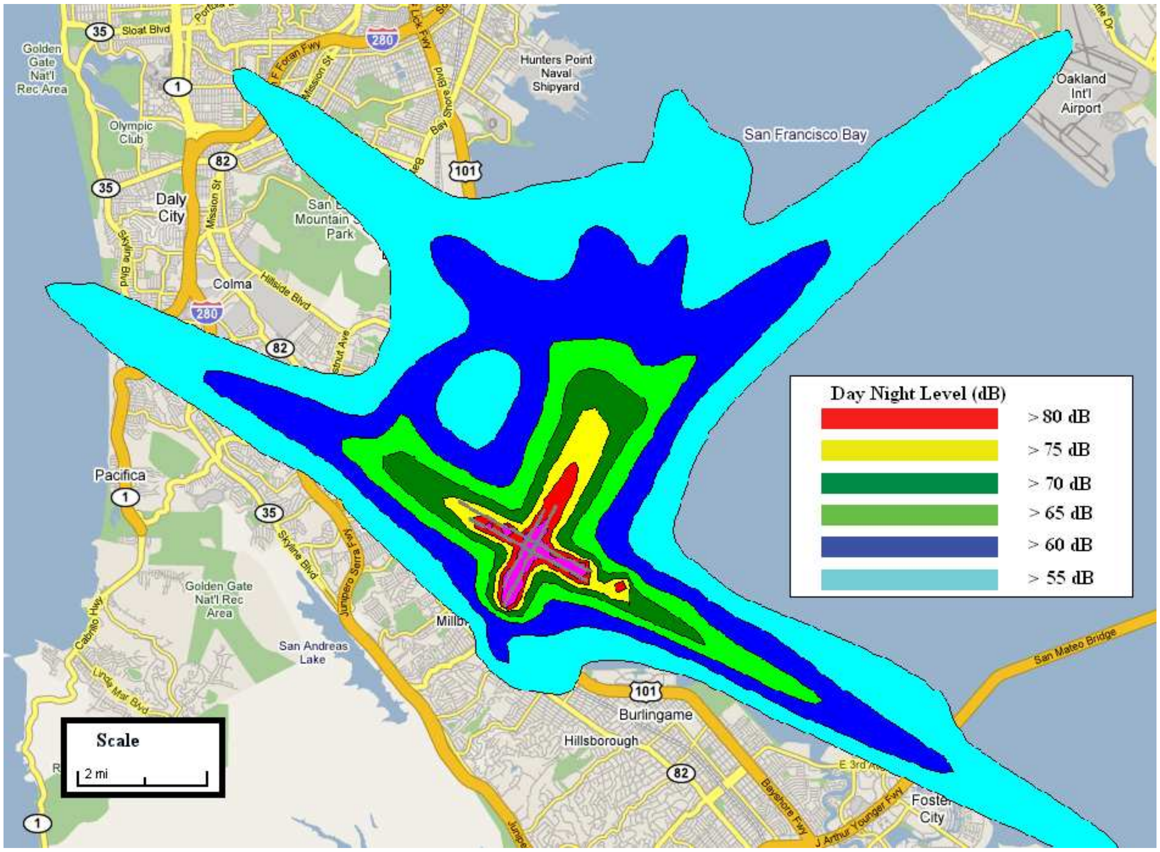

Figure 16: Noise Contour around San Francisco International Airport [Ref. 63]

2.3.2.1 Creation of Noise

The most significant noise sources are the fan and the jet. All of these sounds are generated due to the working principle of the turbofan engine itself, where air is sucked into the front of the nacelle duct while the same amount of air is pushed out at the back with a higher velocity to create a change in momentum that produces thrust.

Within the engine, the fan pulls air into the engine and by doing so, noise is created from the interaction of the fan blades with the streaming air. Once the air passes the fan, it will split down two different paths: the fan duct and the core duct. In the fan duct, the spinning fan blades cause the flow to swirl and create a loss of momentum even before the air exits the nozzle, which in turn reduces the available thrust. To reduce the momentum loss, the air is straightened out by the implementation of a set of exit guide vanes, called stators. The interaction of the fan blade and the stators is a significant source of fan noise since the wakes of air from the fan blades hit the stators at the regular rate of blades passing by [Ref. 65]. On the other hand, in the core duct, after passing through the fan, the air is further compressed by stages of smaller fans called rotors, separated by a set of stators to straighten the flow. Thus again, the fan noise created here is mainly due to the rotor-stator interaction effects, similar to those mentioned for the fan duct flow. Turbomachinery by itself is defined as devices in which energy is transferred either to or from a continuously flowing fluid by the dynamic action of one or more moving blade rows. In an engine unit, the rotating and stationary elements of fans, compressors and turbines are the main sources of what is termed as turbomachinery noise, where each of the mentioned sources can generate significant tonal and broadband noise [Ref. 66].

In detail, noise produced by the fan can be caused by a diversity of effects, generally resulting from the inlet boundary layer or inflow distortions interacting with the fan, noise from the fan itself, and the fan wakes interacting with stators or struts [Ref. 62]. Alternatively, it can also be implied that all fan noise is due to flow inhomogeneities that interact with the surface, which can be either inflow distortions being cut by the rotating fan blades, blade wakes sweeping across outlet guide vanes (stators), or turbulence passing near the blades or stators [Ref. 67].

Overall, there are two main categories of noise: the tonal noise and broadband noise. These components can be clearly differentiated in a typical depiction of sound spectrum for the turbofan noise, which is shown in Figure 17 [Ref. 68]. The tonal noise is a sound that is centered on a single frequency, such as the blade or stator passing frequency [Ref. 69]. Therefore, the tonal noise only affects one discrete frequency and its harmonics, which are frequencies that are integer additions of the original one.

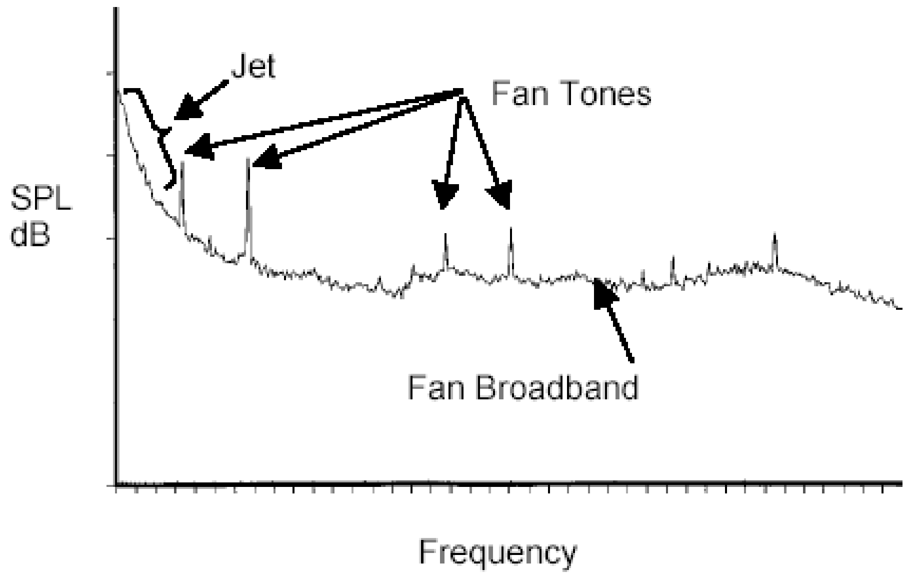

Figure 17: Typical Noise Spectrum for a Turbofan Engine [Ref. 68]

There are several sources of tonal noise in the engine. For rotating components with subsonic tip speeds, the most dominant source is usually the rotor-stator interaction, in which sound tones are generated due to the lift fluctuation on the rotor or stator blades either by the rotor blades intersecting wakes from preceding stator vanes or by the rotating wakes from a rotor impinging on stator vanes. This tonal noise then propagates from the blades as spinning duct modes, both upstream and downstream. Apart from the rotor-stator interaction, other sources of tonal noise also include the rotor-alone sources, such as the ones due to flow distortions. In addition to that, there are also combination tones that are produced when the rotor blade speed exceeds Mach 1. In this case, shock waves are formed at the leading edge of each rotor blade, propagating through the engine inlet as a series of Mach waves. The result is a series of harmonics of the blade passing frequency, usually known as “buzz-saw” noise, and are expressed in three fractions of the fundamental tone of the blade passing frequency, 1/8, 1/4, and 1/2.

Unlike tonal noise, broadband noise corresponds to sounds produced over a wide range of frequencies; in other words, it exists for all possible frequencies of the spectrum. For the engine, the broadband noise is associated with random unsteadiness or turbulence in the flow passing through the blades of the fan, where the noise can result from either inflow turbulence interacting with the fan or fan turbulent wakes impinging on stators and struts or from the combustion process [Ref. 62]. Furthermore, the sources of noise also include turbulences in the boundary layer, as well as blade wakes and vortices.

In general, the source of broadband noise from a turbofan engine can be narrowed down to turbulence in the flow. Turbulence occurs in many ways throughout the engine, such as from the rotor and duct wall boundary layer, and rotor wake flows passing through the stators, as predicted by Ganz et al, or in the combustion chamber, due to the mixing process or the subsequent burning of the fuel [Ref. 70]. The broadband noise then propagates both upstream to the inlet and downstream to the engine discharge.

The cause of engine jet noise is the interaction of the jet flow with the free-stream flow, and in the case of separate flow turbofan engines, the primary and secondary jet flows interactions as well as the interaction of the mixed flow with the free stream. Figure 18 depicts the typical jet noise sources in a separate flow turbofan engine. When two flows start mixing at the exhaust of the nozzle, whether they are the primary with the secondary or the secondary with the free stream, a shear layer is formed. This shear layer is caused by friction between flows that come in contact with each other. The size of the shear layer, that is the distance that it takes for both flows to be completely mixed, depends on the thermodynamics properties of each flow, making it larger as the differences are bigger.

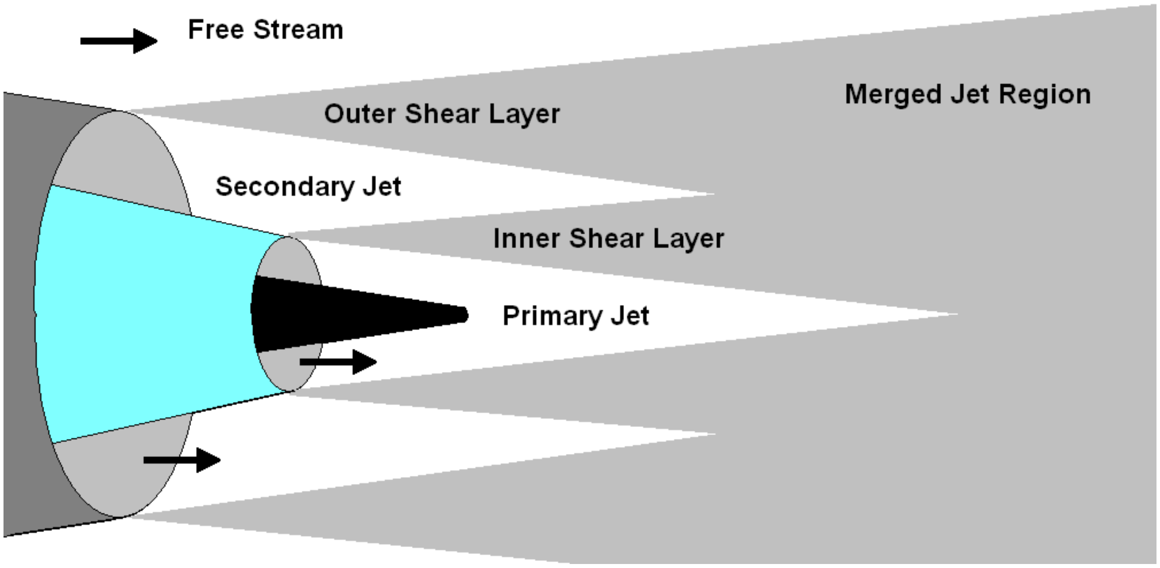

Figure 18: Separate Flow Turbofan Jet Noise Sources

The outer shear layer creates noises that are in the high range of frequencies, while the inner stream shear layer noises are in the mid to high frequencies. The mixed flow interacting with the free stream flow produces the lowest frequency noises of the three, and occurs far away from the exhaust nozzle. In addition to the three mixing noise sources, there can be also a plug separation noise, created by the flow reaching the tip of the plug and separating, creating turbulences, and also shock noise, created whenever the exhaust flow reaches supersonic speeds [Ref. 71].

As with the noise from the engine, the airframe noise is produced by instabilities in the flow around the airframe. Even though flow passing over a surface will always produce noise due to friction, this source is negligible compared to the engine noise during clean configuration operations, and it is also negligible compared to the noise produced by the high lift devices, like the ailerons or slats, and the landing gear, when deployed. High lift devices and landing gear are the most significant noise producers of the airframe, both theoretically and experimentally measured [Refs. 72, 73].

Figure 19: Noise Producing Turbulence over a Wing [Ref. 74]

The main cause for this noise is the fact that the flow separates when passing next to the slats or ailerons, and this turbulence causes noise. Figure 19 shows where the turbulence occurs in a wing [Ref. 74]. In a similar way, when flow passes next to the landing gears, it does not have a laminar profile, but a turbulent one. This causes friction between the turbulent flow and the laminar flow to create noise.

2.3.2.2 Effects of Noise

There are few things that are as harmful as noise and at the same time so common. Noise is present in everyone's everyday lives, and the fact that it is problematic is taken for granted. The fact is that noise is one of the primary causes of decreased quality of life in the world, and is not only detrimental to the instantaneous comfort, but can produce health problems well beyond the hearing system. A study published by the Journal of Environment and Behavior in 1998 found a clear connection between aircraft noise and health effects [Ref. 75]. The effects have been considered in numerous studies and are therefore well known. These effects are varied and change from person to person, but can be grouped in 5 main groups [Refs. 76, 77, 78]:

- Hearing impairment: Noise can cause momentary loss of hearing, but also permanent hearing damage even at low levels, if sustained for long periods of time.
- Ergonomics: This area deals with the overall annoyance that noise produces which can cause a decrease in the comfort levels, thus reducing the ability to perform any task properly.
- Psychology: Related to the previous area, noise will alter the psychological state, increasing stress levels and decreasing the ability to concentrate.
- Blood circulation: Noise will also increase blood pressure levels and heart rate, which can cause more serious health effects in the long run.
- Biochemistry: Although not completely understood, noise can negatively affect blood levels of epinephrine, cholesterol, urine, erythrocyte, and many other compounds, which can damage internal organs, sometimes irreversibly.

Traffic is the most common cause of noise in city life, but aircraft related noise is known to cause more discomfort, even at lower levels [Refs. 79, 80]. Aircraft noise has been shown to have an impact on the depreciation of homes around airports, but at the same time, people want the convenience of having the airport as close as possible so that the benefits of flying are not erased by having a long drive to the airport [Ref. 81]. As described above, aircraft related noise is not only an annoyance but it also has a significant negative impact on psychological disorders [Ref. 82]. Disorders may be more acute for people with pre-existing mental health conditions, as some studies suggest.

Aircraft noise can modify electroencephalogram sleep patterns making it difficult to stay asleep or reducing the repairing qualities of sleep. Exposure to aircraft noise can also be the cause for elevated blood pressure, and there are studies and surveys that imply an increase in irritability, depression, difficulty in getting to sleep and staying asleep, swollen ankles, burns and cuts and other minor accidents, and skin troubles as a result of this noise [Refs. 83, 84, 85]. In addition to these symptoms, aircraft noise exposure has been associated with an increase in the consumption of sedatives, hypnotics, cardiovascular drugs and antacids [Ref. 86]. Studies also suggest that noise exposure in children has been associated with poor reading comprehension and annoyance [Ref. 87]. This reduced comprehension is more visible when a higher degree of concentration is required [Ref. 88]. These facts, along with the detrimental health effects of noise, are enough to make aircraft and engine manufacturers consider noise as a major factor when designing new vehicles.

In summary, noise and emissions are both harmful to human health and the environment, and reducing them is imperative to maintain or improve the quality of human life.

CHAPTER 3. RESEARCH AND HYPOTHESES

In the first chapter, the existing needs to tackle the problem of policy making with respect to noise and emissions produced by aviation were exposed. Those needs were summarized in the research questions. In this chapter, possible alternatives to the answering of those questions are explored, and its strengths and weaknesses analyzed. The background research was performed to determine possible alternatives to the answering of the research questions proposed at the end of the first chapter. These questions were divided into four main categories, which in turn lead to a series of hypotheses that form the backbone of this research work. The first category of questions dealt with the lack of physical relations that exist in the data used to study stringency scenarios. The second area is related to the first, but has to do with the assumption that the technology response used assumes a constant fuel burn penalty for any necessary NOx reduction. The third group of questions handles the fact that stringency analysis and implementation has not usually been done for more than one measure at a time. The fourth group of questions dealt with the lack of a process to calculate the coefficients that represent an aircraft in the fleet analysis tools utilized by policy makers to study different stringency scenarios. Possible solutions to those questions are posed as hypotheses, whose proof of validity is the objective of this research work.

3.1 Observation A. Proprietary Data Clouds Transparency

The first observation was the fact that there is no physical relationship between NOx and fuel burn in the technology response used by policy makers. This lack of transparency is due to the fact that the owners of that type of data, industry, consider it to be highly proprietary, and divulging it could potentially damage their competitive edge.

The answer to the questions posed can be found by researching what tools are available that could perform said task. The reason for this transparency is how the data is to be used. Since it would be utilized for policy making, which affects everybody, it is only fair that the information and data used to develop whatever policy be available to anybody that the policy would affect.

The Ultra-Efficient Engine Technology program (UEET), sponsored by NASA Glenn, was a major contributor to the problem of reducing emissions and fuel burn without decreasing performance. This program had an objective to develop turbine engine technologies that would power future vehicles, reducing fuel burn by 15% and NOx emissions by 70%, with respect to ICAO 1996 standards [Ref. 89]. The way in which this program tested the proposed technologies proved successful in linking the physical characteristics of the aircraft and engine to the different environmental metrics. The UEET program merged into the Vehicle Systems Program (VSP) in 2003. After this merge, the program continued in its efforts, but it included the effect of noise in its studies. A significant effort in the area of reducing noise and emission of aircraft concurrently is the work by Nicolas Antoine for his Doctoral research. His work involves the development of a tool to analyze the noise and emissions of aircraft during the preliminary portion of the design process. He provides insight into the interdependencies between operating cost and emissions and noise produced by the aircraft, by using a genetic algorithm optimizer to find the family of optimum alternatives. The concept of Pareto optimality was used to determine which alternatives fall in the region where trade-offs are made, so more insight was sought to clarify the definition of Pareto optimality and its possible uses. Another tool being developed is the Aircraft Integrated Modelling, from the University of Cambridge, in the UK, that looks at the effects of aviation on the environment.

In addition to these programs, private companies have also addressed this issue. It is worth mentioning the Preliminary Robust Design Analysis Tool for Evaluating customer Return (PREDATER) program by General Electric Aircraft Engines (GEAE), which, although proprietary, has the ability to predict noise and emissions characteristics of different engine configurations [Refs. 90, 91]. One drawback from this tool is that it ignores the effect of the aircraft.

3.1.1 NASA's Advance Technology Programs. UEET and VSP

In 1999, NASA's Glenn Research Center started the Ultra-Efficient Engine Technology Program (UEET), which includes three other NASA centers (Ames, Goddard, and Langley). The programs' objective was to develop new technologies for turbine engines to improve their performance. Along with the NASA research centers, five engine companies (GE Aircraft Engines, Pratt & Whitney, Honeywell, Allison/Rolls Royce, and Williams International), and two airplane manufacturers (the Boeing Company and Lockheed Martin Corporation), were also involved in the research effort [Ref. 92]. The main purpose of this program was to provide technologies that would reduce NOx emissions and that would increase the fuel efficiency of the engines, reducing the CO_2 emissions. The program was divided into seven research projects, each dealing with a specific set of technologies. These projects were divided depending on what area of the engine the technologies would be applied to, and they included emissions reduction techniques, increases in loading for turbomachinery, materials, integration of propulsion system and airframe, and propulsion controls. While all of these projects are of high importance, it is the Propulsion Systems Integration and Assessment project the one that has the biggest potential for the purposes of the research work being explored. A study from it that is especially relevant is the High Fidelity Simulation subproject, which uses the tools developed by the Intelligent Synthesis Environment Program, also from NASA Glenn, to integrate the technologies and determine the possible interactions between them [Ref. 93]. The integration of the tools was done by the Aerospace Systems Design Lab (ASDL) at Georgia Tech, under contract by NASA [Refs. 94, 95, 96]. There were different integrator agents used throughout the development of this environment. One of the first tools used was Isight, to link the inputs and outputs of the different tools. Another integration was performed using UNIX, and TCL scripts. The latest integration was done utilizing the latest NASA's Numerical Propulsion System Simulations (NPSS), which is also used to predict the thermodynamic cycle characteristics of the engine. The tools integrated were a set of other NASA programs, like FLOPS for the mission analysis and ANOPP for the noise prediction effort, although this last one was not part of UEET until the incorporation of the program into VSP [Ref. 97]. These integrated environments were essential to determine the effects of each technology in the different areas being studied. The integration of the different tools was performed in order to be able to identify concurrently what those effects were, and it is this concurrency what is of biggest help for this research work. An environment that could capture at the same time the effect that modifying the physical characteristics of the aircraft and the engine would have on noise and emissions would be ideal for quantifying their interdependencies.

3.1.2 Aircraft Optimization for Minimum Environmental Impact

The work produced by Antoine for his Ph.D. research was motivated by a desire to improve the current capabilities to predict aircraft noise and emissions at an early stage in the design process. Antoine places great emphasis in the fact that improving in one of the areas of interest will most likely damage some of the other, by providing the existing trade-offs between operating costs, cruise emissions, LTO NOx emissions, and noise produced, in different combinations. In order to obtain the trade-off areas, he uses an integrated environment in which a series of programs were utilized to calculate the engine and aircraft performance, along with the emissions and noise produced. The use of the integrated environment allows for the comparison of the different attributes of the aircraft in a level field. An integrated environment permits the inputs to the different modules to be consistent with each other. From Antoine's work it can be determined that an integrated environment is crucial in understanding the trade-offs between conflicting goals in the design of aerospace vehicles. Although some effort is placed into a fleet level effect of the environmental constraints, a more detailed approach would be needed to provide some help to policy makers. He also notes that more sophisticated models, and a thorough process of validation of the tools, is needed in order to obtain realistic results. In his future work section, he points out the need for a tool to analyze non-existing concepts, being this ability critical in the development of policies for future implementation. In order to model concepts that are not real yet, a physics-based environment would be the optimum alternative in order to capture all the intricacies of the aircraft.

3.1.3 Other Relevant Work

These two works presented above are not the only ones existing that are trying to determine tradeoffs between aviation produced environmental measures. GEAE developed an integrated set of tools, called PREDATER, that simulates the performance, in terms of fuel burn, emissions, and noise, and the cost of different engine configurations. This tool uses proprietary GEAE data for its calibration, and neglects to account for the effect of the airframe in the calculations. PREDATER was used in a series of exercises to assess the impact of different technologies, in a collaboration with the NASA UEET program, mentioned above [Ref. 98]. This tool is not publicly available, since it contains proprietary data from GEAE's engine manufacturing history, costs, and performance.

The Institute for Aviation and the environment from the University of Cambridge, in the United Kingdom, has project called the Aviation Integrated Modelling (AIM) project that is developing a policy assessment tool for the environmental effects of aviation [Ref. 99]. This tool is also composed of other tools that, integrated together, provide a global view of the effects of aviation on the environment. Also from the UK, Caves et. al., from the Loughborough University developed an integrated environment in which to determine the noise characteristics of an aircraft in the early stages of the design process [Refs. 100, 101]. Also in the UK, the Integrated Wing Aerospace Technology Validation Programme (IWATVP), led by Airbus, hopes to enable the aerospace industry with an integrated environment in which to assess different technologies that would reduce noise and emissions concurrently from future aerospace vehicles [Refs. 102, 103]. Specifically, the RETIVO (Requirements, Technology Impact, and Value Optimisation) concept, which is applied in this program, has a modular structure that allows for the quantification of the different attributes of the aircraft in a concurrent manner [Ref. 104].

In the United States, the Multidisciplinary Analysis and Design (MAD) Center for Advanced Vehicles, at the Virginia Tech department of Aerospace and Ocean Engineering has been working on integrating design tools for conceptual design since 1994. This center has as its collaborators numerous members of the aerospace industry, as well as NASA, and have performed numerous studies that optimize aerospace vehicles for multiple, conflicting attributes [Refs. 105, 106, 107, 108].

3.1.4 Lessons Learned

Out of all the tools mentioned here, the constant among them is the integrated part of the environment. The tools may change in their detail level, or in the way in which the calculations are produced, but in order to properly model concurrently noise, emissions, and other parameters of the engine and aircraft, all the tools need to be integrated together. This integration includes the use of the same set of inputs to define the engine and aircraft in all the different modules, as well as the same set of assumptions. These two aspects make the results from the different tools be comparable as coming from the same vehicle.

3.2 Observations B and C. Constant Fuel Burn Penalty and No Noise Effect

Observations B and C also dealt with the technology response used by policy makers. This technology response was assumed to be a constant fuel burn penalty for any NOx reduction, and had no impact on the noise produced. Research was performed on current systems to asses the validity of these assumptions. At the same time, the current policy making process is described in detail, along with a simple example of how the constant fuel burn penalty and no noise effect of achieving a NOx reduction affect the policy making process. It was stated in the first chapter that the technology response has the property of determining the limits of achievability for a given system class. This means that it captures what are the maximum levels of reduction that can be obtained in the environmental key measures, and what has to be given up in one to increase the others. The question of how to obtain those limits, assuming that a physics based environment is available to determine the characteristics of a given aircraft/engine combination, can be solved by looking into ways of quantifying the tradeoffs between the conflicting attributes. Methods in this area are usually encompassed in what is known as Multi-Attribute Decision Making (MADM) techniques.

3.2.1 Current Aircraft Relationships Between NOx, Noise and Fuel Burn

In order to determine the validity of the current technology response, in particular the fuel burn and noise effects when reducing NOx, a look at current systems is performed. The plot depicted in Figure 20 shows the LTO NOx percentage above CAEP/6 levels versus the cumulative noise margin to Chapter III levels. A lower value in the NOx is preferable, and a higher value in the noise means a quieter aircraft.

The plot shown in Figure 21 shows a similar relationship, but instead of the cumulative noise margin, the specific fuel used for an LTO cycle is plotted. This overall amount of fuel is divided by the maximum available static thrust of the engine, for comparison purposes.

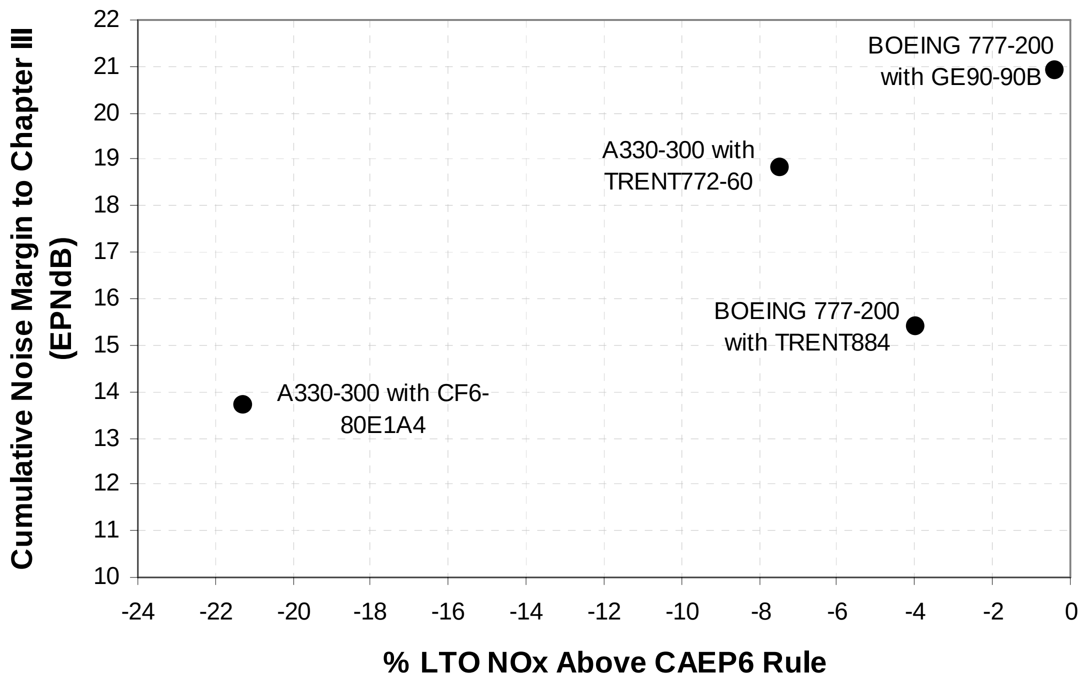

Figure 20: Current Systems' NOx-Noise Interdependencies in 300 Passenger Class

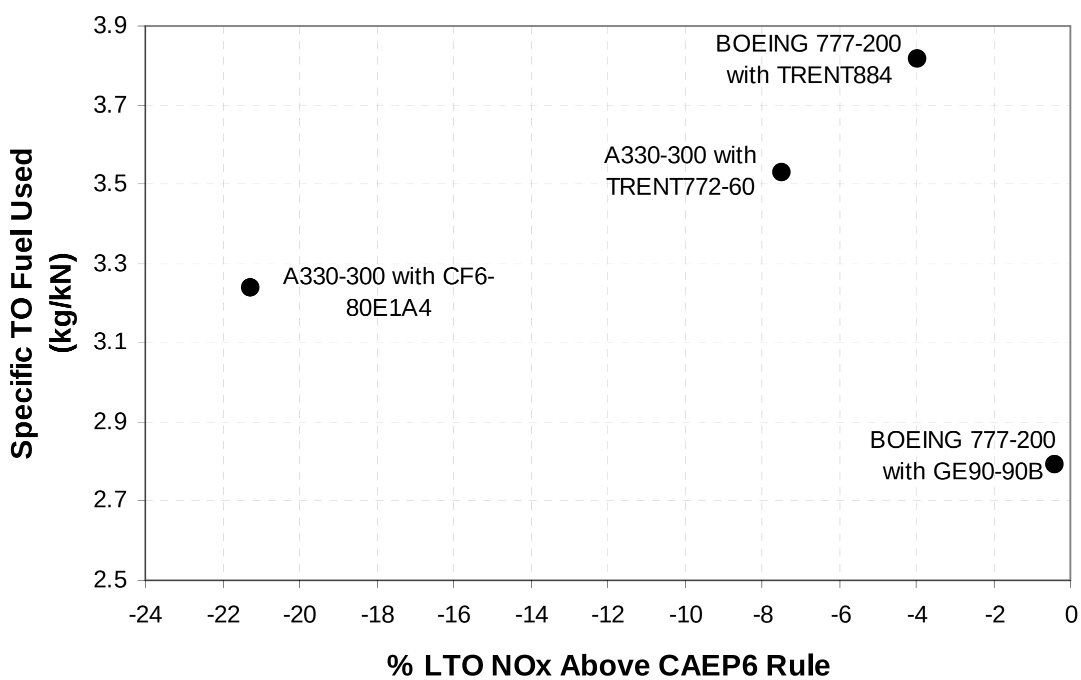

Figure 21: Current Systems' NOx-Fuel Burn Interdependencies in 300 Passenger Class

There are two aircraft used in these plots, the first is the Boeing 777-200, with two of the engines that power it: the General Electric GE90-90B and the Rolls-Royce Trent 884; the other aircraft is the Airbus A330-300, with two engines: from General Electric, the CF6-80E1A4, and from Rolls-Royce the Trent 772-60. The two aircraft are comparable in size, and although the engines in the Boeing are slightly larger than the ones in the Airbus, the mission ranges are similar on both aircraft [Refs. 53, 109].

The results of these graphs show that the best LTO NOx is achieved by the CF6-80 engine, mounted on the Airbus aircraft, and the best noise and fuel burn is achieved by the GE90-90B engine, mounted on the Boeing 777. Comparably, the CF6 engine has a 15% increase in fuel burn with respect to the GE90 engine, and it also is over 7 dB louder. Using the other aircraft/engine combinations, the NOx could be improved from the GE90 engine, moving to any of the Trent engines, but this would increase the noise, and the fuel used by the system. If a technology response were to be extracted from this set of data, it would have to include the relationship that exists between the NOx levels and the noise, this interdependency is too noticeable to be left outside the policy making process. In addition, the constant fuel burn penalty is clearly inaccurate for these systems.

Similarly to what was done with the 300 passenger class aircraft, the aircraft and engines in the 150 passenger class were used to plot the same data. These plots are shown in Figure 22 and Figure 23. The aircraft used were: from Airbus, the A321, with an International Aero Engines V-2531 engine; and from Boeing, the B737-800 with a CFM56-7B24 engine, the B757-200, with Rolls-Royce RB211 and Pratt & Whitney PW2040 engines, and the B767-200ER with CF6-80A and PW4056 engines.

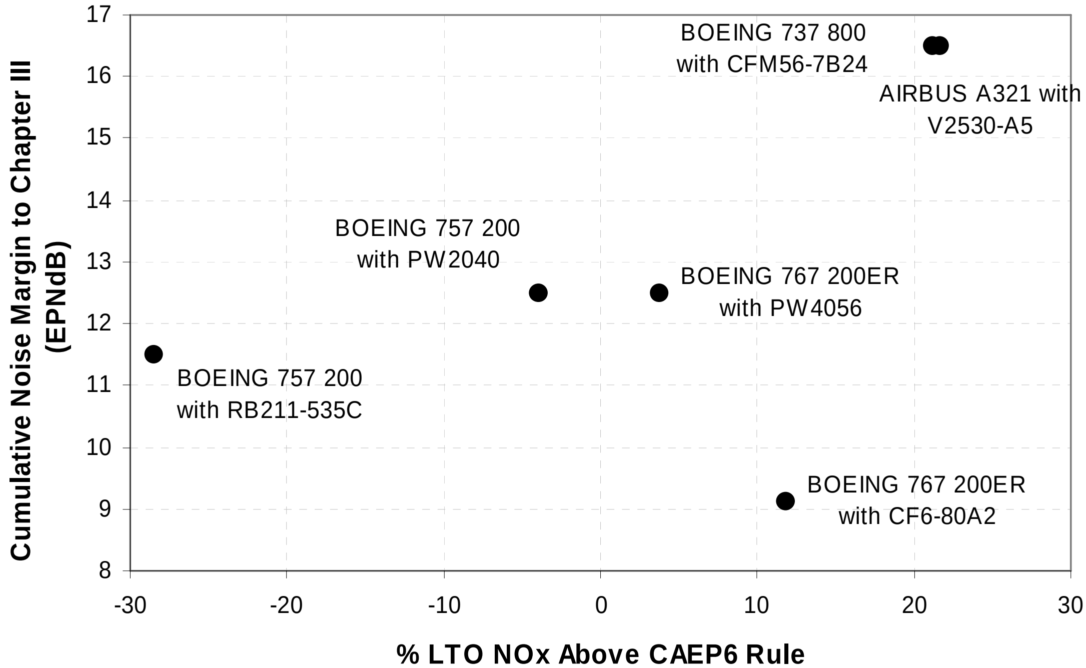

Figure 22: Current Systems' NOx-Noise Interdependencies in 150 Passenger Class

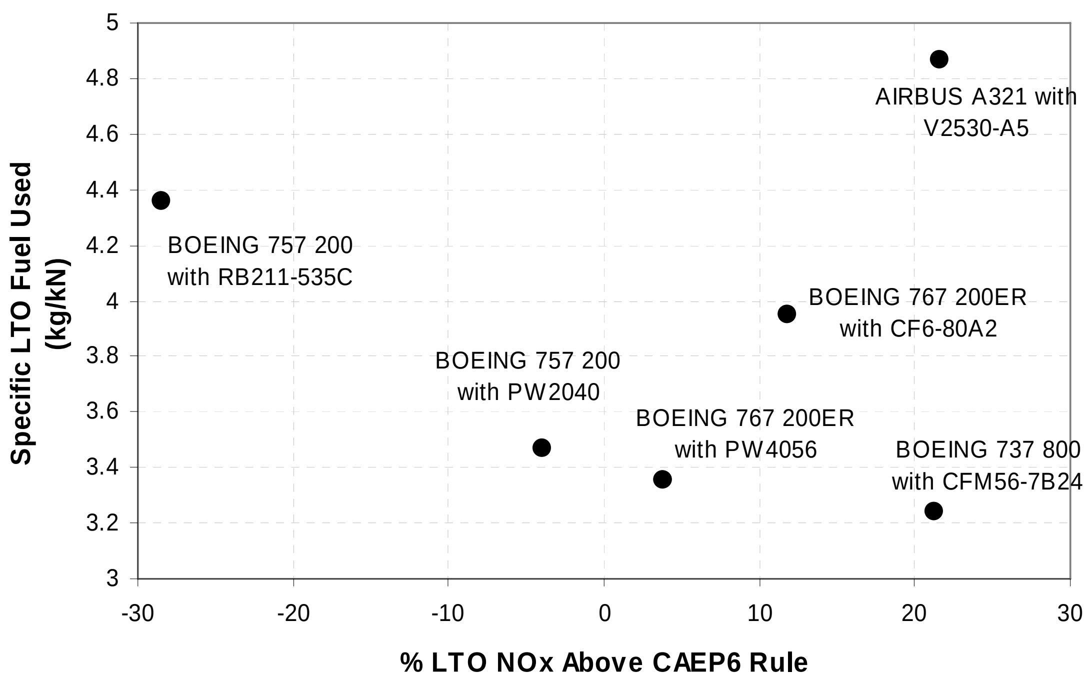

Figure 23: Current Systems' NOx-Fuel Burn Interdependencies in 150 Passenger Class

In this case, the aircraft with the best NOx characteristics is the B757 with the Rolls-Royce engine, but this aircraft also has a quite large fuel usage. The best noise belongs to the B737 with the CFM56 engine and the A321 with the V-2531 engine. Between these two aircraft, the NOx characteristics are quite similar, in the largest of the group, but the fuel consumption is a lot better for the CFM56 powered aircraft. The results are similar to those shown before for the 300 passenger class, in the sense that there exists a relationship between the NOx, noise and fuel burn.

It has been shown here that for these two classes of vehicles the current technology response, with the constant fuel burn penalty and its lack of noise effects, does not capture current systems. In the following section, the current policy making process is delineated, and the differences between having a technology response with noise in it, and a varying fuel burn penalty are shown.

Now that the need for the physical relationships between the three environmental key measures has been proven, it is necessary to find out what techniques are available that would allow for the determination of those tradeoffs. This is where the area of Multi-Attribute Decision Making (MADM) can help in determining a process that would allow the measurement of the interdependencies between the environmental attributes.

3.2.2 Multi-Attribute Decision Making Techniques

Making tradeoffs is not an easy task in the realm of complex systems. When analyzing these systems of systems, many variables come into the equation and the relationships among the conflicting objectives are not readily visible. The engineering area of aeronautics provides a remarkable environment in which to develop system of systems tools, due to the highly interrelated nature of the physic involved in counteracting gravity and creating flying vehicles. As an example to visualize this point an aircraft that needs to be made faster can be utilized. A bigger more powerful engine could be used to increase the speed, but the fuel consumption will increase as well as the overall weight of the aircraft, thus reducing the range. This is a very simple example, but at the same time it serves to show that the complexity of all the systems involved in aeronautics tell us that this decision of how much bigger the engine should be to maximize the objectives is not trivial. Many other aspects of the aircraft will have to be taken into account before an informed decision can be made, such as integration problems, volumetric issues, and overall system performance. Accurate predictions should be made available to minimize the cost of prototyping and reduce the changes in the final stages of production, where it is more costly and less reliable to do so.

Many attempts have been made to develop decision methodologies for multi-dimensional problems in which there are many competing goals and objectives. These methods are usually encompassed in Multi-Attribute Decision Making techniques. Out of the methods that will be considered here, the main attribute that they need to posses to be used in this research work is the capability of quantifying the tradeoffs between the different attributes, and doing so in a completely non-subjective manner. Many of these methods use an Overall Evaluation Criterion (OEC) to evaluate different alternatives, while assigning weights, or importance parameters, to the different attributes. The OEC methods considered here are the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS), Analytic Hierarchy Process (AHP), Weighted Product Model (WPM). These first three methods expand the available OEC alternatives in terms of how to calculate the measurement criterion. Joulia and Le Tallec provide a detailed explanation of some of these tools and how they are applied to an Unmanned Aerial Vehicle conceptual design [Ref. 110]. In terms of techniques that do not use an OEC, concepts such as the Pareto and S-Pareto optimality appear. All these methods and techniques provide a solution to a problem in which many attributes are being optimized by providing the set of variables that optimizes the desired goals. But, OEC or not, they all require the comparison of different alternatives, so a process to come up with said alternatives is needed. There are many possibilities to do so, as pointed out by Ran [Ref. 111]. These techniques include the use of different sampling methods, also called Design of Experiments (DoE). These DoE's are a list of experiments to be run, structured in such a way that the information resulting from the outputs is maximized, while minimizing the number of experiments to run. Each run represents a combination of input variables, which will be utilized in whichever experiment setup is being considered, to produce an output. For the purposes of this research, each DoE run would mean a different aircraft/engine combination, differentiated by the fundamental physical characteristics that define it. These different DoE's can be divided in different categories, depending on what is the final use of the data obtained. Ran provided a differentiation between DoE's for space exploration, and for creation of surrogate models. For this research, the desired techniques will have to perform a space exploration, as extensive as computationally possible. Some of these techniques include the use of a Monte Carlo filtering, and Latin-Hypercube DoE's, and full factorial designs.

During the last couple of years, a number of papers have surfaced that emphasized the need for Multi-Attribute Decision Making techniques, ranging from the use of MADM techniques for UAV concept design, a general aviation single engine aircraft, lunar exploration developments, or multirole fighters [Refs. 110, 112,113,114]. The work by Bandte provides an extensive explanation on many of these MADM techniques, and the attributes that make them suitable for a specific set of problems [Ref. 115].

3.2.2.1 Selection Methods

The main characteristic that the selection method to be used in this research must have, is the ability to capture the tradeoffs between the different alternatives. It was mentioned above that there are two main groups in which to place selection methods for MADM techniques, those having and OEC and those without it. The ones that have the criterion differ in the way in which it is calculated, but they all have in common the solution of a unique “best” solution. Some of these techniques are the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS), Analytic Hierarchy Process (AHP), and he Weighted Product Model (WPM). These three will be explained here, due to the wide array of ways in which the calculation of the OEC is done. The other group of techniques includes those that do not have an OEC to measure the alternatives, but rather a comparison of all the points at the same time. Concepts such as the Pareto, weak Pareto, and S-Pareto fall into this category.

TOPSIS is a multi-attribute decision making scheme that uses an overall evaluation criterion to select the optimum alternative [Ref. 116]. This evaluation criterion is based on the Euclidean distance of the different properties of the alternative to an ideal best and ideal worst points. The ideal best and worst are determined by using the best and worst characteristics of all the alternatives being compared, such that the best will have the conglomerate of the best attributes from all the alternatives, and the worst will do the same, but with the worst characteristics. The distances of each point to the best and worst ideal solutions are obtained by using Equation 4. With those distances, the TOPSIS value, or criterion, is calculated using Equation 5. In the first equation, $x_{i,A}$ is the ith non-dimensional attributes of alternative A, while $x_{i,A}$ is the best ith non-dimensional attribute out of all the alternatives. W_i are the particular weight for each attribute. These weights are used so that a bigger importance can be given to one attribute or the other.

Equation 4: Euclidean Distance

$$Dist_{A \to Best} = \sqrt{\sum W_i \cdot \left(x_{i,Best} - x_{i,A}\right)^2}$$

Equation 5: TOPSIS Criterion

$$TOPSIS = \frac{Dist_{A \to Worst}}{Dist_{A \to Best} + Dist_{A \to Worst}}$$

The AHP also uses an overall evaluation criterion to determine which alternative is the optimum. The uniqueness of this method is the way in which this number is calculated. The value for each alternative is calculated using Equation 6 [Ref. 117]. In this equation, the values of the weights W_i have to be such that they add up to 1 [Ref. 118].

Equation 6: AHC Criterion

$$AHC = \sum x_{i,A} \cdot W_i$$

Similarly to TOPSIS and AHC, the WPM uses an overall evaluation criterion to rank the alternatives, but in this case, the number is obtained with Equation 7 [Refs. 119,120]. The weights in this case must be equal 1 when multiplied.

Equation 7: WPM Criterion

$$WPM = \prod {x_{i,A}}^{W_i}$$

These three techniques, TOPSIS, AHC, and WPM, as well as any other OEC methods, provide a single answer to the multi-objective optimization problem. The answer can vary, depending on the relative importance of each attribute, but the final result is always a single point. This single point cannot provide any information about possible tradeoffs between the different attributes being studied, unless multiple weighting scenarios are utilized and compared. And even in this case, the particular weights used could impact the shape of the tradeoffs, so another alternative needs to be considered.

On the other hand, the Pareto optimality concept was proposed in the beginning of the 20th century by the French economist and sociologist Vilfredo Pareto. It states that, given a series of alternatives for the solution of a problem, there exists a subset of those for which no further improvement can be made in any particular direction without degrading one or more of the other areas of interest [Ref. 121]. This theory does not specify which alternative is the optimal for the solution of the problem, since there will be some that improve one of the areas while the rest are left at their minimum. This concept can be applied to multidisciplinary optimization problems as long as there are two or more competing responses to be optimized. Obtaining those points is not a difficult task, and a simple algorithm, like the one presented by Zitzler and Thiele [Refs. 122, 123], can be used to do this for any number of responses.

The other two concepts mentioned above, the weak Pareto and S-Pareto techniques are variations of the original concept of Pareto optimality. The weak Pareto points differs from the original Pareto in "*A point is weakly Pareto optimal if there is no other point that improves all of the objective functions simultaneously. In contrast, a point is Pareto* *optimal if there is no other point that improves at least one objective function without detriment to another function* [Ref. 124]". This means that all Pareto points are weak Pareto, but not the other way around. In addition, all Pareto points lie on the limits of the achievable space, while weak Pareto do not [Refs. 125, 126]. The other related theory is the S-Pareto front. Conceptually, the S-Pareto front and the Pareto front are the same, and the only difference is that for the S-Pareto front, one of the variables is a discrete one, or they come from different architectures [Ref. 127]. But the comparison is made on the same attributes, and the chosen alternatives are all Pareto efficient, no matter which architecture they come from.

The Pareto techniques, either original or S-Pareto, would not yield the same result as the OEC methods. They will not provide the optimum alternative, but rather show which alternatives are not dominated by others. This means that those alternatives represent the limit of improvement, given the set being studied, in all attributes. The non-dominated set of solutions shows the zone where trade-offs can be made. All the points selected as Pareto optimal are solutions to different weighting scenarios described in the other techniques, but this particular concept gives as the answer all the points automatically.

Out of the four methods presented before, the Pareto optimality concept is the only one that intrinsically represents the possible trade-offs between conflicting responses. Although the other possibilities could be modified to achieve a similar result by using different weighting scenarios, the Pareto optimality concept is the only one that provides this information as its result. And the weighting scenarios require the subjective input of a user to work. Therefore, since one of the objectives of this research work is to find these tradeoffs, the Pareto optimality concept will be utilized as part of the process proposed.

3.2.2.2 Design of Experiments

The reason for using a DoE is to maximize the information gathered from the experiments, while minimizing the number of experiments to perform. It was stated before that there is a need to explore the available space defined by the input variables in order to determine the achievable limits defined by the outputs. They way in which the points are to be selected amongst the alternatives is with the concept of Pareto optimality, explained in the previous section. But in order to select from pool of alternatives, there has to be such a pool. Many techniques exist that would explore the space available, but in this research four will be explored: full factorial design, Monte Carlo filtering, Latin-Hypercube, and sphere-packing design.

The full factorial design of experiments is defined by the uniformity of the distribution of the experiments. Each variable to be used is discretized in a number of steps, and all the possible combinations are explored. The number of experiments that result from this technique increases exponentially with the number of variables and the number of discretizations that each variable is divided into. This makes this technique only suitable for cases with very few variables, or when the cost of analyzing each combination is very small. On the other hand, this method insures that all the space defined by the inputs is covered uniformly.

Monte Carlo filtering is a completely random filling technique, in which each input variable is assigned a probability distribution around the ranges it can vary. From those probability distributions, and with a previously determined number of experiments, the settings for each variable are chosen. This means that the experiments will be randomly distributed around the space defined by the input variables, depending on the distribution used. For a truly uniform coverage, a constant probability distribution can be assigned to each variable, so that the overall space is explored. This technique can be used as an addition to a full factorial when a multi-level full factorial would mean too many cases to run. The Monte Carlo filtering tends to explore the inside of the design space, as defined by the inputs. It is very fast to create a design of these characteristics, since it only relies on a random number generator. A drawback is that it cannot warranty that there will not be any correlation between the variables.

The Latin-Hypercube technique is somewhat in between the full factorial and the Monte Carlo filtering. It is a technique that divides the ranges for the input variables in uniform spaces, called bins, and then selects a point randomly inside each bin, so that the space is uniformly covered [Refs. 128, 129]. It provides good distribution on the space, but it can be costly, computationally to avoid correlation between the variables.

The Sphere-packing design utilizes the concept of the maximization of the minimum distance between points to evenly spread the points in the design space [Ref. 130]. This concept can be thought of as having each point surrounded by a hyper-sphere (sphere in multiple dimensions), and those spheres cannot be crossed by the spheres of other points. This technique assures that the points are uniformly spread in the design space, but it is quite costly, computationally. In addition, it tends to cover the edges of the space, more than the inside, for cases with multiple variables.

Out of the four techniques described here, the full factorial produces the most uniform distribution over the available space, but it also requires the use of more points to do so, especially if the number of variables is large. To avoid this a compromise can be reached by using a 2 or 3 level full factorial, which would explore the edges of the space, and then utilize a Monte Carlo filtering technique, with uniform distributions on the variables to explore the inside of the space. This combination is very fast in being produced, and it provides a good coverage of the available space.

3.2.3 Lessons Learned

A common denominator in the first three observations is the technology response used currently in the policy making process. The main question asked is how to improve it, how to provide policy makers with more physically sound, transparent information about the tradeoffs that exist between noise and emissions, and what happens if a stringency is set in one or more of them. Based on the information gathered through the research shown herein, a solution would be to use an integrated, physics-based environment, composed of publicly available tools, to create a new technology response. This technology response would be formed by a series of replacement aircraft, which would expand the available design space, and capture the physical relationships between the environmental key measures. In order to determine what the tradeoffs are, the concept of Pareto optimality can be used on the possible alternatives to isolate those that represent the achievable limits. And to create the pool of alternatives, to select the Pareto from, the design of experiment techniques, such as the full factorial with Monte Carlo filtering, can be used to explore the available space, thus determining the achievable limits for a given class of vehicles.

3.3 Observation D. No Process to Calculate Databases' Coefficients

The last question asked in the previous chapter was whether it would be possible to create a process to calculate the coefficients that define an aircraft, to be used in the fleet analysis tools. The first step in order to create such process is the understanding of the coefficients, and the databases they are part of. These coefficients are used in the fleet analysis tools to capture the capabilities of the current aircraft in the fleet, without jeopardizing the proprietary information that is the actual performance of those systems. It is this fear to divulge proprietary data what has stopped the different companies from developing a process to calculate all the coefficients. Only two documents exist that explain in little detail how to calculate a minimal part of the coefficients, one from Boeing and one from Airbus. Not even with both together, the majority of the coefficients are captured.

During the CAEP/6 meeting, which took place in Montreal in 2004, the members agreed that the interdependencies between environmental effects of aviation were complex and very significant when trying to achieve some improvement in any of those effects [Ref. 131]. This idea was not new, it was previously noted in CAEP/2, the second meeting of the committee, back in 1992 [Ref. 132]. In order to observe these interdependencies, the US FAA is in the process of developing a suite of tools to help in the CAEP decision making process [Ref. 133]. This suite of tools is encompassed in the Aviation Portfolio Management Tool (APMT). The workings of these tools were shown in section 2.2. The tool that has the most significance for this are of the research is the Aviation Environmental Design Tool, AEDT. The AEDT calculates the effect of aircraft fleet operations on the environment, from both emissions and noise. The aircraft used in

AEDT are modeled using the databases mentioned in the beginning of this document, the databases containing the BADA and SAE AIR 1845 coefficients. The AEDT integrates four other tools currently used by the FAA in the calculation of noise and emissions. These tools are separated into noise and emissions related, and whether the results are for global or local effects. For local noise effects, the Integrated Noise Module (INM) is used. Similarly, the Emissions and Dispersion Modeling System (EDMS) is used for localized emissions effects. The Model for Assessing Global Exposure from Noise of Transport Airplanes (MAGENTA) utilized INM for global noise assessment and the System for assessing Aviation's Global Emissions (SAGE) is used to calculate emissions effects worldwide.

In addition to the AEDT, other tools created around the world also use the BADA coefficients to represent aircraft performance characteristics. In the UK, the already mentioned University of Cambridge AIM project utilizes this database to assess the impact of aviation in the environment, a similar task to that of AEDT, but using a different set of tools [Refs. 99, 134]. The European Union Tempus GLOBE project also uses the BADA coefficients to predict the performance of aircraft for analysis of CO_2 emissions into the atmosphere [Ref. 135].

The BADA and SAE AIR 1845 coefficients are structured in a series of tables which contain data regarding aircraft performance, noise, and emissions. These tables or databases contain information for all commercial aircraft currently flying. The databases are divided into 3 main categories: aircraft performance, noise, and emissions. The types are self explanatory and the different tables in each of them are explained in the following sections.

3.3.1 Aircraft Performance Input Requirements

This set of tables defines the behavior of the aircraft during the different stages of its mission. There are two main types of data contained in the aircraft performance databases: the ones that define the aircraft and its attributes, like engine type, and the ones that describe the actual performance of the aircraft. The latter is composed of coefficients used in equations that approximate the real aircraft performance. The actual contents of each database will be explained in detail later in this thesis, but they are highlighted in Table 2.

Table 2: Aircraft Performance Tables

Name	Description
aircombo.dbf	This file contains links between different aircraft and engine identifiers used in the different databases. It also specifies the number of engines.
aircraft.dbf	This file describes the aircraft and the engine. It contains maximum gross takeoff and landing weights, maximum landing distance, and sea level static thrust of each engine.
bada_acft.dbf	This file also contains information describing the aircraft and the engine, but it does so in more detail than *aircraft.dbf*. In addition to the weight of the aircraft and the maximum allowable payload, it contains a description of the flight envelope.
bada_apf.dbf	This file defines the way in which the aircraft performs climbs and descents segments by providing speeds and transition Mach numbers.
bada_config.dbf	This file describes the aerodynamic performance of the aircraft during the different segments. It includes stall speed, zero lift drag coefficient, and lift induced drag coefficient.
bada_fuel.dbf	This file describes the fuel usage of the engine for the different segments of the mission.
bada_thrust.dbf	This file describes the thrust available from the engine for the different segments of the mission.
equipment.dbf	This file contains links between different aircraft and engine identifiers used in the different databases.
flaps.dbf	This file defines the aerodynamic performance of the aircraft while using high lift devices.
Procedur.dbf	This file describes the performance of the aircraft during approach and departure operations for different takeoff gross weights. There are three departure procedures: ICAO A, ICAO B, and INM Standard.

Name	Description
prof_pts.dbf	This file contains the same information as *procedur.dbf*, but for procedures not included in such file. The information can interchangeably come from either of these two files.
profile.dbf	This file contains the maximum takeoff gross weight for different stages. Each stage is a mission with a specific range, defined in *stg_len.dbf*.
stg_len.dbf	This file contains the minimum and maximum ranges for the nine allowable stages.
thr_gnrl.dbf	This file contains the coefficients used to calculate the thrust available for cruise as a function of velocity, altitude, temperature, and power setting.
thr_jet.dbf	This file contains the coefficients used to calculate the maximum thrust available for different mission segments, as a function of the velocity, altitude, and temperature. This file only contains information for jet aircraft.
thr_prop.dbf	This file contains the coefficients used to calculate the thrust available for propeller driven aircraft.

3.3.2 Noise Specific Input Requirements

The data required in terms of noise is called Noise Power Distance (NPD) curves which define the noise level of the aircraft at different power settings and at different distances from the aircraft. The noise levels are specified in four different categories, sound exposure level (SEL), effective perceived noise level (EPNL), maximum A-weighted noise level, and maximum perceived noise level, corrected for tone (PNLt). The approach and takeoff configurations are also differentiated. Figure 24 shows an example of the NPD for EPNL for a B777-200ER aircraft powered by two GE90-90B engines. The noise related information also includes the spectrum for departure and approach configurations in A-weighted scale at a distance of 1,000 ft at the point of maximum sound level. These two data sets are included in the files called *npd_curv.dbf*, for the NPD data, and *spectra.bin*, for the spectral data.

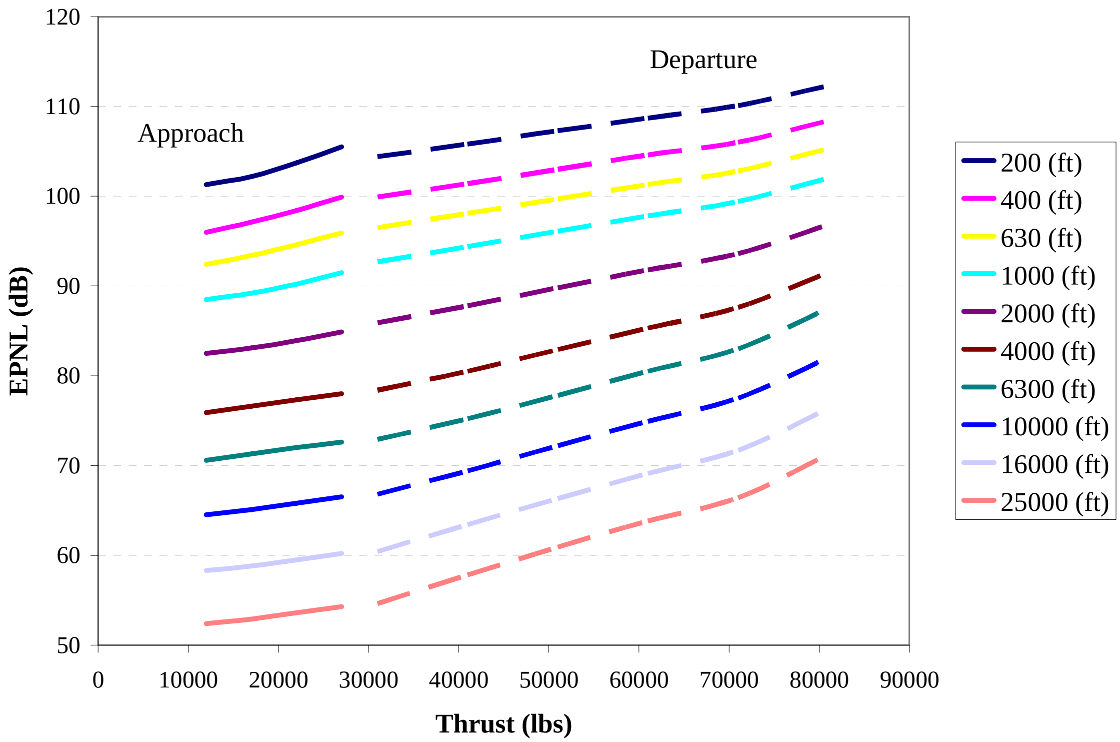

Figure 24: Sample NPD curve for B777-200ER with two GE90-90B Engines

3.3.3 Emissions Specific Input Requirements

The required data for emissions calculations is included in the file *eng_emis.dbf*. This file contains information about the engine for the four power settings specified by the ICAO as takeoff, climb out, approach, and idles, being 100%, 80%, 30%, and 7% respectively, at sea level static conditions. The information includes the fuel flow in kilograms per second, carbon monoxide, hydrocarbons, and nitrogen oxides in grams per kilogram of fuel, and smoke number for the four conditions specified above.

All the tables shown here define the performance characteristics of an engine-aircraft combination. These characteristics can be used to model fleet level operations, and therefore reproduce or predict the local or global noise and emissions impacts of aviation.

The transparency of these coefficients is necessary, since there are a lot of other tools that use them, and the consequences of the results not being as clear as possible are of great importance for policy making.

With respect to documents relating how the databases are populated, there are only a few available, and the do not cover the complete database. One of these documents is the study performed by Forsyth, Guilding, and DiPardo, on the equation used by the FAA Integrated Noise Module (INM) [Ref. 136]. This study describes a process to calculate thrust coefficients for take off and initial climb, to populate the thr_gnrl table described above, as well as some aerodynamic data for the flaps database. This effort was mostly directed to using Boeing provided data to calculate coefficients for Boeing aircraft. Another important document is the work prepared by van Boven, with respect to the calculation of SAE AIR 1845 coefficients for Airbus aircraft [Refs. 137, 138]. These two documents lack in the information regarding the calculation of any BADA coefficients, and many of the SAE AIR 1845.

Using all the documents mentioned above, a process can be created to determine the coefficients that characterize an aircraft/engine combination in the databases. At the same time, a series of assumptions have to be made regarding what type of data needs to be used. This data could come from either modeling and simulation environments or from flight tests, but the coefficients would always represent said aircraft, without jeopardizing the proprietary information used to create them.

3.4 Hypotheses

The background research was performed to determine possible alternatives to the answering of the research questions proposed at the end of the first chapter. These questions were divided into four main categories, which in turn lead to a series of hypotheses that form the backbone of this research work. The first category of questions dealt with the lack of physical relations that exist in the data used to study stringency scenarios. The second area is related to the first, but has to do with the assumption that the technology response used assumes a constant fuel burn penalty for any necessary NOx reduction. The third group of questions handles the fact that stringency analysis and implementation has not usually been done for more than one measure at a time. The fourth group of questions dealt with the lack of a process to calculate the coefficients that represent an aircraft in the fleet analysis tools utilized by policy makers to study different stringency scenarios. The answer to the first three sets of questions is the *creation of a new technology response that would physically link noise, NOx, and fuel burn,* while for the fourth, the answer is the *creation of the process to determine those coefficients*. The linkage between the aircraft characteristics and its environmental effects has to be done with non-proprietary, publicly available tools, so they can be used in policy making. The use of a physics based, integrated environment, like the one created for UEET or by Antoine, is a perfect solution, which would link the physical characteristics of the aircraft and engine to the environmental key measures concurrently. This concurrency is needed, due to the interactions that were shown to exist between the environmental effects for current systems. In addition, these interdependencies are different for different systems, so a different technology response should be used. The assumption that any NOx improvement will require a 2% fuel burn penalty is not appropriate, and it can be shown using the physics based environment that the three key measures need to be addressed simultaneously. This forms the second hypothesis:

Hypothesis.1. The technology responses cannot be assumed to be constant due to the complexity of aircraft and engines interactions, and the interdependencies between noise, NOx, and fuel burn.

To explore the available space, the different design of experiment techniques can be used. In addition, the concept of Pareto optimality can be used to find the tradeoffs between the key measures. At the same time this concurrency would allow for the quantification of the tradeoffs between them. Using the physics based environment, the feasible technology limits can be obtained. These technology limits can be thought of as the best that could be achieved by a newcomer to the industry. Instead of using a fixed fuel burn penalty for any NOx reduction needed, a series of replacement aircraft can be used to model the existing trade-offs between the three key measures for a given technology level. In addition, the concept of the Pareto optimality can be used to determine the limits of the available space. Requirements also state that replacement aircraft must be chosen such that they will expand across the available space uniformly and that they will be clearly distinct from existing remaining aircraft. The third hypothesis can then be formulated in two parts as:

Hypothesis.2. The technology responses can be created as replacement aircraft that would substitute the ones that do not meet a required stringency requirement.

Hypothesis.3. The replacement aircraft can be chosen as a subset of the Pareto optimal from a complete space exploration. The maximization of the minimum Euclidean distances between the selected points can be used as the criterion for choosing this subset.

Linked to this third hypothesis is the fact that there is no clearly explained process for the calculation of all the coefficients that represent an aircraft in the different databases for their use in the fleet analysis tools. Such process could be used to any real or conceptual aircraft, increasing the capabilities of the stringency analysis process.

The creation of these two processes: the calculation of the technology response, being aircraft class specific, as well as the development of the coefficients that define an aircraft in the fleet databases, are the main hypotheses of this research work. The following chapter outlines and describes in detail the two proposed processes.

CHAPTER 4. APPROACH

It was described in the motivation section, CHAPTER 1, that the main objective of this research work was to improve the actual policy making procedure in terms of aviation environmental protection. Specifically, the part to be improved is the technology response applied to aircraft that do not meet a required stringency. The gaps in the existing process were described, and possible alternatives proposed in the hypotheses shown before. These gaps included the lack of transparency in the technology response used by CAEP in their stringency analyses, and the lack of a process by which to calculate the coefficients that are used in those analyses to represent different aircraft. The proposed solution to the first problem consists in the utilization of a physics based modeling and simulation environment to link the fundamental characteristics of the engine and aircraft to the key measures. This environment would also be used to create a new technology response, in the manner of a series of replacement aircraft, which would represent the achievable limits, and the tradeoffs, between the environmental measures. The second problem is solved by developing a process to calculate said coefficients.

From the linkage of the physical characteristics to the key measures, the interdependencies that exist between the environmental key measures can be observed and quantified. At the same time, the physics based environment could model aircraft and engines that could potentially be designed and manufactured in the future, the new technology response. The timeframe for the creation of these aircraft and engines would have to be linked to the time of introduction of the policies being studied. This linkage would allow for the different variables that represent the inputs to the environment to be varied or not, and what level they should be set to if not used. The utilization would depend on whether they are representative of a technology level or are in fact design variables. For a given timeframe of implementation, there would also be different scenarios that could be implemented, depending on the overall level of reduction that is needed to meet the new stringency being studied. These scenarios could represent a swap of the combustor, a re-fan of the engine, a complete new engine design, or even a whole new aircraft design. These different scenarios would be differentiated by the inputs to the environment that are actually varied. Using this variability, and given a set of ranges for the variables, a space exploration could be performed that would represent possible alternatives to replace the vehicles or engines that do not meet the studied stringency. In addition, the concept of Pareto optimality can be used to determine the achievable limits of the key measures for the different scenarios. The Pareto front would represent the quantification of the tradeoffs between the key measures.

This overall step of creating the technology response is fundamental in the overall policy making process, since it is the one that provides the information relating the interdependencies between noise and emissions interdependencies at the aircraft level. If this information is not correct, the results provided by the other tools in the policy making process cannot have any validity. At the same time, this step converts the aircraft performance into manageable data that the other tools can utilize. The flow of information in the actual policy making process is shown in Figure 25. The proposed process would fit in the AC Data box, providing the information about the interdependencies between noise and emissions, at the aircraft level.

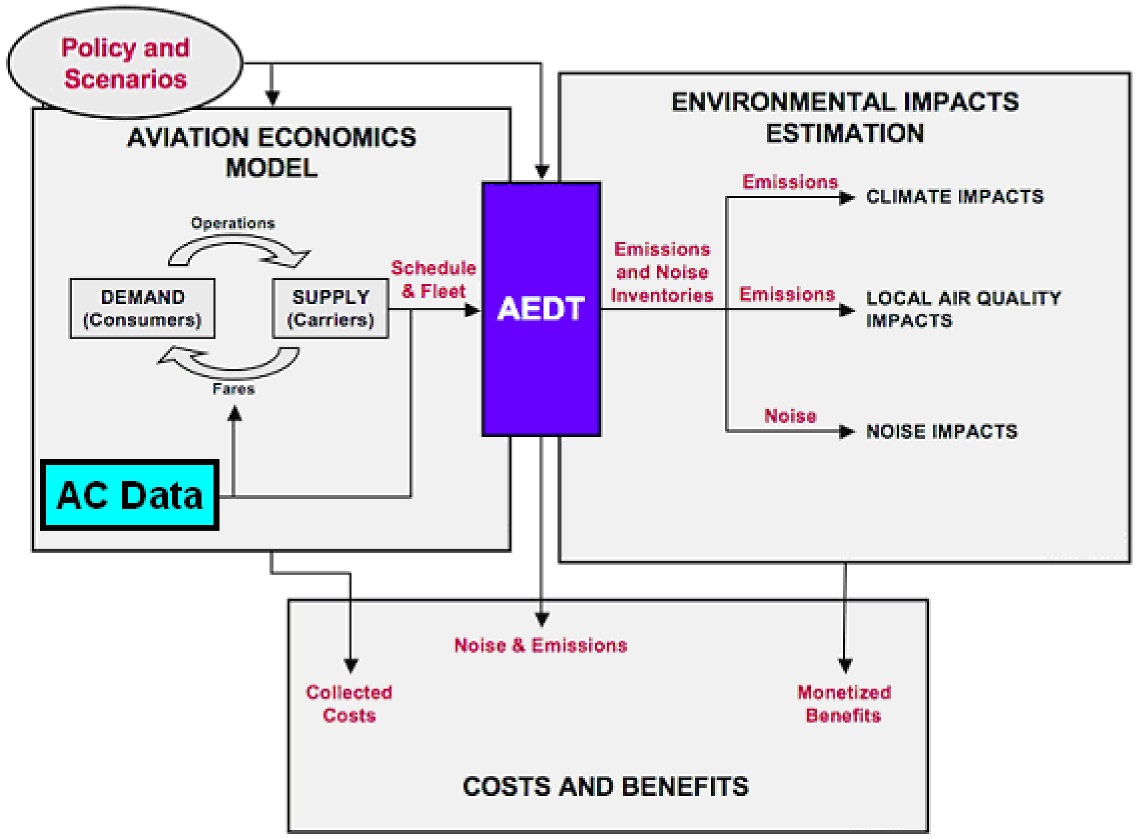

Figure 25: Flow of Information in Current Policy Making Procedure [Ref. 29]

This process of determining the replacement aircraft for those in the databases that do not meet proposed stringency has been reduced to a series of simpler steps. These steps are:

1. Identification of a physics based modeling and simulation environment in which to reproduce the environmental effects of different engine and aircraft configurations.

2. Determination of technology response scenarios. This step is defined by the determination of the inputs to the environment that represent the variables that will change depending on the scenario to be utilized, and those inputs that are fixed.

3. Exploration of the available space given the input variables.

4. Establishment of Technology Response. This is done by determining Pareto Optimal (PO) points out of space exploration results.

The process here delineated is depicted in Figure 26 and it represents the first of the two main contributions of this research work. This process has the final objective of determining the technology response for a particular vehicle or class of vehicles. The technology response has the form of a series of replacement aircraft to those in the fleet that do not meet the stringency being studied. In order to use these aircraft in the fleet analysis tools, their performance must be converted to entries into the databases of coefficients, defined by BADA and SAE AIR 1845. It was stated before that a process to create this coefficients does not exist, so it was created in this research work. This process is the second main contribution of the research. The process to calculate the technology response, and the process to calculate the database coefficients, will be explained in detail in the following two sections.

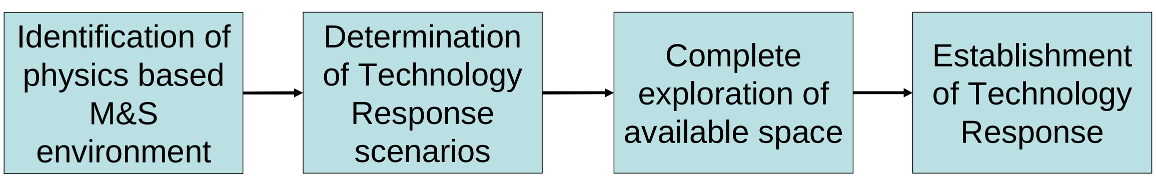

Figure 26: Proposed Method Steps

4.1 Calculation of Technology Response

The first step in the process is the identification of the physics based environment to be used. This step is performed by going through a series of checks for each candidate environment being studied. These checks are shown in Figure 27, in a flow structure. The environment must have a set of specific characteristics in order to serve as the provider of the information to be passed to the other steps of the process.

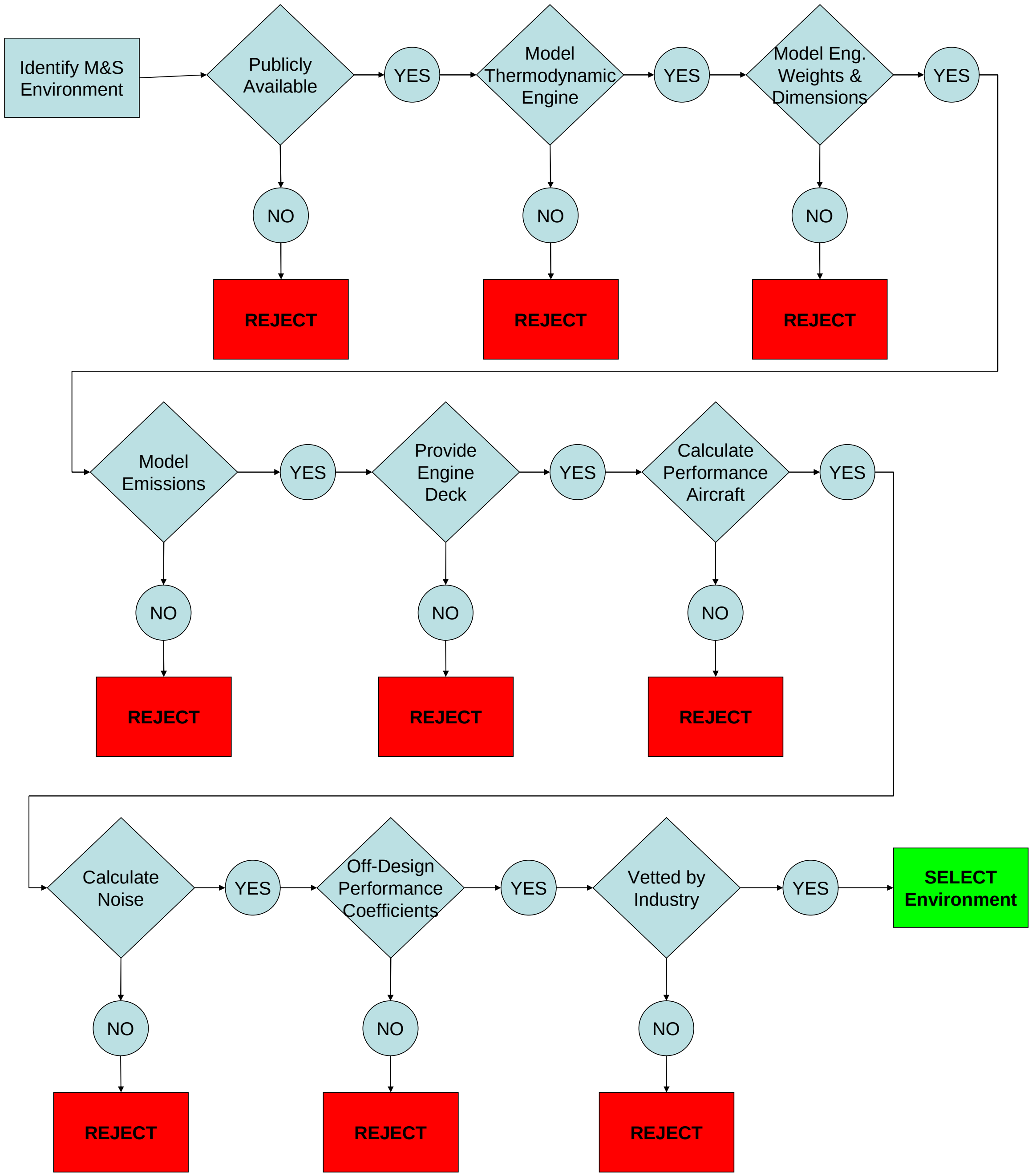

Figure 27: Identification of Environment Flow Chart

The first characteristic that the environment must posses is being *publicly available*. This requisite is linked to the research questions posed in the first chapter: how to determine the fundamental parameters that affect the environmental measures, using non-proprietary data and tools. In addition, the environment has to be able to perform the specific tasks depicted in Figure 28. These tasks start with the ability to *model an engine in terms of its thermodynamic cycle characteristics*. Based on these characteristics, the environment has to also provide an estimate on the *dimensions and weights of the engine*. The thermodynamic cycle analysis has two other main tasks: provide the emissions correlation system with the required information to calculate the *emissions characteristics* of the engine. These emissions must be based as much as possible on physics, or the best available correlations. The actual industry standard is the use of P_3-T_3 correlations to calculate the emissions index of the engine. These correlations are then used to predict the LTO emissions of the engine, a fundamental output of the environment. The next characteristic that the environment must have is the ability to provide the aircraft missions analysis tool with the engine deck, so that it can calculate the *flight performance of the aircraft*. This flight performance is defined as the fuel burn used for a given range, and it is also one of the three fundamental outputs that the system must produce. The noise prediction module requires information about the thermodynamic cycle, as well as the dimensions and weights of the engine and airframe to calculate the *noise characteristics* of the aircraft. These noise characteristics are the certification noise levels, and are the third output needed from the environment. Since the environment has to be used to *calculate the database coefficients*, the list of outputs increases to the flight performance for different missions, as well as different takeoff and landing procedures. This requirements are defined in section 4.2, where the whole process to calculate the coefficients is explained in detail.

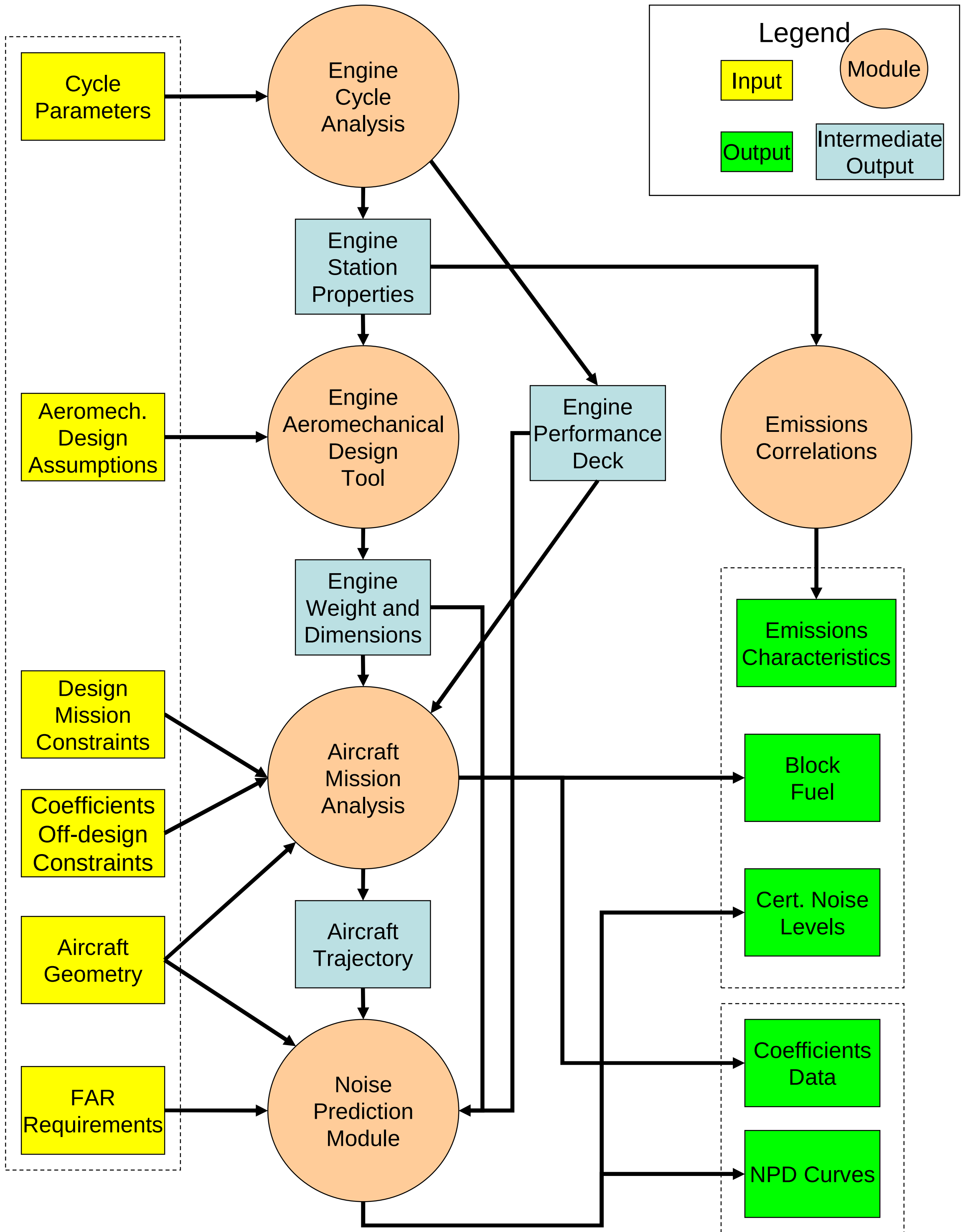

Figure 28: Environment Requirements

In addition to performing the tasks described, the environment has to be *vetted by industry members* so that its results are credible, and it can be used in policy making processes. There are many ways to achieve the validation, but comparing the data obtained with it to real data is the most common of them. In addition to single points, which are useful in determining the accuracy of the system, the trends must also be validated. The trends that the environment produces, depending on the inputs changed, must follow physics, and be in concordance with real life data. The results are not the only thing that should be vetted; the actual procedures used for the calculation of the different parameters must also be checked. In terms of the process to calculate the emissions correlations, it was stated that the P_3-T_3 method is the industry standard, so the environment must be able to produce results using this process. For the fuel burn, the environment has to have the same mission requirements as those used for real flights: in terms of the reserve fuel needed, the loiter times, the cruise done at the same altitudes as it is done by real aircraft, changing those altitudes to optimize fuel burn, and operate under the FAA regulations regarding speed limits below specific altitudes. For the noise characteristics, the certification procedures are quite specific, so the environment must be able to reproduce them accurately.

The next step in the process is the determination of the scenarios to be studied. The process is shown in Figure 29. As it was mentioned before, these scenarios involve different levels of reduction in the area where the stringency is being applied. In addition, the time of implementation of the technology response also plays a role in defining the scenario. It was explained in CHAPTER 2 that the way in which this scenarios are determined in the current policy making process is by just determining the change needed to meet the stringency and comparing the reduction to that has been achieved by other members of the aerospace industry. This led to the determination of the different technology levels used, only one of which, the TL5B, had a fuel burn penalty. For the proposed approach, the characteristics that define each scenario are the inputs to the environment that are being varied, what are their ranges, which inputs are set to a fixed value, and what these values are. Depending on the type of scenario, there would be a varied amount of inputs being varied. For modifications that do not change the aircraft in a substantial manner, the number of variables would be small, while for a larger change, the number of variables would increase. The values of the inputs that are to be fixed depend on the level of technology to be used, which in turn depend on the timeframe of implementation to be used. For short term implementation, current state of the art should be assumed, while for longer term, more advanced technologies can be investigated. The way in which these technologies can be modeled, or the certainty that they would meet the desired objectives, are not the goal of this research work, but rather how to quantify the tradeoffs at the aircraft level, and how those tradeoffs are propagated to the fleet analyses tools.

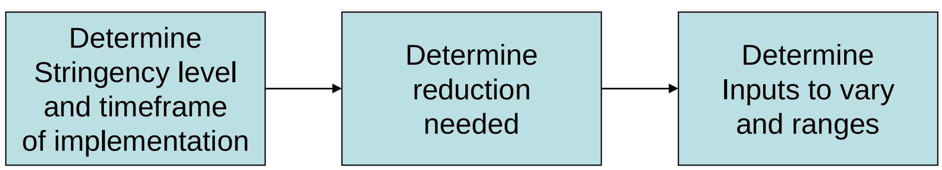

Figure 29: Determination of Scenarios Step Flow Chart

In order to select the replacement aircraft, there has to be a pool of possibilities to choose from. This can be accomplished by performing a complete space exploration on the input variables selected in the previous step. Different options to perform this exploration were explained in the previous chapter. These methods included the used of full factorial designs, Monte Carlo filtering, or Latin-Hypercube designs. The selection of one or the other depends on the time it takes to run each combination, as well as the time available to create the design itself, which can be costly for large number of variables. One key aspect to consider is the fact that in order to determine the feasible limits, the space exploration has to be complete. No area of the design space is to be left unstudied so that all the possible tradeoffs are captured. Independently of the method used for the exploration, the steps that need to be taken to do so are shown in Figure 30.

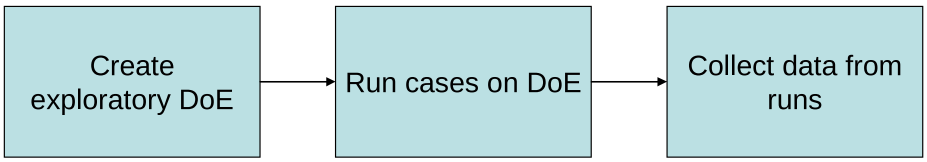

Figure 30: Complete Exploration of Available Space Step Flow Chart

Once this exploration is performed, the last step is the determination of the technology response. This is accomplished by selecting the points that are Pareto optimal. These Pareto optimal points represent the limits of achievability, thus the tradeoffs that can be made between the measures being studied. This set of points is what is called the technology response. The concept of Pareto Optimality was explained in CHAPTER 2; hence here it will only be reminded that Pareto Optimal points are those that, among a bigger group, and given a set of measures, cannot be improved in any of the responses without worsening the other measures. There are many algorithms that will calculate which points are Pareto optimal, but in this research work, the algorithm described by Zitzler and Thiele for its ability to handle multiple responses and its computational speed, will be used [Refs. 122, 123]. The actual implementation of this algorithm is provided in Appendix A of this dissertation. Based on the requirements of the fleet analysis tools used in the policy making process; a number no bigger than 10 aircraft should be used as replacement aircraft for each seat class. This is due to the overwhelming computational resources used to run those tools. If the computational resources were to be increased, the number of aircraft to be used could be increased, providing a more accurate view of the technology response. The number of Pareto optimal points can be smaller or bigger than these 10 aircraft to be used, so in the case that there are more aircraft than available slots, a selection process needs to occur. In this selection process, two major requirements have to be observed:

1. The chosen aircraft will expand the available space, portraying the existing interdependencies between the responses.
2. The chosen aircraft will be significantly different from existing aircraft; which means that they will be more efficient than existing aircraft in the given seat class, at least in one area, while meeting stringency requirements in the rest.

The first of these requirements requires the usage of a technique that would distribute the points uniformly across the available space. In order to do this, the concept of maximization of the minimum distance, or *maxmin* optimization, will be used. This concept is recurrent in many space filling designs of experiments approaches, and other areas where a selection must be made based on dissimilarities [Refs. 139, 140]. This technique provides a uniform distribution of the sampling data across all the variables. The distance that is to be maximized is the Euclidean distance between the points, in the hyper-space created by all the responses. In order to avoid giving more importance to those responses with bigger numerical values, all the responses are to be non-dimensionalized. This will allow the Euclidean distance to be meaningful and portray an accurate description of the space covered by the different possible solutions. Adding the existing aircraft to the distance calculations ensures that the second requirement is also met. Ideally, though, all the aircraft considered Pareto optimal from the space exploration should be used in the fleet analysis tools. This would ensure that all the interdependencies between the key measures are captured and propagated to the policy making process.

4.1.1 Beam Example

In order to shed clarity into the concept of using the Pareto front as the technology response, a simple 2-dimensional example was prepared. In addition, the process by which different points are selected out of this Pareto front is also explained. This example uses the design of a rectangular cantilever beam, of which the length, width, and height can be used as design variables. The beam is to support a load at the end of 1,000 lbs. The two objectives to be optimized are the volume of the beam and the deflection at the tip due to the 1,000 lb load. Figure 31 shows a depiction of the beam as well as the deflection that will occur when the load is applied.

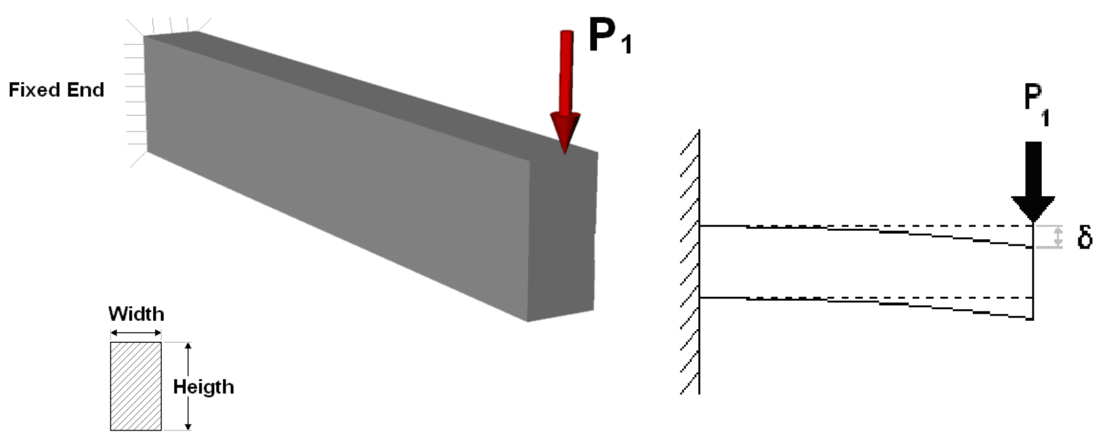

Figure 31: Beam Example Depictions

The material chosen was steel, with modulus of Elasticity of $30 \cdot 10^7$ psi. The ranges given for the design variables are shown in Table 3. The deflection due to the load P_1 was calculated with Equation 8 [Ref. 141].

Table 3: Beam Example Design Variables and Ranges

Variable (units)	**Minimum**	*Maximum*
Height (inches)	4	8
Width (inches)	2	4
Length (inches)	80	120

Equation 8: Bending Deflection due to Load at the end of Cantilever Beam

$$\delta = \frac{L^2 \cdot P_1}{3 \cdot E \cdot I_W}$$

The moment of inertia of the beam, needed to calculate the bending deflection, is calculated with Equation 9.

Equation 9: Moment of Inertia and Volume for Rectangular Cross-Section

$$I_W = \frac{W \cdot H^3}{12}$$

The volume of the beam is simply calculated with Equation 10.

Equation 10: Volume of a Rectangular Beam

$$V = L \cdot H \cdot W$$

Based on the ranges given above, 405 different settings were studied, varying both the height and the width in increments of 0.5 inches and the length in increments of five inches. This leads to four hundred and five (405) different combinations. In addition to these points, five hundred and five (505) randomly chosen points were utilized. The “performance” of these points, that is the volume obtained and the deflection that the resulting beam would endure under the 1,000 lb load, is shown in Figure 32.

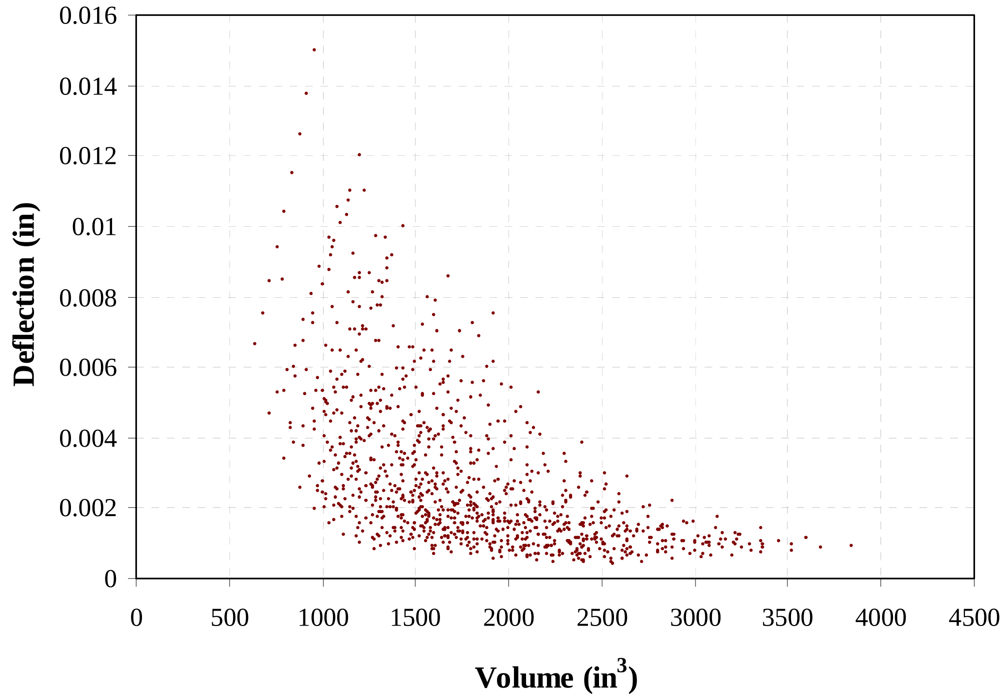

Figure 32: Volume vs. Deflection in Beam Example

In order to avoid problems with the different dimensionality of the two responses, since the actual magnitudes of the two are greatly different, both were non-dimensionalized using the points of minimum volume and minimum deflection. The minimum volume point corresponds to the design variables set to their minimum values, two inches for the width, four inches for the height, and 80 inches for the length.

The point of minimum deflection corresponds to the settings four inches for the width, eight inches for the height, and 80 inches for the length. The corresponding volume and deflection are 640 in^3 and 0.00667 inches for the minimum volume and 2,560 in^3 and 0.00042 inches for the minimum deflection. Using these values, the results can be normalized to values from zero to one with Equation 11. In this equation, max and min correspond to the maximum and minimum values shown above.

Equation 11: Normalization Equation

$$data^* = \frac{data}{\max - \min} - \frac{\min}{\max - \min}$$

The resulting data is used to calculate which of the 1,000 points are Pareto optimal. In this case, that means that those points represent the limit of physically attainable conditions based on the ranges given to the design variables. These points are shown in Figure 33, marked in red, to distinguish them from the rest of the existing points. For this example, there were 17 Pareto optimal designs, but this number is not fixed, it depends on the problem and the variables used.

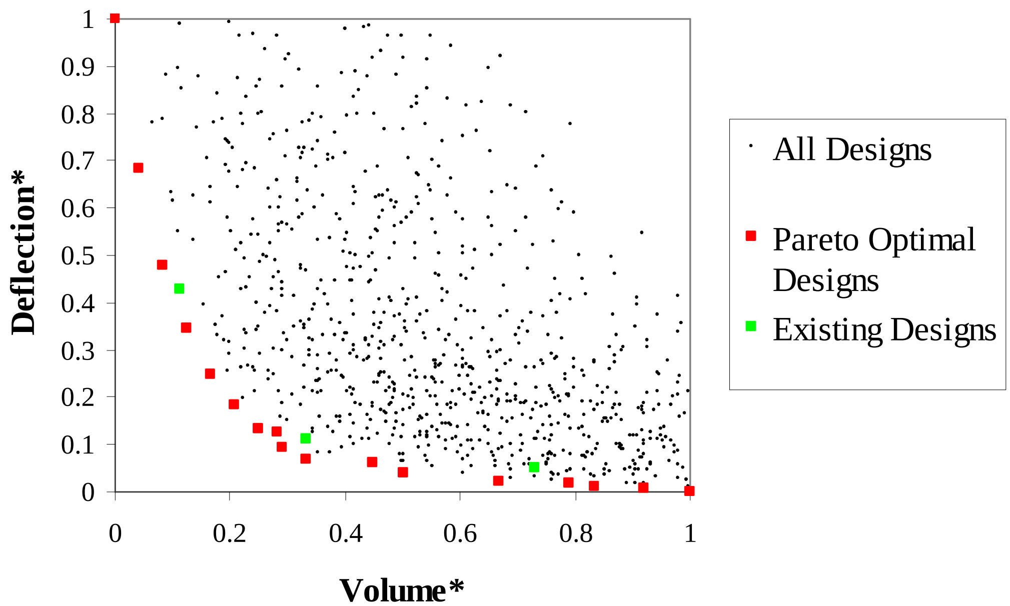

Figure 33: Pareto Optimal Points for Beam Example

Following the same concept of reducing the number of points to be propagated, only 10 of the 17 points will be selected to be used in posterior studies. With the rationale that there will be existing designs in the space, 3 possibilities were added to this example. The way in which these designs achieve the volume and tip deflection is not of importance for this example, and all that matters is that each design has a volume and an associated tip deflection. These points are shown in Figure 33 in green. The chosen points had to be different from the existing points in the space, and they need to cover the space uniformly. This coverage assures that the interdependencies that exist between the two metrics are captured. The first step is to assign a number to each point, so they can be differentiated. Starting from the lowest volume, that point is assigned the number 0, the next volume is number 1, etc. until the 17 points are numbered. The next step is to decide which points are to be utilized. One way to determine this is by ranking the points, using the *maxmin* algorithm. This algorithm is used for design of experiments creation to spread the points as much as possible. The flow diagram of this algorithm is shown in Figure 34.

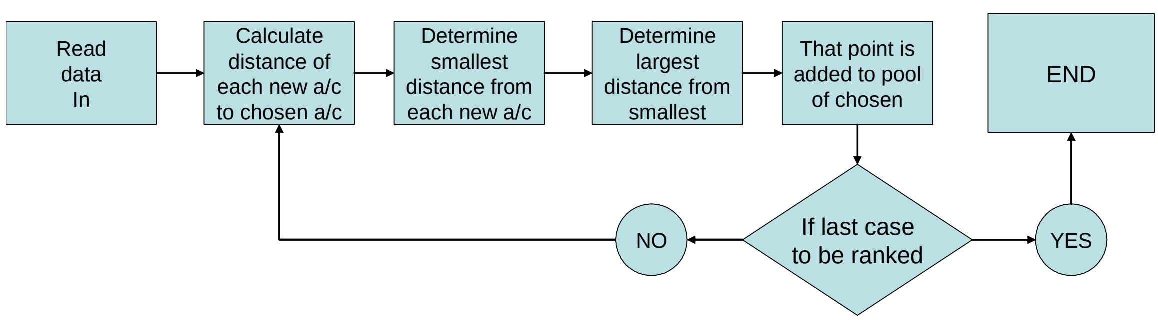

Figure 34: Maxmin Algorithm Flow Diagram

The process starts with the calculation of the distances from the new points, those from which some are to be selected, to those that are already selected. For each new design, the smallest one was chosen to be compared to the smallest distances of the other points. Out of these distances, the point with the largest distance is ranked first. The next chosen point is not the one with the next largest distance. Instead, the first chosen point has to be used now in the calculation of the distances from the possible designs, as if it were an existing design. The process is repeated until all the points have been ranked. The results obtained using this process are listed in Table 4. Depending on the number of points to be selected, different points would be chosen. If five were to be used, then designs 13, 1, 4, 10, and 12 would be chosen. If another one had to be chosen, it would be number 6, and then number 3. The implementation of the ranking process is much simpler than the implementation of algorithm to select a combination, even without the genetic algorithm. It is a much faster method and it provides the best combination every time. These two characteristics make this ranking method the chosen one for this process. The code created to implement this algorithm is provided in Appendix B.

Table 4: Ranking of Designs

Design	**Ranking**	***Design***	**Ranking**
0	1	*9*	14
1	3	*10*	5
2	12	*11*	10
3	8	*12*	6
4	4	*13*	2
5	11	*14*	17
6	7	*15*	9
7	15	*16*	16
8	13		

The differences in what would be called the technology response, that is, the interdependencies between the metrics being tracked, can be seen in Figure 35. This plot shows the lines that connect the chosen points, for three different possibilities: all the

Pareto points, the first 10 in the ranking and the first 5. Clearly, using all the points gives all the information regarding the tradeoffs between the volume and the deflection, but the plot also shows that even with a small number, in the case of 5 chosen, the overall shape of the curve is kept. At the same time, the areas where the points are not being chosen, going from the 17 to 10, and then to 5, are the areas where the existing designs are. This means that those points would not be used anyway for their proximity, and the improvement, if any, on the responses, would be truncated by the cost of implementing a whole new design.

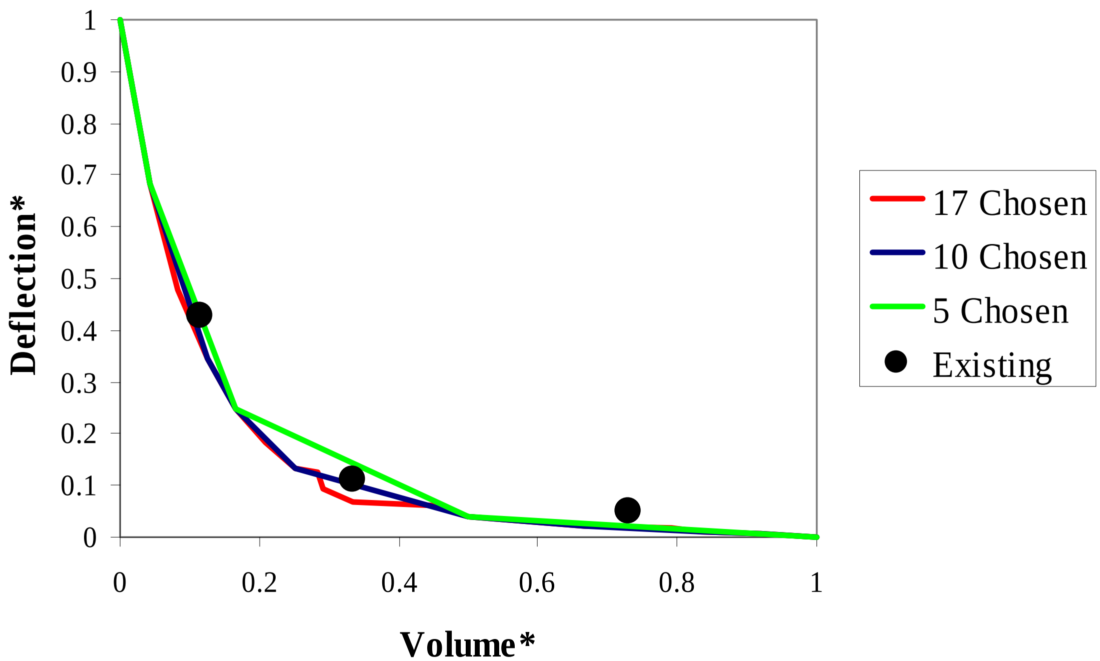

Figure 35: Differences in Technology Response Depending on Number of Points Selected

What his plot demonstrates is the ability of the *maxmin* algorithm to sub-select a set of points that will keep the information regarding the tradeoffs, while differentiating the points from the existing designs.

4.2 Calculation of Database Coefficients

All the coefficients needed to define an aircraft-engine combination are separated into different databases [Ref. 142]. There are three main documents used in the explanation of these coefficients, the BADA User's manual, the AEDT Interface Control Document: Aircraft Performance Module, and the INM user's manual [Refs. 22, 142, 143]. The names of these databases are:

- AIRCRAFT
- PROFILE
- PROCEDUR
- PROF_PTS
- FLAPS
- THR_JET
- THR_GNRL
- ENG_EMIS
- BADA_ACFT
- BADA_APF
- BADA_CONFIG
- BADA_FUEL
- BADA_THRUST

The content of each of these tables will be explained in detail in the following sections. The required data needed to populate these tables and to create an entry into the databases is shown graphically in Figure 36.

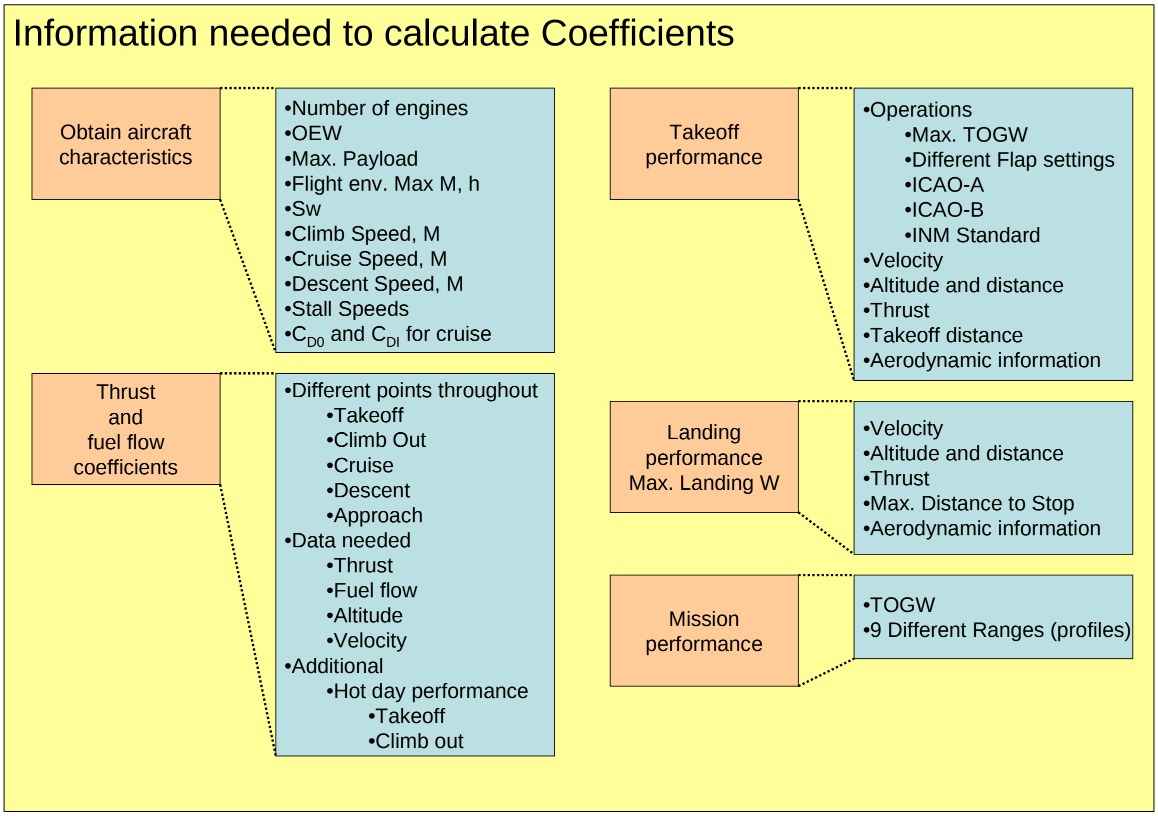

Figure 36: Process to Calculate Coefficients Flow Chart

The process to populate these tables starts with a sample mission, in this case, it was chosen as the design mission. From this mission, a number of parameters are needed: the number of engines in the aircraft, the operational empty weight, the maximum payload allowable, the flight envelope maximum Mach number, altitude, and the wing area. Also from this mission, the common climb, cruise, descent velocities, and Mach numbers are recorded. In addition, the aerodynamic parameters stall speed, zero lift drag, and parasitic drag coefficients for the cruise are obtained from the mission. To calculate the fuel and thrust coefficients, the thrust and fuel flow are obtained from the takeoff, climb, cruise, descent, and approach segments, along with the altitudes and velocities at which they are obtained. Also for the thrust coefficients, a takeoff and climb out for a hot day are needed. Again the thrust, velocity, and altitude are recorded and used to calculate the coefficients. Another takeoff needed is that done at maximum takeoff gross weight. This is done to record the takeoff performance in terms of velocity, altitude, and thrust used. Similarly, the approach at maximum landing weight is needed, also in terms of velocity, thrust, altitude, and also the maximum distance to stop the aircraft. Also, although regular operations would not require them, the takeoff performance for the available flap settings has to be recorded, so that the fleet analysis tool can determine the aerodynamic characteristics of those flap configurations. Lastly, the trajectory, thrust, and velocity for the ICAO A, ICAO B, and STANDARD procedures, as described in CHAPTER 4, are recorded for the *procedur* database. Also from these procedures, the takeoff gross weights for different mission ranges are recorded.

The AIRCRAFT file contains information about the aircraft and its performance. The data required includes the maximum takeoff gross weight, and the maximum landing weight in pounds, the maximum distance to stop from touchdown in feet, and the static thrust of each engine in the aircraft in pounds. The maximum payload is also required, and it is obtained from a regression as a function of the number of passengers, as seen in Figure 37. This equation was obtained from a careful study of maximum payload versus passengers of existing airliners. The equation has two forms, one for cases where the number of passengers is less than 425, shown in Equation 12, and one for more than 425 passengers, shown in Equation 13.

Equation 12: Maximum Payload for less than 425 passengers

$$MaxPayload = \exp\begin{pmatrix} 10.024 - 6.420\cdot 10^{-4}\cdot[\#ofPassengers] + 5.041\cdot 10^{-5}\cdot[\#ofPassengers]^2 \\ -1.284\cdot 10^{-7}\cdot[\#ofPassengers]^3 + 9.083\cdot 10^{-11}\cdot[\#ofPassengers]^4 \end{pmatrix}$$

Equation 13: Maximum Payload for more than 425 passengers

$$MaxPayload = 136212 + (50 \cdot [\#\text{of passengers}])$$

The fact that the curve in Figure 37 flattens out at the end of the graph is very likely due to the trade between payload and fuel available, rather than structural factors. Along with the data described above, the AIRCRAFT database also contains descriptors that uniquely define the aircraft/engine combination.

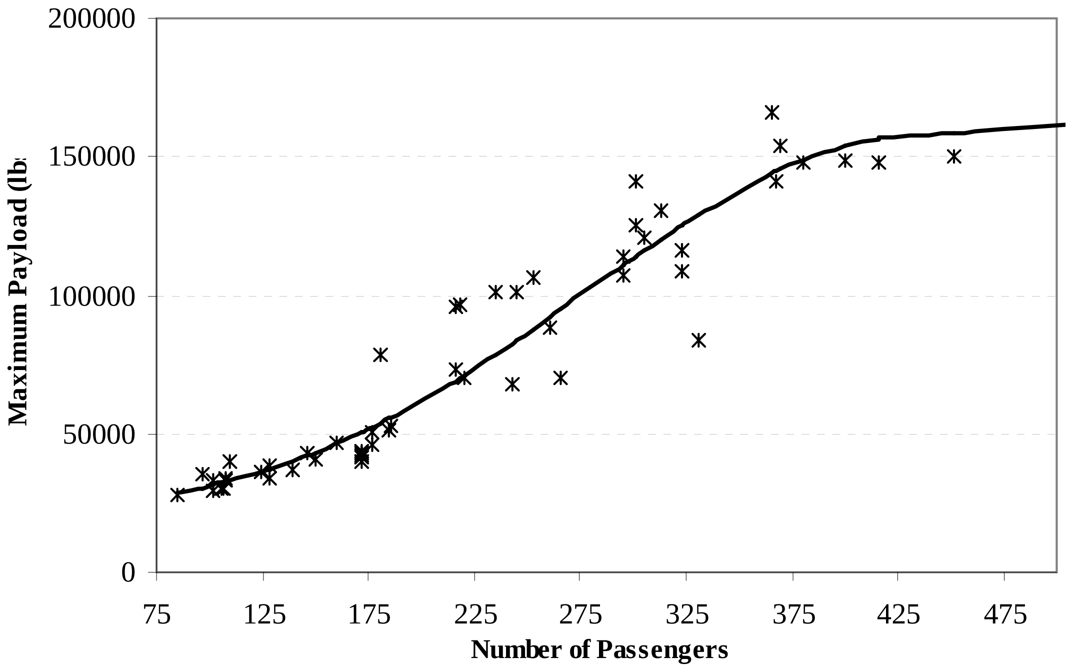

Figure 37: Maximum Payload vs. Passengers

The data in the PROFILE database deals with the operations of the aircraft for different mission ranges. The data includes the Takeoff Gross Weight (TOGW) in pounds of the aircraft needed to fly a mission of a specific range in nautical miles. There are up to nine stages that have to be populated shown in the following table, depending on the size of the aircraft. For larger aircraft all the stages could be flown, but smaller ones may not reach the longer ranges.

As in the AIRCRAFT database, the PROFILE also has descriptors that define the aircraft, but is also has the type of operation (A for approach and D for departure).

Table 5: Stage Number and Associated Ranges (nmi)

Stage Number	1	2	3	4	5	6	7	8	9
Maximum Range (nmi)	500	1,000	1,500	2,500	3,500	4,500	5,500	6,500	---
Minimum Range (nmi)	0	500	1,000	1,500	2,500	3,500	4,500	5,500	6,500

As its name indicates, the FLAPS file contains the information regarding the aerodynamic performance of the aircraft under different flap settings. There are 3 coefficients for each flap setting, COEFF_R, COEFF_CD, and COEFF_B, listed in Table 6. The first coefficient, COEFF_R, is obtained by inversing the lift to drag ratio for the different configurations. The coefficient is therefore non-dimensional. The second coefficient is obtained with Equation 14

Table 6: FLAPS Table Calculated Values

Parameter	Description	Units
COEFF_R	Drag-over-lift ratio	N/A
COEFF_C_D	Takeoff and landing calibrated airspeed coefficient	knt/lb^1/2
COEFF_B	Takeoff distance coefficient	ft/lb

Equation 14: Calibrated Airspeed Coefficient

$$COEFF\_CD = \sqrt{\frac{V^2}{M_{\max}}}$$

In this equation, M_{max} is the maximum takeoff gross weight in pounds, and V is the velocity in knots at the point above the 35 ft obstacle. The units of this coefficient are knots/lb$^{1/2}$. The third coefficient, COEFF_B, is used to calculate the ground roll for different flap settings with Equation 15.

Equation 15: Ground Roll

$$Sg = \frac{COEFF\_B \cdot \theta \cdot \left(\frac{W}{\delta}\right)^2}{N \cdot \left(\frac{Fn}{\delta}\right)_2}$$

Where Sg is the ground roll distance in ft, θ is the temperature ratio at the airport's elevation, W is the departure profile weight in pounds, δ is the pressure ratio at the airport, N is the number of engines, and $\left(\frac{Fn}{\delta}\right)_2$ is the corrected net thrust per engine at the 35 ft obstacle point during takeoff, also in pounds.

The PROF_PTS database is formed by the aircraft performance during landing for the operation of maximum landing weight, but it could also contain the aircraft performance for takeoff at different gross weights, and procedures. The values needed are the distance on the runway from touchdown in feet, the altitude, also in feet, the velocity in knots, and the trust setting, in pounds.

The PROCEDUR file contains the performance of the aircraft during standard approach procedure and during standard and ICAO A, ICAO B, and STANDARD takeoff procedures. It can also contain the landing performance of the aircraft. The values needed include altitude (ft), distance (ft), velocity (knots), rate of climb(ft/min), angle of attack, and thrust in pounds at different points during takeoff and landing. The actual coefficients are classified in only 3 types, PARAM1, PARAM2, and PARAM3, and change depending on the operation, the step type, and the thrust setting at that time. The calculated values are listed in Table 7.

Table 7: PROCEDUR Table Calculated Values

<table>
<tr><th>Operation</th><th>stepType</th><th>thrType[1]</th><th>PARAM1</th><th>PARAM2</th><th>PAAM3</th></tr>
<tr><td rowspan="4">Approach</td><td>Level</td><td>All thrusts</td><td>Altitude (ft)</td><td>Calibrated Airspeed (knots)</td><td>Distance (ft)</td></tr>
<tr><td>Descend</td><td>All thrusts</td><td>Altitude (ft)</td><td>Calibrated Airspeed (knots)</td><td>Descent Angle (degrees)</td></tr>
<tr><td>Land</td><td>All thrusts</td><td>Distance (ft)</td><td>0</td><td>0</td></tr>
<tr><td>Decelerate</td><td>All thrusts</td><td>Distance (ft)</td><td>Calibrated Airspeed (knots)</td><td>Percent of Static Thrust</td></tr>
<tr><td rowspan="7">Depart</td><td>Level</td><td>All thrusts</td><td>Altitude (ft)</td><td>Calibrated Airspeed (knots)</td><td>Distance (ft)</td></tr>
<tr><td rowspan="2">MaxTakeoff</td><td>T,C,N</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>U</td><td>0</td><td>0</td><td>Thrust (lbs)</td></tr>
<tr><td rowspan="2">Climb</td><td>T,C,N,R</td><td>Altitude (ft)</td><td>0</td><td>0</td></tr>
<tr><td>K,U</td><td>Altitude (ft)</td><td>0</td><td>Thrust (lbs)</td></tr>
<tr><td rowspan="2">Accelerate</td><td>T,C,N,R</td><td>Rate of Climb (ft/min)</td><td>Calibrated Airspeed (knots)</td><td>0</td></tr>
<tr><td>K,U</td><td>Rate of Climb (ft/min)</td><td>Calibrated Airspeed (knots)</td><td>Thrust (lbs)</td></tr>
</table>

The ICAO A takeoff procedure is depicted in Figure 38. The schedule has 4 specific segments. The first is a constant speed climb at full power. Then a cutback is performed to the climb thrust level and climb is continued until 3,000 ft altitude is reached. These two segments are to be performed with full flap configuration. At 3,000 ft, the flaps are retracted and the aircraft accelerates to 250 knots at which point climb is resumed until 10,000 ft. this velocity is specific for a class of vehicles, in this case a large aircraft. For different classes, the velocity would be modified accordingly. This is also true for all the velocities shown in the following procedures.

[1] T = MaxTakeoff, C = MaxClimb, N = MaxContinue, R = ReduceThrust, K = UserCutback, U = UserValue

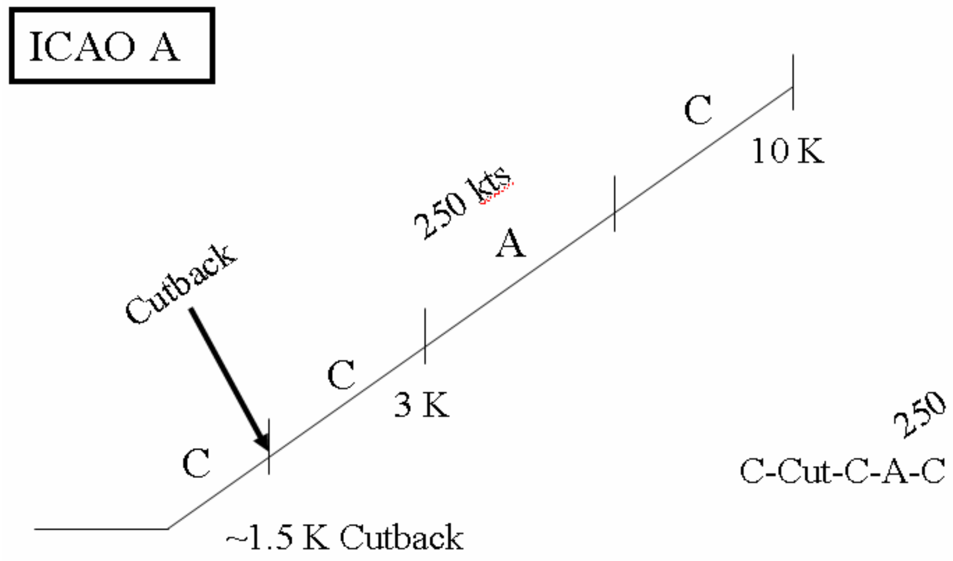

Figure 38: ICAO A Takeoff Procedure

The ICAO B procedure is depicted in Figure 39 and it includes 5 segments. The first segment is a climb to 1,000 ft., and then an acceleration takes place after retracting all the flaps. A cutback is performed and climb is continued until 3,000 ft altitude is reached. At that point, the aircraft must accelerate to 250 knots and continue climb to 10,000 ft.

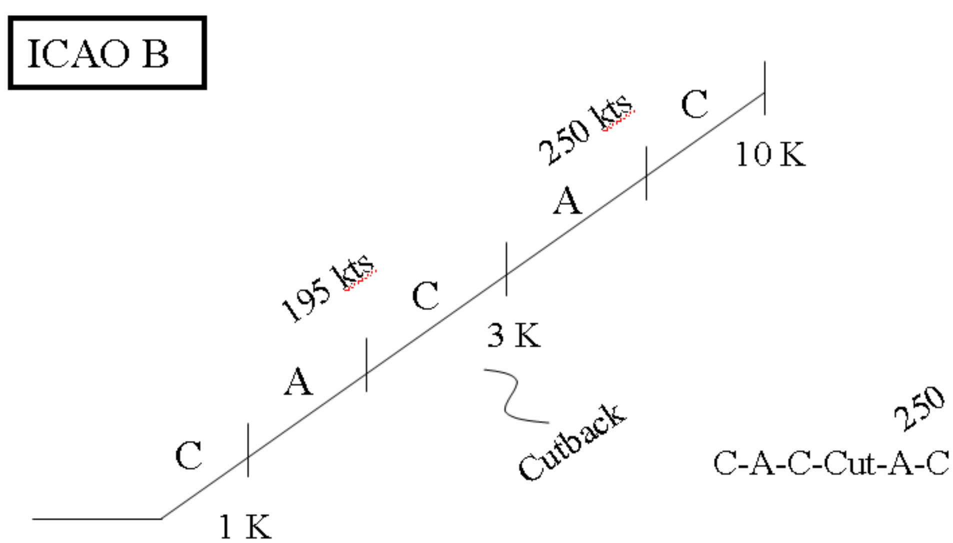

Figure 39: ICAO B Takeoff Procedure

The INM standard profile flies the same takeoff profile segments as the design mission with modifications to engine cutback and flap settings. The engine cutback occurs at 190 knots instead of 1,000 ft altitude. Part flap occurs at 210 knots and the clean aircraft begins at 3,000 ft altitude. This is very similar to the ICAO B profile. The INM Standard procedure is shown in Figure 40. Based on each of the profiles flown, different FLOPS runs were executed.

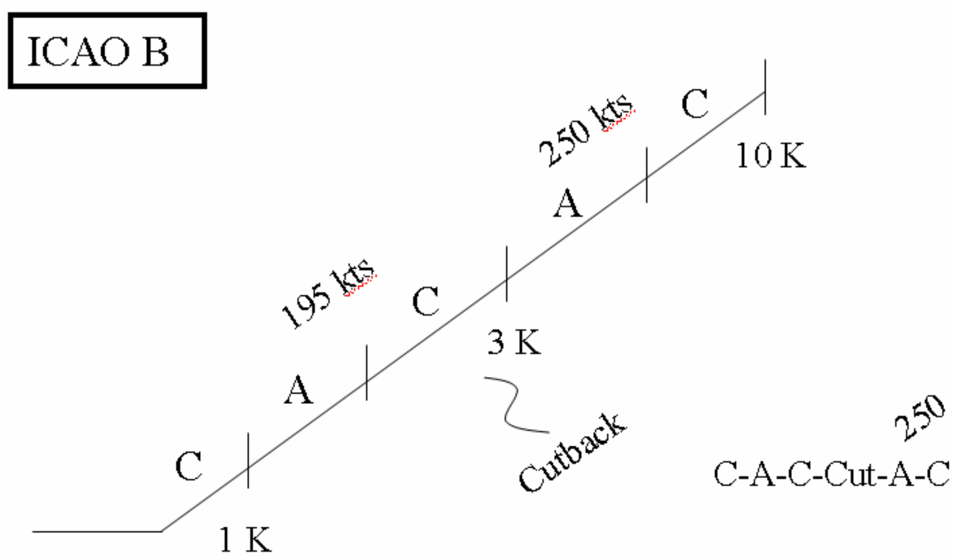

Figure 40: INM Standard Takeoff Procedure

The THR_JET file contains coefficients used to calculate the thrust produced by the engines at different altitudes, velocities, and temperatures, as well as for different procedural steps. The steps include maximum thrust in pounds for takeoff, climb out, and cruise, all at standard day and high temperatures. Equation 16 is the main equation used to solve the thrust.

Equation 16: Thrust Equation

$$\left(F_n / \delta_{am} \right) = E + F \cdot V_C + G_a \cdot h + G_b \cdot h^2 + H \cdot T_{am}$$

Where:

F_n = Net thrust per engine (lbs) at altitude

$\delta_{am} = P_{am}/P_{ref}$ (Ref. Pressure = sea level)

V_C = True airspeed (knots)

h = Altitude (ft)

T_{am} = Ambient temperature in which the airplane is operating (deg C)

The units for the coefficients are the following:

E → pounds

F → pounds / knot

G_a → pounds / feet

G_b → pounds / feet^2

H →pounds / deg K

For the low temperature (Standard Day) takeoff, the values for the coefficients are obtained using 3 points along takeoff procedure of the aircraft. The first point is the initial point in the procedure, which is the brake release point. From it, the altitude at which takeoff takes place, and the thrust exerted at that moment, are obtained. The first coefficient is then calculated with Equation 17, which is basically the corrected thrust of one engine if the takeoff occurs at sea-level.

Equation 17: First Thrust Coefficient for Takeoff

$$E = \frac{F_{n1}}{\#\ of\ Eng}$$

The velocity at that same point is also required to be used later, and the altitude, thrust, and velocity of a second point is also needed. The velocities are true airspeeds at those points. With these two sets of values, the rest of the parameters can be calculated. First the thrust needs to be converted to corrected thrust with Equation 18.

Equation 18: Thrust Conversion to Corrected Thrust

$$F_{n2Corrected} = \frac{F_{n2}}{\left(1 - \frac{h_2}{145450}\right)^{5.2561}}$$

Then the parameter G_a can be obtained with Equation 19.

Equation 19: Altitude Thrust Coefficient for Takeoff

$$G_a = \frac{F_{n2Corrected} - F_{n1} \cdot \frac{V_2}{V_1}}{h_2 - h_1 \cdot \frac{V_2}{V_1}}$$

And the parameter F with Equation 20.

Equation 20: Velocity Thrust Coefficient for Takeoff

$$F = \frac{F_{n1} - h_1 \cdot G_a}{V_1}$$

To calculate the parameter H, data from a high temperature takeoff is needed. The static takeoff thrust is obtained and then converted like before with Equation 18. The temperature differential from Standard Day in degrees Kelvin is required to calculate parameter H, which is done with Equation 21.

Equation 21: Temperature Thrust Coefficient for Takeoff

$$H = \frac{F_{n1HT} - E}{15 + \Delta T}$$

The coefficient G_b can be assumed to be 0 for takeoff operations.

A similar process as the one used for takeoff is to be used to calculate the parameters for the climb out procedure. In this case, 4 points are needed. From them, the thrust, which was converted as before with Equation 18 to corrected thrust, the true airspeed, and altitude are required, and the parameters are calculated, solving the linear system of equations defined by Equation 22.

Equation 22: Climb Out System of Equations

$$\left(F_n / \delta_{am} \right)_1 = E + F \cdot V_{C,1} + G_a \cdot h_1 + G_b \cdot h_1^{\ 2}$$
$$\left(F_n / \delta_{am} \right)_2 = E + F \cdot V_{C,2} + G_a \cdot h_2 + G_b \cdot h_2^{\ 2}$$
$$\left(F_n / \delta_{am} \right)_3 = E + F \cdot V_{C,3} + G_a \cdot h_3 + G_b \cdot h_3^{\ 2}$$
$$\left(F_n / \delta_{am} \right)_4 = E + F \cdot V_{C,4} + G_a \cdot h_4 + G_b \cdot h_4^{\ 2}$$

The equations to calculate the coefficients for climb out thrust are Equation 23. They are the solution to the system of equations shown in Equation 22.

The high temperature coefficient H was already obtained for takeoff conditions, so the same value can be used.

Using the same equations as for climb out, but with points extracted from the cruise segment, the cruise thrust parameters are obtained. In this case, the parameter for temperature is 0, since cruise is performed at pressure altitude and the temperature is constant with pressure. Also, the effect of the square of the altitude is negligible in this thrust, so the coefficient G_b is assumed to be 0.

The THR_GNRL file contains the same parameters as THR_JET but only for the cruise segment.

Equation 23: Climb Out Thrust Coefficient Calculations

$$G_b = \frac{\dfrac{\dfrac{\left(F_n/\delta_{am}\right)_4 - \left(F_n/\delta_{am}\right)_1}{V_{C,4}-V_{C,1}} - \dfrac{\left(F_n/\delta_{am}\right)_2 - \left(F_n/\delta_{am}\right)_1}{V_{C,2}-V_{C,1}}}{\dfrac{h_4-h_1}{V_{C,4}-V_{C,1}} - \dfrac{h_2-h_1}{V_{C,2}-V_{C,1}}} - \dfrac{\dfrac{\left(F_n/\delta_{am}\right)_3 - \left(F_n/\delta_{am}\right)_1}{V_{C,3}-V_{C,1}} - \dfrac{\left(F_n/\delta_{am}\right)_2 - \left(F_n/\delta_{am}\right)_1}{V_{C,2}-V_{C,1}}}{\dfrac{h_3-h_1}{V_{C,3}-V_{C,1}} - \dfrac{h_2-h_1}{V_{C,2}-V_{C,1}}}}{\dfrac{\dfrac{h_4^2-h_1^2}{v4-v1} - \dfrac{h_2^2-h_1^2}{v2-v1}}{\dfrac{h4-h1}{V_{C,4}-V_{C,1}} - \dfrac{h2-h1}{V_{C,2}-V_{C,1}}} - \dfrac{\dfrac{h_3^2-h_1^2}{v3-v1} - \dfrac{h_2^2-h_1^2}{v2-v1}}{\dfrac{h3-h1}{V_{C,3}-V_{C,1}} - \dfrac{h2-h1}{V_{C,2}-V_{C,1}}}}$$

$$G_a = \frac{\dfrac{\left(F_n/\delta_{am}\right)_3 - \left(F_n/\delta_{am}\right)_1}{V_{C,3}-V_{C,1}} - \dfrac{\left(F_n/\delta_{am}\right)_2 - \left(F_n/\delta_{am}\right)_1}{V_{C,2}-V_{C,1}}}{\dfrac{h3-h1}{V_{C,3}-V_{C,1}} - \dfrac{h2-h1}{V_{C,2}-V_{C,1}}} - \frac{\dfrac{h_3^2-h_1^2}{V_{C,3}-V_{C,1}} - \dfrac{h_2^2-h_1^2}{V_{C,2}-V_{C,1}}}{\dfrac{h3-h1}{V_{C,3}-V_{C,1}} - \dfrac{h2-h1}{V_{C,2}-V_{C,1}}} \cdot G_b$$

$$F = \frac{\left(F_n/\delta_{am}\right)_2 - \left(F_n/\delta_{am}\right)_1}{V_{C,2}-V_{C,1}} - \frac{h_2^2-h_1^2}{V_{C,2}-V_{C,1}} \cdot G_b - \frac{h_2-h_1}{V_{C,2}-V_{C,1}} \cdot G_a$$

$$E = \left(F_n/\delta_{am}\right)_1 - h_1^2 \cdot G_b - h_1 \cdot G_a - V_{C,1} \cdot F$$

The ENG_EMIS file is composed of data referring to the performance of the engines in terms of emissions. It includes the net thrust at sea level static conditions (kN), the unadjusted and adjusted fuel flow for the 4 points required by the ICAO (Takeoff, Climb out, Approach and Idle) in kg/sec, and the emissions coefficients at the same 4 points (gr/kg) for NOx, CO, HC, PM, and also the smoke number.

In the BADA_ACFT file, information about the aircraft is presented. This information includes the number of engines, and three different masses. Those masses are the reference mass, which was chosen as the takeoff gross weight of stage length 5, a maximum mass, which is the maximum takeoff gross weight, the minimum mass, which is the operational empty weight, and the maximum allowable payload. The calculation of the maximum payload was explained on the AIRCRAFT file description. The units of the masses are metric tons. The other parameters are the weight gradient at maximum altitude (ft/kg), the maximum operational speed, Mach number, and altitude (ft), the maximum altitude at maximum takeoff gross weight and ISA (ft), the temperature gradient (ft/deg C) and the wing area (m^2). The temperature gradient is 0 because the aircraft flies at pressure altitude, so no temperature differential exists. The weight gradient and the maximum altitude at maximum gross weight are calculated by obtaining the altitude at top of climb of two of the stage lengths calculations, in this case, lengths 7 and 5 respectively, and their respective takeoff gross weights. The top of climb coincides with the highest point where a rate of climb of 300 ft/min can be achieved. Then the weight gradient is calculated with Equation 24 and the maximum altitude is obtained with Equation 25.

Equation 24: Mass Gradient with Altitude

$$mass\_grad = \frac{h_2 - h_1}{m_1 - m_2}$$

Equation 25: Maximum Altitude

$$fenv\_h\max = h_1 - mass\_grad \cdot \left(MA\_\max - m_1\right)$$

The BADA_APF file contains speeds and Mach numbers for climb, cruise, and descent segments. The Mach numbers are all equal to the nominal cruise Mach number. There are 2 speeds for climb and 2 for descent. The first climb speed is the average climb speed below 10,000 ft and the second is from 10,000 ft to the transition altitude. The first descent velocity is the velocity from the transition altitude to 10,000 ft and the second is below 10,000 ft. These speeds need to be converted from True Airspeed to Corrected Airspeed. First they are transformed into m/s from knots, and then the velocities are transformed into CAS with Equation 26.

Equation 26: True Airspeed to Calibrated Airspeed

$$V_{CAS} = \left[\frac{2(P_0)_{ISA}}{\mu(\rho_0)_{ISA}} \left\{ \left(1 + \frac{P}{(\rho_0)_{ISA}} \left[\left(1 + \frac{\mu}{2} \frac{\rho}{P} V_{TAS}^2 \right)^{1/\mu} - 1 \right] \right)^{\mu} \right\} \right]^{1/2}$$

The BADA_CONFIG file is formed with aerodynamic characteristics of the aircraft at the different segments of the mission; during cruise, takeoff, initial climb, approach, and landing. The data includes the stall speed in knots, the parasitic drag coefficient, and the induced drag coefficient. The stall speeds are calculated using a reference speed, taken as the stall speed of the aircraft during takeoff at sea level conditions and a reference mass, taken as the takeoff gross weight of stage 5. The specific stall speeds for the other segments are obtained in Equation 27.

Equation 27: Stall Velocities

$$V_{stall\ Cruise} = V_{ref} \cdot \sqrt{\frac{M_{Cruise}}{M_{ref}}}$$

$$V_{stall\ Initial\ Clmb} = V_{ref} \cdot \sqrt{\frac{M_{Initial\ Clmb}}{M_{ref}}}$$

$$V_{stall\ Approach} = V_{ref} \cdot \sqrt{\frac{M_{Approach}}{M_{ref}}}$$

The overall drag coefficient is defined as $C_D = C_{D,0} + C_{D,2} \cdot C_L{}^2$. The induced drag coefficient, $C_{D,2}$, is the same for all the segments with clean configurations, which are the climb out, cruise, and approach segments. It is calculated with Equation 28.

Equation 28: Induced Drag Coefficient for Climb Out, Cruise, and Approach

$$C_{D,2} = \frac{1}{\pi \cdot AR \cdot E}$$

In this equation, AR is the aspect ratio and E is the Oswald efficiency factor.

Using the drag and lift coefficients for any point along the drag polar of the aircraft, the zero lift drag coefficient is calculated with Equation 29.

Equation 29: Zero Lift Drag Coefficient

$$C_{D,0} = C_D - C_{D,2} \cdot C_L{}^2$$

In a similar way, the zero lift drag coefficients for climb out and approach are obtained. Any two values for C_L and C_D are needed to calculate $C_{D,0}$ and $C_{D,2}$. Then Equation 30 is used to calculate $C_{D,2}$ and Equation 29 is used to calculate $C_{D,0}$.

Equation 30: Induced Drag Coefficient for Landing and Takeoff

$$C_{D,2} = \frac{C_{D2} - C_{D1}}{C_{L2}{}^2 - C_{L1}{}^2}$$

The BADA_FUEL file contains coefficients that approximate the fuel consumption at different points during the mission. For maximum thrust, the Thrust Specific Fuel Consumption is to be obtained with Equation 31.

Equation 31: Thrust Specific Fuel Consumption for Climb Out

$$\eta = \frac{Fuel}{F_N} = C_{f1} \times \left(1 + \frac{V_{TAS}}{C_{f2}}\right)$$

The two parameters, C_{f1} and C_{f2}, are obtained with the fuel flow, thrust, and true airspeed at two points during the initial climb segment and with Equation 32 and Equation 33.

Equation 32: First Fuel Flow Coefficient for Climb Out

$$C_{f1} = \eta_1 - V_{TAS1} \cdot \frac{\eta_1 - \eta_2}{V_{TAS1} - V_{TAS2}} = \frac{Fuel_1}{F_{n1}} - V_{TAS1} \cdot \frac{\frac{Fuel_1}{F_{n1}} - \frac{Fuel_2}{F_{n2}}}{V_{TAS1} - V_{TAS2}}$$

Equation 33: Second Fuel Flow Coefficient for Climb Out

$$C_{f2} = C_{f1} \cdot \frac{V_{TAS1} - V_{TAS2}}{\eta_1 - \eta_2} = C_{f1} \cdot \frac{V_{TAS1} - V_{TAS2}}{\frac{Fuel_1}{F_{n1}} - \frac{Fuel_2}{F_{n2}}}$$

The units for these coefficients are kg/min/kN for C_{f1} and knots for C_{f2}.

For descent, which represents idle conditions, the equation to obtain the minimum fuel consumption is Equation 34.

Equation 34: Fuel Flow for Descent

$$f_{\min} = C_{f3} \times \left(1 - \frac{h}{C_{f4}}\right)$$

As before, 2 points during the descent are needed, from which the fuel flow and altitude are required. Then the coefficients are calculated with Equation 35 and Equation 36.

Equation 35: Third Fuel Flow Coefficient for Descent

$$C_{f3} = f_{D,4}$$

Equation 36: Fourth Fuel Flow Coefficient for Descent

$$C_{f4} = -C_{f3} \cdot \frac{h_{D,3}}{f_{D,3} - f_{D,4}}$$

The units are kg/min for C_{f3} and feet for C_{f4}.

The cruise fuel flow coefficient is obtained by using the first two fuel flow coefficients and any point during cruise, for which the thrust, true velocity, and fuel flow are needed. The coefficient is then obtained with Equation 37.

Equation 37: Cruise Fuel Flow Coefficient

$$C_{f\,Cr} = \frac{f_{Cr}}{\left(T_{Cr} \cdot C_{f1} \cdot \left(1 + V_{TAS\,Cr} \cdot C_{f1}\right)\right)}$$

This equation renders the coefficient unitless.

The BADA_THRUST file contains the coefficients used to calculate the thrust of the engines during climb at maximum power. The equation in which they will be used is Equation 38.

Equation 38: Maximum Power Climb Thrust

$$T_{\text{max climb}} = C_{Tc1} \cdot \left(1 - \frac{h}{C_{Tc2}} + C_{Tc3} h^2\right) \cdot \left(1 - C_{Tc5}\left(\Delta T_{ISA} - C_{Tc4}\right)\right)$$

To calculate the coefficients, 3 points during climb have to be used. Their respective thrusts and altitudes are needed. A data point from a high temperature condition must also be used. The easiest alternative is the sea level static thrust for high temperature. The coefficients are then obtained by linear interpolation between the points and have the following units:

C_{Tc1} →Newtons

C_{Tc2} →Feet

C_{Tc3} →1/Feet^2

C_{Tc4} →Degrees C

C_{Tc5} →1/Degrees C

The coefficient C_{tc4} can be assumed to be 0, and the coefficient C_{tc5} can be obtained with Equation 39.

Equation 39: Fifth Thrust Coefficient

$$C_{Tc5} = \frac{T_{\text{max climb}1} - T_{\text{max climb}1\,High\ Temp}}{\Delta T_{ISA} \cdot T_{\text{max climb}1}}$$

The first thrust coefficient is calculated using Equation 40, the second and third with Equation 41.

Equation 40: First Thrust Coefficient

$$C_{Tc1} = T_{\text{max climb}1}$$

Equation 41: Second and Third Thrust Coefficient

$$C_{Tc2} = -\frac{h_2 \cdot T_{\text{max climb}1}}{T_{\text{max climb}2} - T_{\text{max climb}1} - h_2^{\,2} \cdot \left(\dfrac{h_2 \cdot \left(T_{\text{max climb}3} - T_{\text{max climb}1}\right) + h_3 \cdot \left(T_{\text{max climb}1} - T_{\text{max climb}2}\right)}{h_3^{\,2} \cdot h_2 - h_2^{\,2} \cdot h_3} \right)}$$

$$C_{Tc3} = \frac{h_2 \cdot \left(T_{\text{max climb}3} - T_{\text{max climb}1}\right) + h_3 \cdot \left(T_{\text{max climb}1} - T_{\text{max climb}2}\right)}{\left(h_3^{\,2} \cdot h_2 - h_2^{\,2} \cdot h_3\right) \cdot T_{\text{max climb}1}}$$

4.3 Overall Proposed Process

Up to this point, the two processes, one for creating the technology response, and the other to create the coefficients that represent and aircraft in the databases for fleet analyses, have been separated. Figure 41 shows the merging of these two processes proposed in this research work.

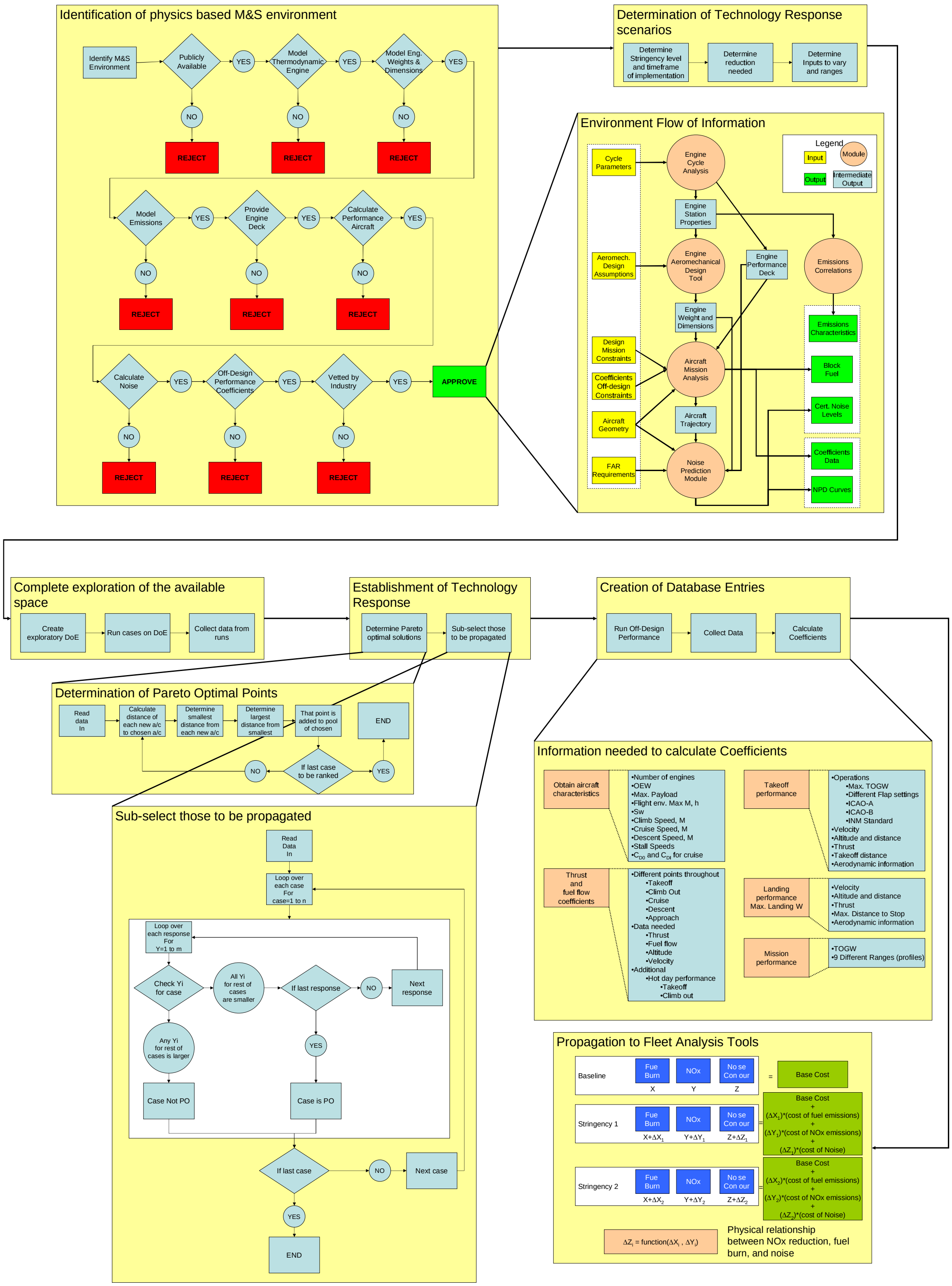

Figure 41: Process for the Quantification of Interdependencies between Environmental Metrics

CHAPTER 5. IMPLEMENTATION

In the previous chapter, the proposed approach was described. This approach has two main areas. The first one is the determination of a series of replacement aircraft to those that do not meet a stringency level, representing the technology response. The second one is the creation of a process for the calculation of the database coefficients that would represent an aircraft/engine combination in the fleet analysis tools utilized to study the mentioned stringency. In this chapter the particular implementation of these two processes is shown. The first step of the process was the identification of the environment to be used. The environment chosen is what is known as the Environmental Design Space (EDS). This environment is part of the APMT, the suite of tools being developed under the FAA, to assist in the CAEP policy making process [Ref. 133]. This tool is being developed by the ASDL at Georgia Tech, and it is the evolution from the work of UEET/VSP programs, previously mentioned. The integrated set of tools has been updated with the latest available versions of the tools, and with the incorporation of all the necessary modifications to meet the characteristics described in the previous chapter. This environment is described in detail in the following section, while moving through the steps of the process to select the environment to be used, as described in the previous chapter. Its validity is proven through the modeling of a real life aircraft, the Boeing 777-200ER with the GE90-94B and the PW4090 engines, and allowing for members of the aerospace industry to evaluate the results. At the same time, the trends that the environment produces, when deviated from the validated point by changing some of the inputs, were also vetted by the same industry group. This process is also useful in determining the linkage between the fundamental aircraft and engine characteristics and the environmental key measures.

In the process to create the technology response, the next step in the process is the determination of the inputs to be used, depending on the scenario to be studied. For this research work two scenarios are used: a re-fan of the engine, and a complete overhaul of the propulsion system. The first one will change the fan, leaving the core as it is in the baseline engine, and the second one will modify the whole engine. The baseline engine was chosen as the model of the GE90-94B, for its newer introduction year, and its higher performance. The reduction that the second scenario would provide will be greater than the first one, in terms of the three environmental measures being studied. After the determination of the inputs, and the creation of the exploratory design of experiments, the results are to be utilized to establish which aircraft are Pareto optimal. Out of those, the ones to be selected as the technology response are chosen.

The other area of this research work that will be shown here is the creation of an entry into the databases used for the fleet analysis tools. Following the creation of the technology response for the baseline vehicle, the results from implementing the process to populate the database are shown for that baseline. In addition, the database entries for the aircraft chosen as the replacement vehicles will be compared to the entries for the baseline case, to prove that the process does in fact propagate the characteristics of the different aircraft. One step further will be taken, and all the aircraft will be run through the fleet analysis tools, to show that this propagation of characteristics is continued. This final step is taken to compare the actual technology response, the constant 2% fuel burn penalty, to the proposed herein, the selection of the replacement aircraft, and how it can affect the policy making process.

5.1 Environment Identification

The development of the environment is not the focus of this research work, but rather finding the appropriate one. It was stated before that any environment that met the criteria described in the approach section would provide the same conclusions as to the validity of using the process delineated in this research work. Based on this, the environment used will be explained in detail, to show that it meets the requirements expressed in the previous chapter. At the same time, other environments considered are shown, and the reasons for not choosing them are listed. Table 8 lists the characteristics that the environment needs to have, as explained in the approach section, along with the environments considered, and the matches they have in those areas. The following sections describe the chosen environment, EDS, and how it satisfies the requirements shown.

Table 8: Comparison of Possible M&S Environments

Characteristic	EDS UEET/VSP Evolution	Antoine s Environment	Cambridge AIM	Virginia Tech M&S Environment	Company Specific Tools
Publicly Available	YES	YES	YES	YES	NO
Model engine thermodynamics	YES	YES	NO	YES	YES
Model engine weights and dimensions	YES	NO	NO	YES	YES
Model emissions	YES	NO	NO	NO	YES
Model aircraft performance	YES	YES	NO	YES	YES

Characteristic	EDS UEET/VSP Evolution	Antoine s Environment	Cambridge AIM	Virginia Tech M&S Environment	Company Specific Tools
Model noise	YES	YES	NO	YES	YES
Can be modified to calculate BADA and SAE AIR 1845 coefficients	YES	NO	NO	NO	YES
Calculates NPD Curves	YES	NO	NO	NO	YES
Vetted by Industry	YES	NO	NO	NO	YES

5.1.1 Publicly Available

The first characteristic listed in this table is being publicly available. This was a requirement for the environment due to the fact that it is going to be used for policy making purposes, and it should be open to anybody that would be affected by those policies. The only environments in this list that do not meet this characteristic are the company specific tools, which are proprietary of each particular company. As it was stated before, the chosen environment, EDS, is composed of NASA tools, including CMPGEN, NPSS, WATE, FLOPS, and ANOPP. All these tools are publicly available, and can be purchased for use from the specific NASA Research Centers.

5.1.1.1 CMPGEN Module

CMPGEN is a NASA Glenn analysis tool used to generate component maps for the fan, LPC, and HPC [Ref. 144]. The user-defined inputs for each component include the design point pressure ratio, the corrected flow, corrected flow per area, and stall margin. The program uses these design point values along with built-in empirical relationships to calculate off-design data for corrected flow, efficiency, and pressure ratio as a function of corrected speed and pressure ratio. The ranges of corrected speed and pressure ratio for use in component map generation are also specified by the user.

5.1.1.2 NPSS Module

The Numerical Propulsion System Simulation (NPSS) is an aerothermal-mechanical computer simulation that is capable of modeling physical interactions within an engine model. NPSS is under continuing development by NASA Glenn Research Center and is supported by the U.S. aero-propulsion industry and the Department of Defense in hopes of lowering concept-to-production development time and reducing the need for full-scale tests or more sophisticated analysis tools [Refs. 145, 146]. Version 1.6.4v is currently integrated into the environment.

NPSS is an object oriented simulator which performs steady state and transient off-design performance prediction by calling upon a number of varying fidelity tools which are controlled using the NPSS solution algorithm. At this time, NPSS offers the following capabilities:

- Complete model definition through input files
- NIST (National Institute of Standards and Technology) compliant thermodynamic gas-properties package
- Analytical solver with auto-setup, constraints, and discontinuity handling
- Steady-state and transient system simulation
- Flexible report generation

- Built-in object-oriented programming language for user-definable components and functions
- Support for distributed running of external codes
- Support for test data matching analysis

5.1.1.3 WATE Module

Weight Analysis of Turbine Engines (WATE) was developed by the Boeing Military Airplane Development group as a subprogram for the NASA Engine Performance Program (NEPP) in 1979. The main focus of this program was to provide weight and dimension estimates for propulsion systems for use in conceptual design. The environment currently utilizes an updated version, WATE++, which has been moved to the same language as NPSS. WATE estimates the weight and dimensions of both large and small gas turbine engines. Approximations made within WATE are based on historical correlations, material properties, geometric characteristics, and component parameter information. Sizes and weights for the inlet, fan, compressor, turbine, burner, mixers, nozzles, ducts, splitters, and valves are calculated.

5.1.1.4 FLOPS Module

The FLight OPtimization System (FLOPS) is a multidisciplinary computer program developed for conceptual and preliminary design and evaluation of advanced aircraft concepts [Ref. 147]. The environment currently runs FLOPS version 6.1.2, which consists of eight modules:

- Weights, aerodynamics

- Engine cycle analysis – Not utilized for the environment
- Propulsion data scaling and interpolation
- Mission performance
- Takeoff and landing
- Noise – Not utilized for the environment
- Cost analysis – Not utilized for the environment
- Program control

Through the program control module, FLOPS may be used to analyze a point design, parametrically vary certain design variables, or optimize a configuration. The weights and aerodynamics modules use statistical and empirical methods to estimate respective metrics, i.e. component weights and aerodynamic performance. The engine cycle analysis module is based on a modified version of NEPCOMP (Navy Engine Performance Computer Program) designated QNEP (Quick Navy Engine Performance Program). This module is capable of internally generating an engine deck (thrust, fuel flow, etc.) at various Mach-altitude combinations. Following the engine deck module, the propulsion module sizes the engine by making use of scaling laws. The mission performance module takes the information calculated in the previous modules and determines the performance characteristics of the aircraft. The takeoff and landing module calculates the requirements necessary to meet the performance demands at takeoff and landing and with the available data calculated attempts to ensure that the aircraft meets all FAR 25 requirements. The noise footprint module based on the FOOTPR program generates takeoff and climbout profiles for the aircraft and computes the noise footprint contour data and/or noise levels at user specified or FAA locations. From the cost analysis module, the airframe Research, Development, Testing and Evaluation (RDT&E) and production cost, engine RDT&E and production costs, and direct and indirect operating costs are estimated to provide a life cycle cost for subsonic transport aircraft. Most of the input data required for these modules is contained in a Namelist formatted input file. Many values have default settings to provide reference values for new users. FLOPS also has the capability of using data from external tools, specifically engine performance decks. In lieu of the internal engine deck generation capabilities, the environment generates the performance deck within NPSS and the propulsion weight and dimensions in WATE and passes the data to FLOPS.

5.1.1.5 ANOPP Module

The Aircraft NOise Prediction Program (ANOPP) was developed by the NASA Langley Research Center and uses a database of empirical data to approximate the noise emissions of a given aircraft [Ref. 71]. This database comes with the program, but can be edited by the user if desired. The program contains over 25 modules. Each one performs a specific part of the prediction, generally divided by the component in the engine or the aircraft that produces the noise. Not all the components exist in all the vehicles, so not all the modules are used here. There are four functional levels of the code, each with a specific purpose and level of fidelity. Level I provides noise predictions as a function of observer location, Level II adds time dependency to Level I, Level III adds frequency effects, and Level IV gives more detail in the spectral data. Therefore, Level IV will be the one used in this research work since it provides the most data for each specific vehicle.

5.1.2 Model Engine Thermodynamics and Weights and Dimensions

The next two characteristics deal with the ability of the environment to model the engine thermodynamically and also calculate its dimensions and weights. The environment create by the University of Cambridge, AIM, does not provide this data, since it uses as inputs the BADA coefficients, thus not capturing the thermodynamics or weights of the engine. Although the environment created by Antoine for his PhD work models the thermodynamics of the engine, it lacks in the calculation of the dimensions and weights. The way in which EDS models the thermodynamics of the engine is through NPSS, and the weights and dimensions, through WATE. These two modules were described in the previous section, but their overall connectivity is explained here. The fundamental architecture of the environment is based on a multiple point design (MPD) for the engine based on airframe thrust requirements and a design loop is iterated until convergence is reached between the engine capability and airframe requirements. The base logic for the environment revolves around NPSS simultaneously solving four design points. The Aero Design Point (ADP) is considered the component design point, with fan pressure ratio (FPR), low pressure compressor pressure ratio (LPCPR), and high pressure compressor pressure ratio (HPCPR) specified at this point. The bypass ratio (BPR) at the ADP is determined by specifying an Extraction Ratio, which is the ratio of the bypass exhaust pressure to the core exhaust pressure. The ADP combustor exit temperature is set by specifying a maximum temperature and a throttle ratio. The airflow is determined by specifying the thrust required at top of climb (TOC). The resulting airflow at ADP is taken to be 100% corrected flow (W2R). Turbine Cooling Flows are determined at the Takeoff condition (maximum combustor exhaust temperature). Design and Power

Management variables are included in addition to variables provided by Auto Solver Setup for continuity and work balance. Finally, solver variables are added to specify the scaling points for the fan and compressor maps and to determine the turbine cooling flows using the Coolit algorithm. The independent variables used for convergence in the MPD are listed in Table 9. The convergence criteria for the design case is a thrust and fuel balance of the engine and airframe. The convergence architecture is based on the following logic:

- Generate initial component maps
- Perform the MPD based on an initial guess of the four thrust requirements
- Create engine flowpath, with engine dimensions and weights
- Generate the engine performance deck through the flight envelope
- Fly the aircraft through FLOPS to obtain actual thrust requirements at the four points
- Iterate until thrust available equals thrust required

Table 9: List of Varied Independents

Vary…	To Satisfy
ADP BPR	ADP Extraction Ratio (= 1.0)
ADP Airflow	TOC Thrust
ADP FAR	ADP T4
TOC FAR	TOC Airflow
Takeoff FAR	Takeoff T4
SLS T4	SLS T4
Fan Design Pt Rline	Fan Design Pt Surge Margin
LPC Design Pt Rline	LPC Design Pt Surge Margin
HPC Design Pt Rline	HPC Design Pt Surge Margin
HPT Vane Pct Flow	Coolit Calc at Takeoff
HPT Blade Pct Flow	Coolit Calc at Takeoff
LPT Vane Pct Flow	Coolit Calc at Takeoff
LPT Blade Pct Flow	Coolit Calc at Takeoff

5.1.3 Model emissions

The next item in the table is the capacity of the environment to model the emissions of the engine, with the highest degree of similarity to real engines as possible. It was stated in the previous chapter that the industry standard of doing so is the use of the P_3-T_3 method. The only environment that meets this requirement is EDS.

Within the environment, an emissions correlation exists for a given engine type that is based on the P_3-T_3 method for certified engines [Ref. 148]. The P_3-T_3 method provides an approach to predict NOx Emission Indexes (EINOx) at altitude using a method for correcting ground level measurements. The EINOx measurements, taken during current ICAO Annex 16 certification engine testing, and contained within the ICAO Emissions Databank, are corrected to the altitude condition, based on combustor operating environment at both ground level and altitude. The NEPAIR method builds on the process defined by ICAO in Annex 16's Landing and Takeoff analysis as depicted in Figure 42 and as described by Normal, et. al [Refs. 26, 148]. The emissions calculations require that the engine performance deck be based on standard day conditions with no customer bleed or horsepower extraction. As a result, the fuel flow and emission indices for nitrous oxides (NOx) are determined for the takeoff, climb-out, approach, and idle conditions which are consistent with the ICAO definitions. In addition, the pressure ratios and maximum thrust values are defined as inputs to the environment, the emissions certification level is calculated per CAEP/6 limits. In addition, the engine performance deck supplied to FLOPS contains the emissions emitted for each Mach, altitude, and throttle setting. While FLOPS is flying the mission, the emissions are also calculated based on the thrust required, Mach-altitude combinations, and the fuel flow.

Subsequently, the NOx emitted is determined and extracted from the output file over the entire design mission.

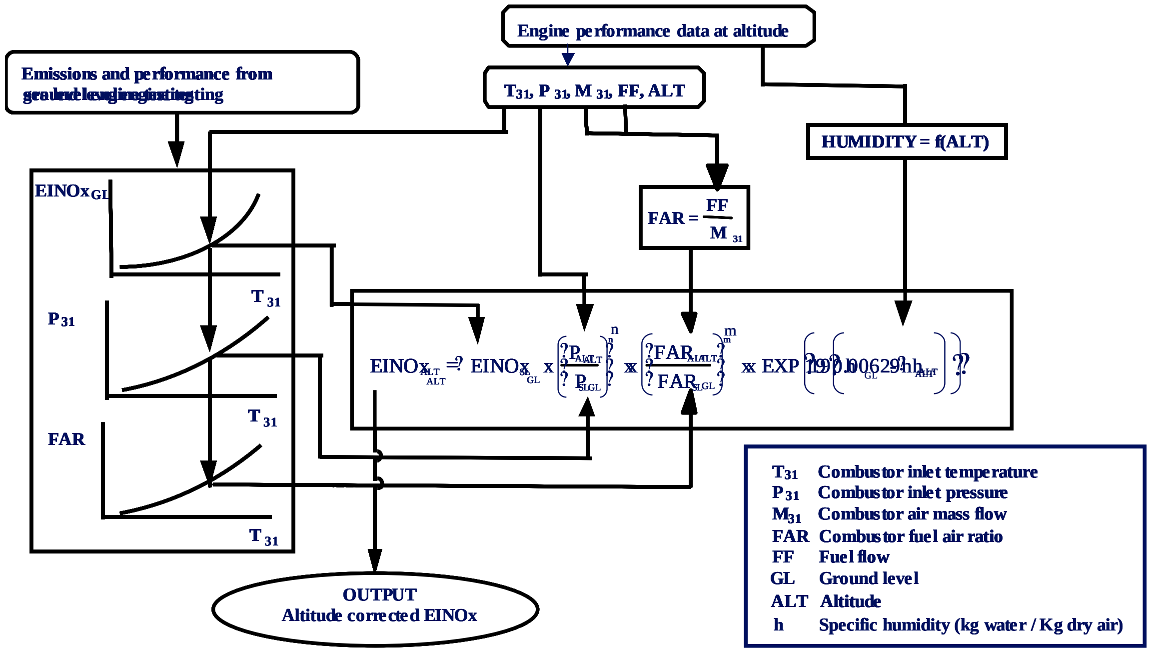

Figure 42: ICAO Annex 16 Volume II NOx Emissions Correction Scheme [Refs. 26, 148]

5.1.4 Model aircraft performance

Similar to modeling the engine, the environment has to also be able to model the aircraft's performance, based on its physical characteristics. As mentioned before, the AIM does not capture this physics, since it uses the BADA coefficients to model the aircraft, and the PREDATER environment does not account for the aircraft either.

For a given number of passengers, aircraft geometry, and a design range, the vehicle is flown within FLOPS to determine the aircraft weights and mission fuel usage. As a result of flying the mission, the fuel used is a direct result. The primary assumptions associated with the maximum takeoff weight and fuel usage include:

- 210 pounds per passenger, including baggage

- Westbound step cruise, with 4,000 ft increments for current technology aircraft
- No extra cargo, other than passengers and their baggage
- Top of climb excess rate of climb must be 300 feet per minute or greater
- 5% fuel reserves
- 200 nm alternate airport allowances

5.1.5 Model Noise and NPD Curves

The environment to be used must be able to determine what the certification noise levels are, as determined by the FAA. The process to do so is delineated in the Code of Federal Regulations Title 14, Part 36 [Ref. 24], and the only environment capable of following it is EDS, through the integration of the different tools. At the same time, the environment needs to also provide the set of NPD curves that are unique to a aircraft/engine combination, for its use in the fleet analysis tools. EDS is also capable of producing these curves, thanks to the latest model of ANOPP. To determine the certification noise levels, NPSS is executed at the proper ambient conditions per Federal Aviation Regulations (FAR), specifically at +18°F from standard day below 15,000 ft altitude. The engine performance deck is regenerated and the aircraft is flown in FLOPS for the FAR trajectories. The trajectories are then passed to ANOPP to determine the noise levels for the given vehicle. ANOPP also needs the engine performance at different combinations of Mach number and altitude for different power settings, but requires a different format than FLOPS. An engine state table is produced for each engine component, which ANOPP uses to calculate the noise produced for that component. The state tables include the mass flow, the fuel to air ratio, temperature, pressure, area, and rotational speed at the inlet and exit of all the components. ANOPP also uses engine geometry, requiring parameters like the tip and hub diameter of the fan, the fan tip relative Mach number, fan-rotor spacing, number of fan blades and stator vanes, combustor entrance area, number of blades of the last turbine stage, nozzle plug diameter, and the diameters of the nozzles, which are outputs from WATE. In addition, the geometry of the aircraft, specifically the fuselage dimensions, wing area and span, and flap area and span, are also required as inputs to ANOPP. The trajectory of the aircraft is composed of the distance, the altitude, the Mach number, the power setting, the angle of attack, and flap and landing gear settings, and is also necessary for calculating noise propagation. Given this data, ANOPP will calculate the noise certification levels for each of the three observers. These levels are calculated using the geometric and cycle information of the engine from NPSS and the trajectory provided by FLOPS, which ANOPP uses to define where to start the propagation of the noise produced. ANOPP then calculates the noise perceived at the three certification observers, following FAR part 36 requirements. ANOPP calculates the effective perceived noise levels for each individual component as well as the overall aircraft noise level. The NPD curves, on the other hand, are calculated only for the whole aircraft, not individual components. Instead of using a trajectory, ANOPP calculates the noise levels at different distances from the aircraft and at different thrust settings, for both approach and landing configurations.

5.1.6 Modified to Calculate BADA and SAE AIR 1845 Coefficients

This item deals with the propagation of the tradeoffs between the key measures to the fleet analysis tools, which has two parts. The first part was explained in the previous section, with the calculation of the NPD curves. The second part is more elaborate and it includes all the coefficients that define an aircraft/engine combination in the databases used for the fleet analysis tools. The environment must have the ability to be modified to calculate these coefficients from fundamental performance data. A process was developed in this research work that calculates the data needed to populate the databases that those tools use as inputs. In order to do this, a series of specific performance tables needed to be created by the environment. This data was explained in the previous chapter. Out of the environments listed, the only one with the known ability to do so is EDS.

5.1.7 Vetted by Industry

Another key requirement was the validation of the environment by industry experts, so that they feel confident that the results obtained, and the policy made with those results follows the same trends as their internal tools. In order for the results of the modeling and simulation experiments to be performed to be of any validity, the environment has to show the ability of reproducing real aircraft and engine combinations. In addition to these single points, the trends that the key measures have with respect to the input variables have to be realistic and follow physical relationships. These trends have to be vetted by industry experts who have the experience and background to determine the accuracy of the results. A previous validation was made in the assumptions made in the calculation of the different parameters, like using the MPD method for the overall definition of the engine thermodynamic cycle, the use of the P_3-T_3 method for emissions calculations, the different assumptions made about the design mission of the aircraft, and the following of the FAR rules regarding noise certification levels calculation.

The validation of the overall environment is made on the results from single aircraft/engine combinations and from the trends of the environment, once deviated from that single point. One main aircraft type is reproduced for this research work: a 300 passenger long range aircraft. Within this class, there is a specific aircraft that is used for the validation of the environment: the Boeing 777-200ER both with the General Electric GE90-94B engine and the Pratt & Whitney PW4090 engine. Extensive research was performed to obtain as much public domain, non-proprietary information, about the two systems so that they could be represented by the environment. The areas that the environment had to be able to match are:

- Certification noise levels, from the ICAO databases
- Certification NOx levels, both for the 4 thrust settings determined by ICAO and also the LTO NOx level
- Fuel burn in terms of fuel flow for the 4 thrust settings determined by ICAO
- Fuel burn in terms of overall mission fuel for a series of ranges and payloads

All these values had to be obtained while keeping the known geometric characteristics of the aircraft and the engine, as well as the engine cycle parameters that were available. The trends that were created to be validated by industry experts were the certification noise levels versus the fan diameter, and the percentage of NOx emissions above CAEP/6 versus the increase in fuel burn. Both of these plots are to be done for an exploration based on fan and overall pressure ratios.

One of the most important aids in the creation of this aircraft model is the Boeing Airport Planning Document [Ref. 149]. From it, basic weights and dimensions are obtained to be input into the environment, as well as mission information, which is used to calibrate the model in terms of cruise drag characteristics. The main characteristics of the aircraft are shown in Table 10. These parameters are used as inputs to FLOPS, the program of the environment that sizes the aircraft for a design mission.

Table 10: B777-200ER Main Characteristics

Wing Area	ft^2	4,605
Wing Span	Ft	199.92
Wing Aspect Ratio	----	8.679
Max. Operating Takeoff Gross Weight	Lbs	656,000
Operational Empty Weight	Lbs	304,500
Fuselage Length	Ft	206.4
Fuselage Width	Ft	20.7
Max. Payload	Lbs	125,500
Max. Landing Weight	Lbs	470,000

The design mission has a range of 8,048 nmi for a typical load, in this case, 30 first class and 271 tourist passengers, which corresponds to a payload of 63,210 lbs, assuming a weight of 180 lbs per passenger plus 30 lbs of baggage.

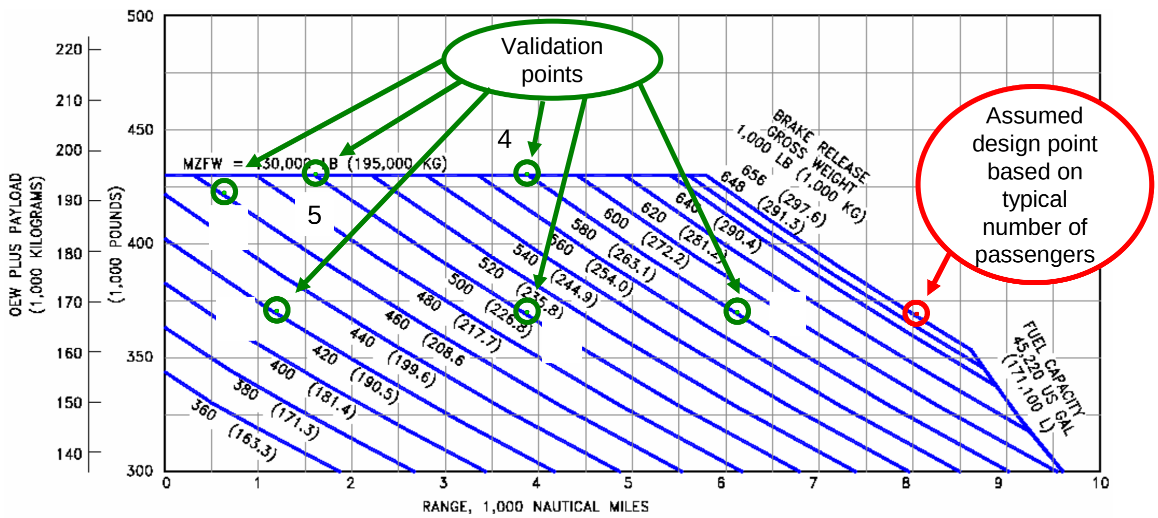

Figure 43: Payload Range Chart for B777-200ER [Ref. 149]

This mission is performed utilizing 4000 ft step change increments for a westbound flight. The reserves utilized are those needed to reach an alternate airport 200 nmi away from the primary one, hold for 30 minutes, and then 5% additional fuel. This mission can be seen in Figure 43, along with the other ranges that are used to calibrate the cruise drag characteristics. The ranges utilized, along with the payloads and takeoff gross weights required, are shown in Table 11. Also seen there are the TOGW that the environment calculates for those missions. The differences between the obtained values and the required values are always less than 1%.

Table 11: Calibration Missions for B777-200ER

Mission	Range	Payload	Required TOGW	Environment TOGW	Difference
Design	8,048	63,210	656,000	655,995.6	0.00 %
1	6,178.1	63,210	580,000	581,438.1	0.25 %
2	3,914.6	63,210	500,000	501,818.3	0.36 %
3	1,255.7	63,210	420,000	421,272.2	0.30 %
4	3,883.1	125,500	580,000	580,402.2	0.07 %
5	1,600.6	125,500	500,000	500,887.3	0.18 %
6	674.5	115,500	460,000	460,726.6	0.16 %

These results are obtained utilizing the variables shown in Appendix C. These numbers define the engines utilized in the environment uniquely. Two different engines were used in the validation process, in order to insure that the space being investigated is properly captured. These two engines are the General Electric GE90-9$B and hte Pratt and Whitney PW4090. Both of these engines are mounted in the same airframe, that of a representation of a B777-200ER, with the dimensions and parameters shown above. In addition to the fuel used for different missions, there are a number of parameters that are used to calibrate the models. These parameters are the Certification noise levels, from the

ICAO databases, the certification NOx levels, both for the 4 thrust settings determined by ICAO and also the LTO NOx level; and the fuel burn in terms of fuel flow for the 4 thrust settings determined by ICAO. These values are obtained by the environment for both engines, and the results are listed in Table 12.

Table 12: Calibration Results for GE90-94B and PW4090

Engine	Parameter	Units	Objective	Environment	Difference
GE90-94B	Cutback Noise Level	EPNdB	91.1	92.6	1.62%
	Sideline Noise Level	EPNdB	96.4	95.4	-1.06%
	Approach Noise Level	EPNdB	98.3	97.4	-0.91%
	LTO NOx	gr/kN	70.76	70.1276	-0.89%
	Takeoff Thrust NOx (100 %)	gr/kg	56.41	56.696	0.51%
	Climb Out Thrust NOx (85%)	gr/kg	41.74	41.539	-0.48%
	Approach Thrust NOx (30%)	gr/kg	17.38	17.151	-1.32%
	Idle Thrust NOx (7%)	gr/kg	6.09	6.211	1.99%
	Takeoff Thrust Fuel Flow (100 %)	kg/sec	3.514	3.489	-0.68%
	Climb Out Thrust Fuel Flow (85%)	kg/sec	2.848	2.85	0.08%
	Approach Thrust Fuel Flow (30%)	kg/sec	0.908	0.913	0.54%
	Idle Thrust Fuel Flow (7%)	kg/sec	0.296	0.274	-7.43%
PW4090	Cutback Noise Level	EPNdB	93.9	94.7	0.88%
	Sideline Noise Level	EPNdB	98.2	99.3	1.12%
	Approach Noise Level	EPNdB	99.2	99.1	-0.10%
	LTO NOx	gr/kN	80.08	77.776	-2.88%
	Takeoff Thrust NOx (100 %)	gr/kg	61	61.084	0.14%
	Climb Out Thrust NOx (85%)	gr/kg	42.8	43.558	1.77%
	Approach Thrust NOx (30%)	gr/kg	13.19	13.58	2.96%
	Idle Thrust NOx (7%)	gr/kg	4.29	4.197	-2.17%
	Takeoff Thrust Fuel Flow (100 %)	kg/sec	3.898	3.562	-8.61%
	Climb Out Thrust Fuel Flow (85%)	kg/sec	2.977	2.913	-2.13%
	Approach Thrust Fuel Flow (30%)	kg/sec	0.957	0.957	-0.01%
	Idle Thrust Fuel Flow (7%)	kg/sec	0.268	0.261	-2.47%

As mentioned before, the environment must be validated for the results obtained with it to be of any use. This validation is done in two parts, the first of which was shown in the previous section. The second part of the validation is the assurance that the trends provided by the environment are acceptable with respect to industry standards. The trends to be validated are the certification noise levels versus the fan diameter of the engine and a carpet plot of the NOx level versus the fuel burn. Both these plots are to be made based on an exploration of the fan and overall pressure ratio of the engine. For the particular example of the 300 passenger model described in previous section, the ranges for the fan pressure ratio are 1.6 to 1.8, and for the overall pressure ratio from 26 to 52. This overall pressure ratio is obtained by varying the high pressure compressor pressure ratio, from 13 to 23, and leaving the low pressure compressor unchanged. These ranges along with a variation of 0.5 in the FPR and 2 in the HCPPR provide 24 points to be run.

Using the environment all the points are run, and the results recorded. Figure 44 shows the first of the plots to be validated. It depicts the certification noise levels versus the fan diameter. The fan diameter is a direct function of the fan pressure ratio, since the overall pressure ratio has little effect on it. The trends shown in the plot represent linear approximations for the data calculated in the environment. For the approach noise level, the trends show a reduction of 0.19 dB per inch of increase in diameter. For the sideline noise level, the slope almost doubles to over 0.36 dB per inch, and for the cutback noise level, the slope is 0.25 dB per inch. These trends were validated by members of industry, who cannot provide confirmation data, due to its proprietary nature.

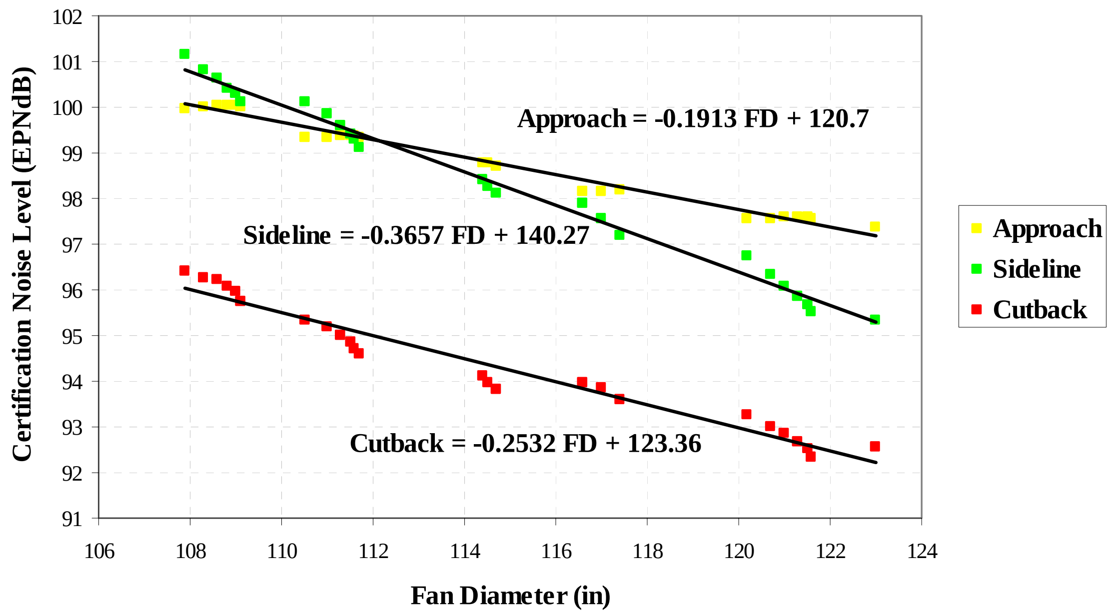

Figure 44: Certification Noise Levels vs. Fan Diameter

In terms of the carpet plot depicting the NOx levels and the fuel used, the results obtained are shown in Figure 45. As mentioned before the OPR varies from 26 to 52, and each lined grouping represents an increase of two points in the pressure ratio. The fan pressure varies from 1.6 to 1.8, at intervals of 0.5 points. It is clear that FPR has a negative slope with respect with both the metrics, the lower it is, the better the results are in both areas. For the OPR, the interaction is more complicated: increasing it reduces the fuel burn, but it increases the NOx levels. At the lower OPRs the effect on NOx is not as noticeable as at the higher end, and the opposite is true for the fuel burn. The trends shown here were also validated by members of the aerospace industry.

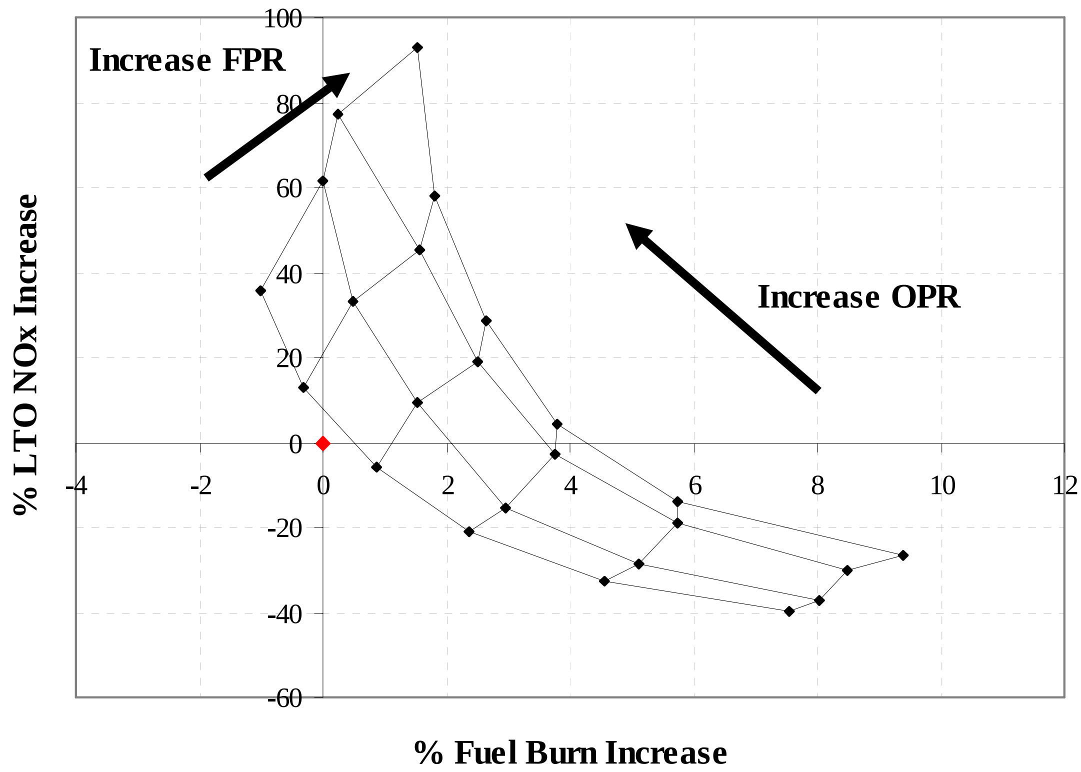

Figure 45: NOx Above CAEP/6 vs. % Fuel Burn Increase

5.2 Determination of Scenarios

After obtaining the environment in which to model the physical characteristics of the aircraft, the following step in the determination of the replacement aircraft is the definition of the scenarios to be used. As stated before there are two scenarios that will be used, a re-fan and a complete overhaul of the engine. Both scenarios are the possible response to a stringency level reduction, being a re-fan the answer to a smaller reduction, while the whole engine overhaul can be thought of as the answer for a larger reduction needed. Compared to the current process, the first scenario can be equated to a TL2 or 3, while the second is closer to a TL5 response. For this research work, it was assumed that the stringency taking place is in the NOx emissions, and the effects to be observed are the noise and the fuel burn characteristics. For the first scenario, only the fan is changed, leaving the core exactly as it is in the baseline engine. This could be thought of as if the required reduction in NOx was small, and the amount of time to implement it was also short. The second scenario contemplates a complete new design of the whole engine. In this case the reduction on NOx is more significant, and there exists more time to develop the new engine.

For the first scenario, only two variables are to be used, the fan pressure ratio and the extraction ratio. The reason for choosing these two variables for this scenario was given by the members of the aerospace industry that validated the environment, as the main aspects that would change if an engine were to be equipped with a new fan. This leaves the core of the engine unchanged, and it only modifies the characteristics of the fan. The units and ranges of these two variables are shown in Table 13. The second scenario requires more parameters to be varied. According to the same industry experts that validated the environment and its trends, there are seven main inputs that should be varied to represent a new engine design, keeping the technology level constant. These seven variables are shown in Table 13, along with the units of each one, as well as the ranges used. The rest of the variables were set to the values of the GE90 representation, shown in Appendix C, which is also considered as the baseline case.

These variables are used to explore the space to determine the limits in terms of fuel burn for a mission of 6,000 nautical miles, the Landing-Takeoff (LTO) cycle NOx emissions, and the cumulative certification noise level. For all the cases, the vehicle itself remains fixed, being that of a model of a Boeing 777-200ER.

Table 13: 300 Passenger Example Design Variables

Variable	Units	Minimum	Maximum
Extraction ratio at Aero Design Point (Bypass Pt/Core Pt)	--	1.0	1.1
FPR at Aero Design Point	--	1.55	1.75
HPCPR at Aero Design Point	--	9	22
LPCPR at Aero Design Point	--	1.2	2.5
Top of Climb thrust target	lbs	18000	22000
Mass flow ratio of Top of climb to Aero Design Point	--	1.02	1.08
Takeoff thrust	lbs	78000	82000

The linkage between these inputs and the environmental metrics being tracked can be seen on Figure 46. This figure represents the effect that changing each of the input variables would have on the environmental metrics. All the settings for the inputs are for the baseline case, and the slopes represent the variation due to each input individually, leaving the rest at the same level. If one of the inputs were to change its value, the slopes of the responses with respect to the other inputs would also change to adjust to the new position in the space defined by the inputs.

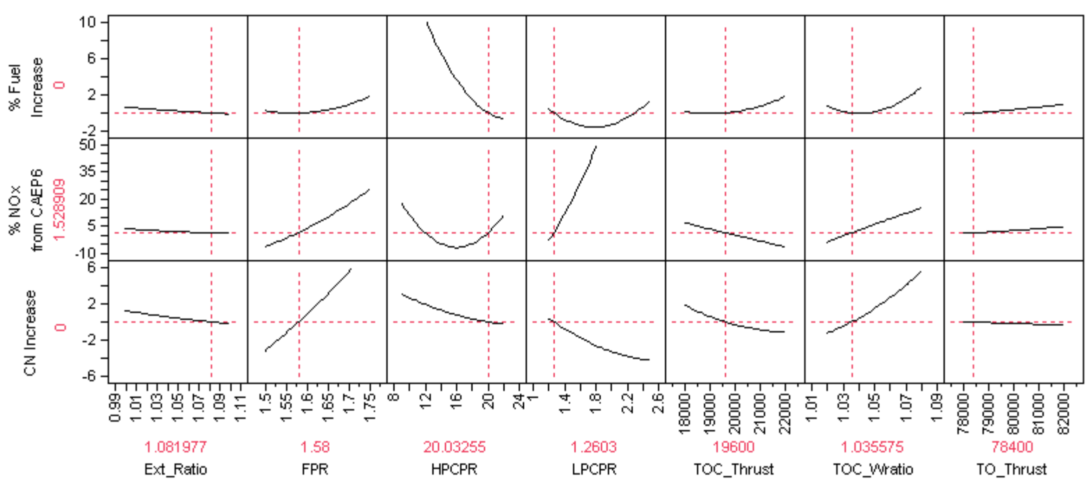

Figure 46: Linkage of Physical Parameters to Environmental Metrics

Out of this plot, it can be inferred that the baseline case is at the forefront of the capabilities. It would be possible to reduce the fuel burn, NOx, or noise individually, but there would be a negative effect on the other metrics. For example, the fuel burn can be reduced by 1.5% with an increase of the LPCPR to around 1.8. But this increase would also increase the NOx level to almost 50% over CAEP/6 levels. The NOx could be reduced to over 6.5% below CAEP/6, by reducing the HPCPR to 15, but the fuel burn would increase almost 4% and the noise by 1 dB. There is clearly a very delicate equilibrium to be achieved when modifying these inputs, in order to optimize all the metrics at the same time.

5.3 Exploration of the Available Space

For the first scenario, since there are only two variables, the space exploration is performed using a ten level full factorial sampling. This leads to 100 cases to run, with variation in the FPR of 0.022 points, and 0.011 points in the extraction ratio. The full factorial ensures that the whole space defined by the input variables is covered, and the discretization of the variables in 10 levels allows for a fine enough coverage of the space, but without sacrificing on the time it takes to run all the cases. For the second scenario a similar approach with a 10 level full factorial sampling would mean 10^7 cases to run, which would be impossible, due to limited computational resources and limited time available. Instead, a sampling of the space consisting of 5,000 cases is created using two sets of cases. The first set uses a 3 level full factorial design, which consists of 2,186 cases. The second set of points consists of randomly selected points from within the ranges of the input variables, creating a widespread exploration of all the variables. The first set of cases allows for the exploration of the edges of the space, while the second set explores the interior of the space. For all of the cases the fuel burn, NOx, and noise level are calculated and recorded.

5.4 Determination of the Technology Response

For the first scenario the results are shown in Figure 47, Figure 48, and Figure 49. This figure represents the noise, NOx, and fuel burn characteristics of the 100 deviations from the baseline. It is clearly seen that based on the two variables used, the NOx and the noise are highly correlated. This means that reducing one automatically reduces the other. This is not the case with the fuel burn, where it can be seen that there are tradeoffs to be made between them.The obvious clumping of points shown in the plots represents the different levels in the fan pressure ratio. The clumping of points in the center noise versus fuel burn plot represent the change in the number of stages of the low pressure turbine, due to the loading reaching the limits of the materials used in the blades. The number of stages is seven in the bottom group, and it goes down to four in the top two points shown. The Pareto points in this set of data are only two of the points, shown in the graph in green. The baseline aircraft is shown in red. The limits of achievability are determined by the Pareto points. The first Pareto point in the set, the one closer to the baseline, does not reach to meet CAEP/6 NOx levels, so it is futile to move forward with it. The point that reduces NOx the most represents a change in the fan to the lowest fan pressure ratio and the highest extraction ratio. This leads to a lower NOx, meeting CAEP/6 levels by over 1%, and reducing the noise from the baseline over 1 EPNdB. The cost of achieving this is an increase in fuel burn of almost one half of a percent. This aircraft will be used in subsequent comparisons to the results obtained applying the second scenario rules.

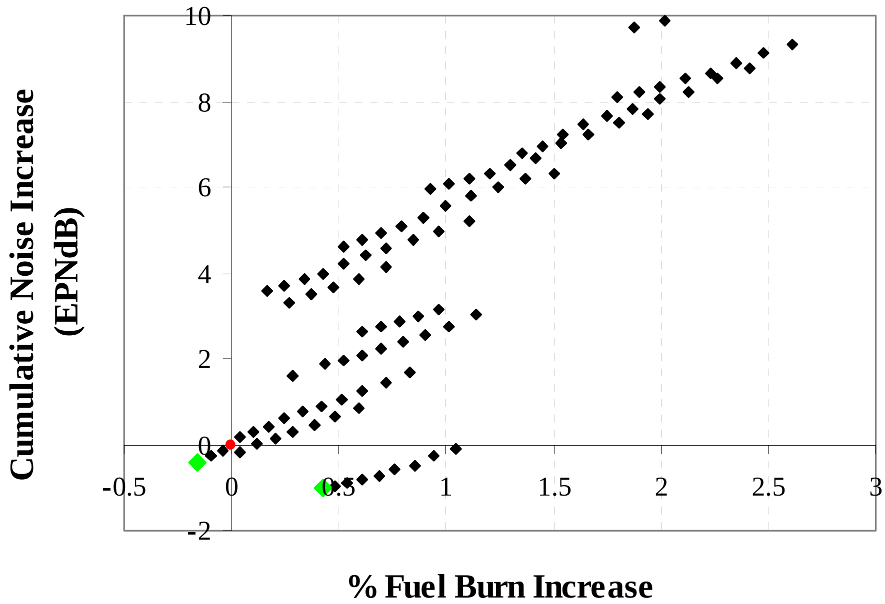

Figure 47: Scenario 1 Results, CNM vs. FB

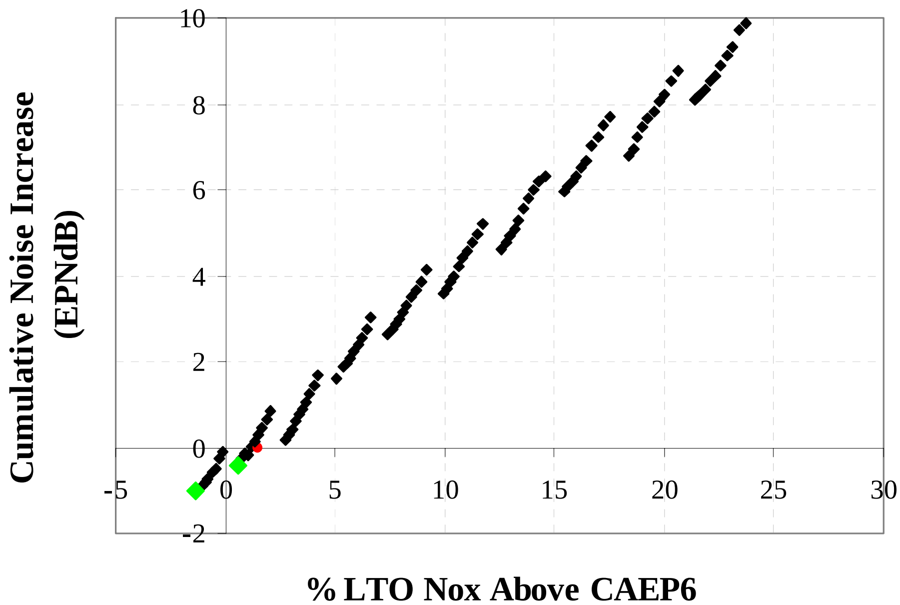

Figure 48: Scenario 1 Results, CNM vs. NOx

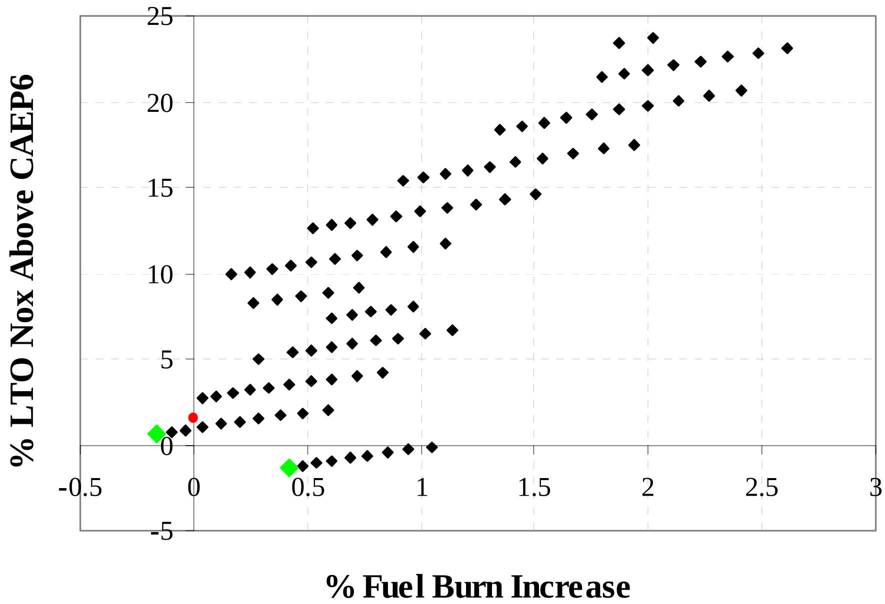

Figure 49: Scenario 1 Results, NOx vs. FB

The second scenario results are shown in Figure 50, Figure 51, and Figure 52. These plots represent the fuel burn increase from a baseline case, the NOx emissions with respect to CAEP/6 levels, and the cumulative noise margin increase, also from the baseline case, for each of the points studied. As in the previous scenario, the green points are the Pareto and the red is the baseline. The points that did not meet CAEP/6 NOx levels were removed from the graph, as they cannot be used for stringency analysis. Similarly to what was shown in the results of scenario 1, in order to reduce the NOx from the baseline level, a penalty has to be taken in the either noise or fuel burn, or on both of them. If the results obtained in the two scenarios were to be compared, it can easily be appreciated how the reduction in NOx, noise, or fuel is much bigger in the second scenario than the first. This is due to fact that there were more variable inputs to explore the space. The number of Pareto points in this second scenario that meet CAEP/6 NOx limits is 55.

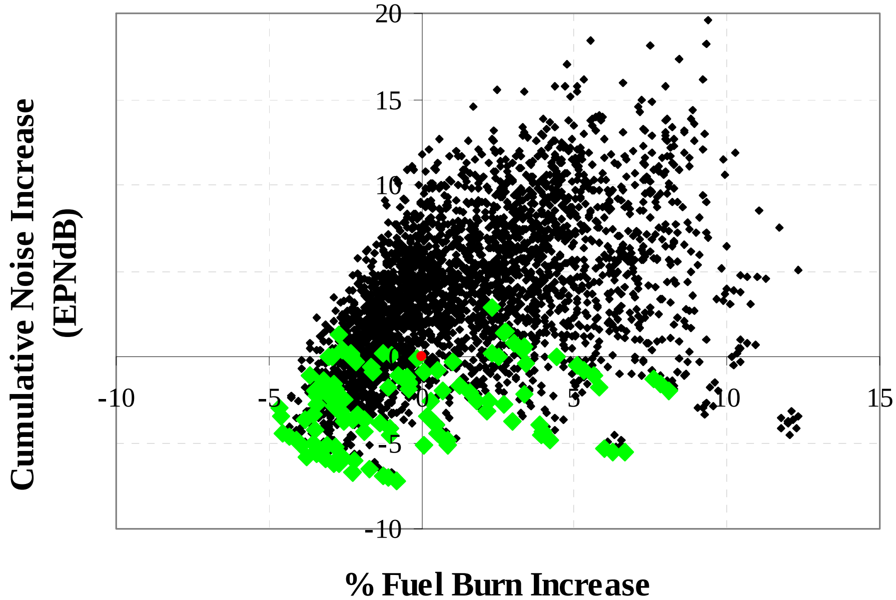

Figure 50: Scenario 2 Results, CNM vs. FB

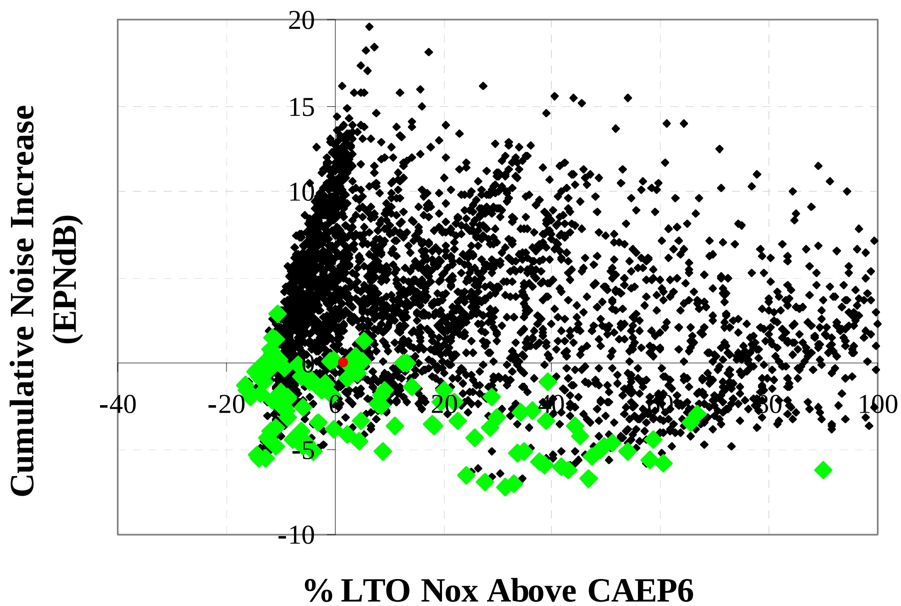

Figure 51: Scenario 2 Results, CNM vs. NOx

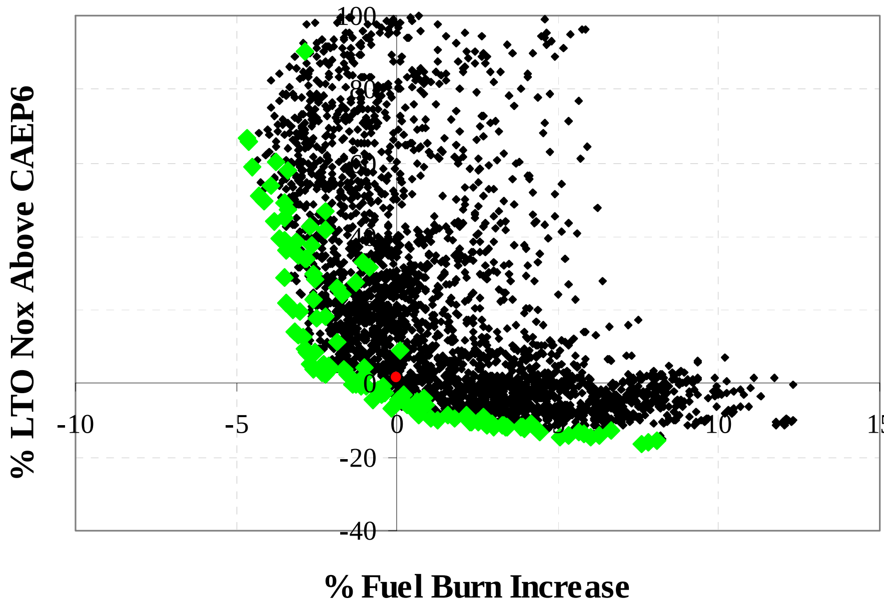

Figure 52: Scenario 2 Results, NOx vs. FB

It was mentioned before in this document that the fleet analysis tools utilized for stringency scenarios are not unlimited in their computational resources, so they cannot use all the aircraft in the Pareto front for those analyses. The true representation of the limits of physical achievability is shown with all the points, but a subset can be used to represent it, without loosing the main tradeoffs between the environmental measures. Another way to represent these tradeoffs is by creating an equation that would link the three key measures. The work by Goel et al. shed a new light in this area [Ref. 150]. They used the Pareto efficient points and regressed one of the objectives as a function of the other objectives. This allowed for the exploration of the design space and the understanding of the complex trade-offs that exist. One way to do this is by fitting an equation on NOx, as a function of noise and fuel burn. This is shown in Figure 53.

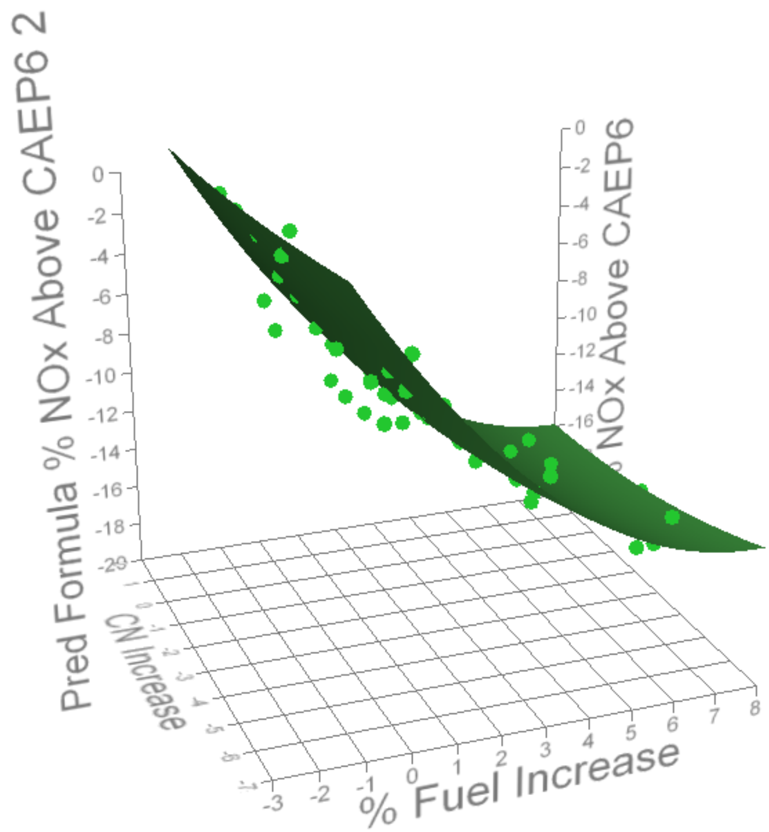

Figure 53: Regression Equation for NOx as a Function of Noise and Fuel Burn

The fit of this equation is not perfect, but it represents a first approximation of the shape and the tradeoffs between NOx, noise and fuel burn. One can assume that this equation has a quadratic form, but this is by far not the only option. Any type of mathematical formulation can be used to do this linkage. The quadratic form was chosen here for its simplicity, and the versatility that it possesses. Figure 54 shows the contour plot of this quadratic equation for the NOx level above CAEP/6 that could be achieved, and the consequent noise and fuel burn increases.

This plot shows that the relationship between NOx and noise is not as important as the one of NOx with fuel burn. Also, as the reduction in NOx gets larger, the penalty in fuel burn is also steeper. This means that for a reduction from 0% to 2 % below CAEP/6 levels the fuel burn penalty is roughly 0.5%, but from 10% to 12%, the penalty is closer to 2% in fuel burn, and the effect on noise is also noticeable.

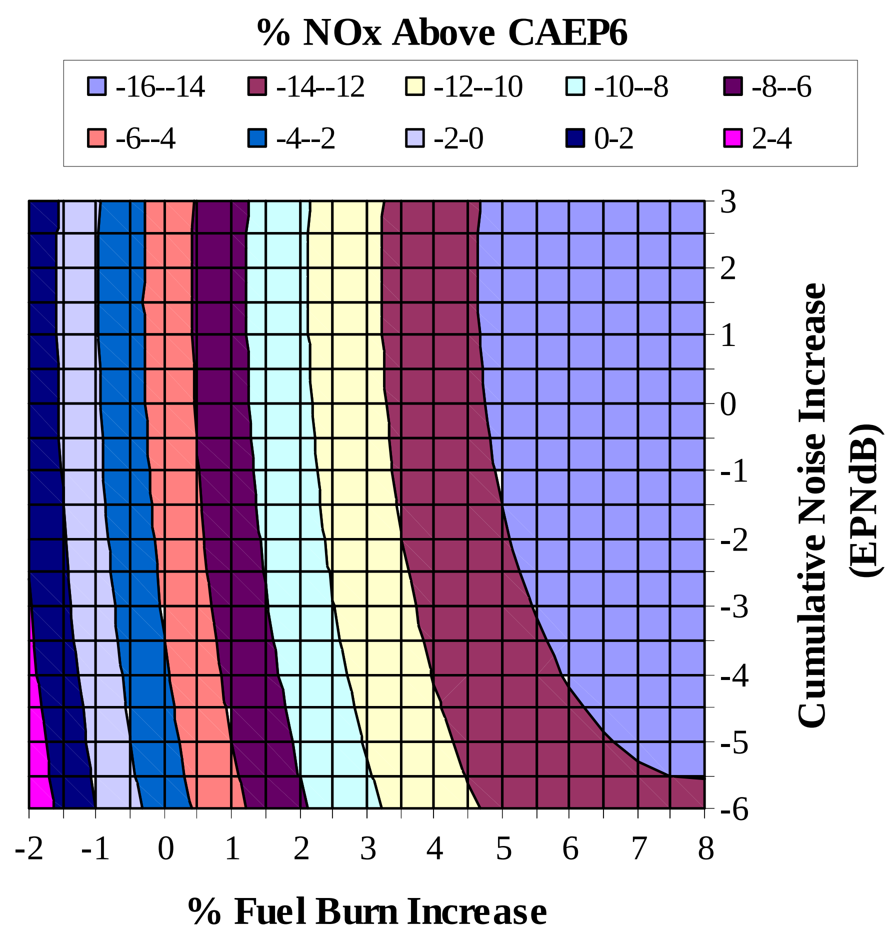

Figure 54: Contour Plot of NOx vs. Noise and Fuel Burn Increase

If the actual CAEP process is recalled, a 2% fuel burn penalty is applied to those aircraft that do not meet a required NOx stringency. This would mean, in the example presented above, the baseline vehicle would be substituted in the databases by a replacement aircraft which would have the exact same performance characteristics, but burning 2% more fuel than the original. The NOx levels of this replacement aircraft would be low enough to meet the stringency, but there is no change in the rest of the parameters, such as noise, or performance. This approach is rather magical, since the replacement aircraft looses whatever link to reality the original model had. But if the data shown above were to be used, the true feasible limits could be found. And from those limits, a set of replacement aircraft could be selected that could be used by the fleet analysis tools in their calculations. This approach would provide a more physically related set of responses so that stringency could be studied in real physically attainable terms. Worth noting is the lack of information on any noise related effects that the current technology response provides.

5.4.1 Aircraft Selection for Technology Response

The previous section provided the Pareto optimal aircraft that represent the physical limits of attainability for the system being studied. In this section, a subset of those aircraft will be chosen to be utilized in the fleet analysis tools for stringency studies.

In scenario 1 there were 55 aircraft that were Pareto optimal, and met the CAEP/6 NOx levels. These aircraft expand the available space defined by the input variables and the ranges imposed. This number is too large to be used by AEDT in their calculations, due to limited computational resources. To solve this problem, the process outlined in CHAPTER 4 is used for the selection of 5 aircraft out of those 55. The table of Pareto points, along with their fuel burn increase, the NOx above CAEP/6, and the cumulative noise increase, is in Appendix D. Also included in this table are the settings for the input variables used in each case. All these cases are shown in Figure 55 in a tri-dimensional graph created by the three key measures, fuel burn increase, NOx level above CAEP/6, and cumulative noise increase. Also in this figure are included the points chosen to be passed to the fleet analysis tools, colored in green, and the baseline case, depicted in red. The tradeoffs that need to be performed to decrease any of the attributes, in terms of the other attributes are shown in this figure.

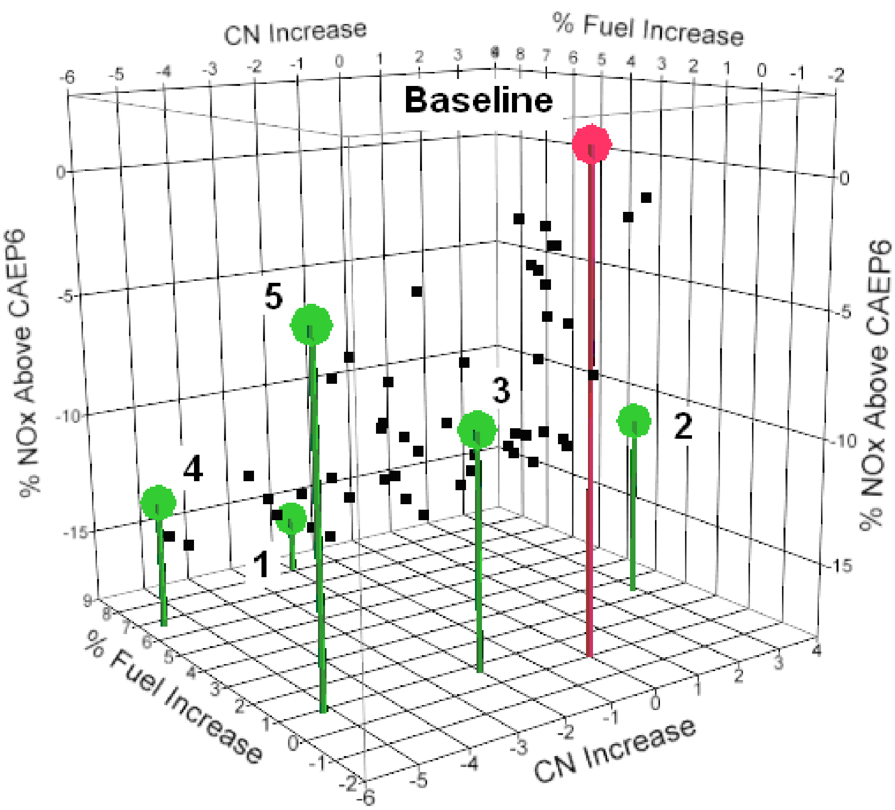

Figure 55: Chosen Points for AEDT

Aircraft 4 has the lowest noise of the group, while Aircraft 5 has the lowest fuel burn, and Aircraft 1 has the lowest NOx. From this last point, noise could be improved, moving to Aircraft 4 but with a penalty in NOx, but a benefit in fuel burn. At the same time, if fuel burn needed to be reduced more, it could be done moving to any of the other aircraft, but the noise would increase, or so would the NOx.

The selection of the aircraft is performed using the algorithm described in CHAPTER 4, which maximizes the minimum distance between the chosen points. These points are also shown in Table 14, with their respective values for the calculated key measures. The first step in this process involves the non-dimensionalization or normalization of the responses so that they can be compared and their magnitude differences do not affect the final result. This normalization is performed utilizing the maximum and minimum values for each response from the 82 cases, plus the baseline case, which in this case will be used as the existing aircraft, from which all the others have to be significantly different.

Table 14: 300 Passenger Example Chosen Aircraft

Aircraft	% Fuel Increase	% NOx Above CAEP/6	Cumulative Noise Increase
Baseline	0	1.529	0
1	8.102	-15.677	-1.977
2	2.310	-10.608	2.836
3	0.549	-7.605	-4.477
4	6.665	-12.818	-5.581
5	0.853	-3.892	-5.193

The normalization equation was shown in CHAPTER 4 as Equation 11, repeated here: $data^* = \frac{data}{\max - \min} - \frac{\min}{\max - \min}$. This leads to a series of points that have 3 characteristics, in the range from 0 to 1. In the case of the responses being utilized, here a 0 means it is the best option, and 1 it is the worst. After this step, the algorithm described in Appendix B is used to rank the alternatives.

The five points chosen are varied in their main characteristics. The values of the inputs to the environment that create these aircraft are shown in Table 15. All five points have a low FPR, and a high top of climb thrust. The rest of the parameters are diverse enough that the vehicles are consistently different from each other.

Table 15: 300 Passenger Example Chosen Aircraft Inputs

Aircraft	Extraction Ratio	FPR	HPCPR	LPCPR	TOC Thrust	TOC Wflow ratio	TO Thrust
Baseline	1.081977	1.58	20.03255	1.2603	19600	1.035575	78400
1	1.1	1.55	15.5	1.2	22000	1.02	82000
2	1.1	1.55	15.5	1.2	22000	1.08	78000
3	1.1	1.55	15.5	1.85	22000	1.02	78000
4	1.055	1.55	9	2.5	22000	1.02	82000
5	1.1	1.55	15.5	1.85	22000	1.02	82000

5.5 Calculation of Database Coefficients for Baseline

The aircraft chosen have to be added to the databases of vehicles used for the fleet analysis tools. This process was outlined in CHAPTER 4. The results for the five chosen aircraft from the second scenario, and the one from the first scenario, are given in Appendix E. The results for the baseline are also shown here in graphical form. These results are the database entries for each of the vehicles for all 18 of the necessary databases. In this section a comparison of some of the coefficients from the selected aircraft to those of the baseline are presented. Then an example of how these aircraft could be used in a stringency scenario is shown, comparing the results of using the actual technology response to those obtained using the proposed replacement aircraft.

5.5.1.1 BADA_CONFIG

It was stated before that this database contains aerodynamic information about the aircraft. This information is provided in the form of two parameters, $C_{D,0}$ and $C_{D,2}$, to be used in the equation $C_D = C_{D,0} + C_{D,2} \cdot C_L{}^2$. Figure 56 shows the drag polars for takeoff and landing used in the environment and the corresponding approximations using the calculated coefficients. These coefficients are shown in Table 16. Also in this table are the aerodynamic coefficients for cruise, initial climb and approach conditions, and the stall velocities for the same five configurations.

Table 16: BADA_CONFIG Coefficients

Condition	Vstall (knots)	$C_{D,0}$	$C_{D,2}$
Cruise	150	0.0120521	0.0589768
Takeoff	145	0.0408948	0.0430555
Initial Climb	149	0.0298541	0.0589768
Approach	116	0.047278	0.0589768
Landing	98	0.0862868	0.0436541

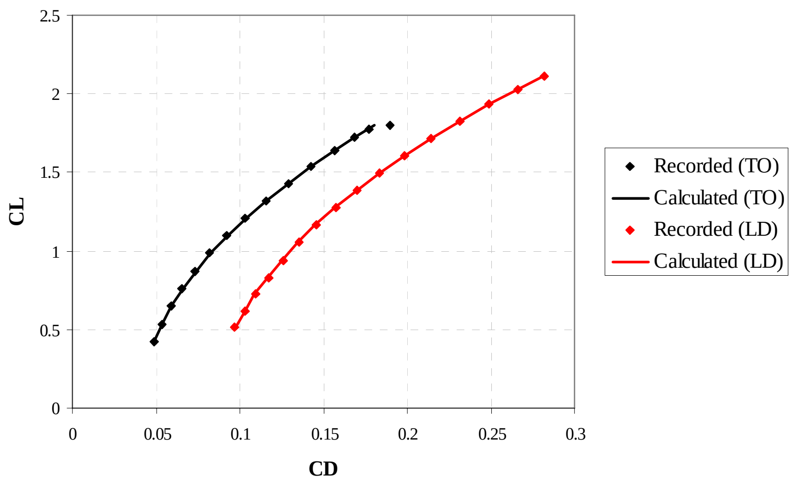

Figure 56: Takeoff and Landing Aerodynamic Data

5.5.1.2 BADA_FUEL

This database is formed by coefficients that approximate the fuel burn of the engine for different flight conditions, specifically the maximum thrust specific fuel consumption for climb at maximum power and the minimum fuel flow for descent. In Figure 57, the recorded specific fuel consumption along with the approximation calculated using the coefficients can be appreciated. In Figure 58, both the recorded fuel flow and the approximation can be seen.

Table 17: BADA_FUEL Coefficients

Cf1	Cf2	Cf3	Cf4
0.471858	439.103	41.571	66615.73

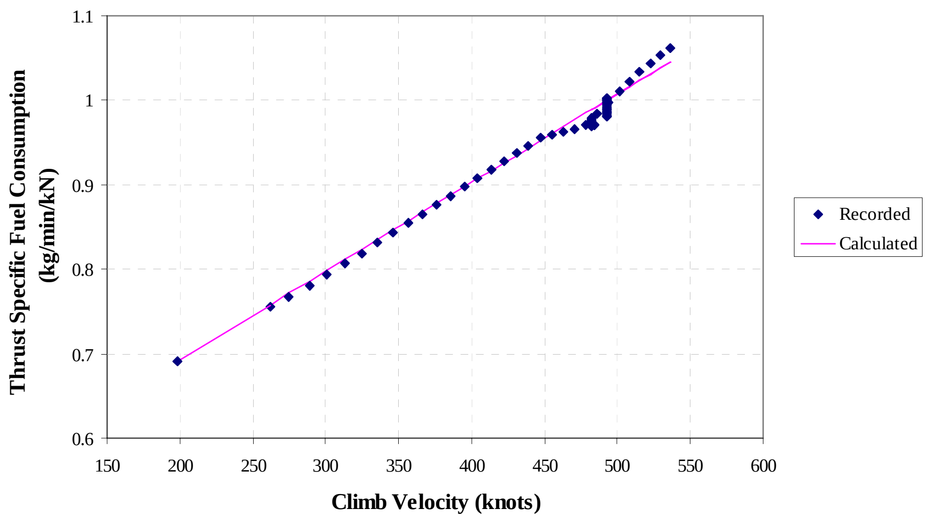

Figure 57: Climb Thrust Specific Fuel Consumption

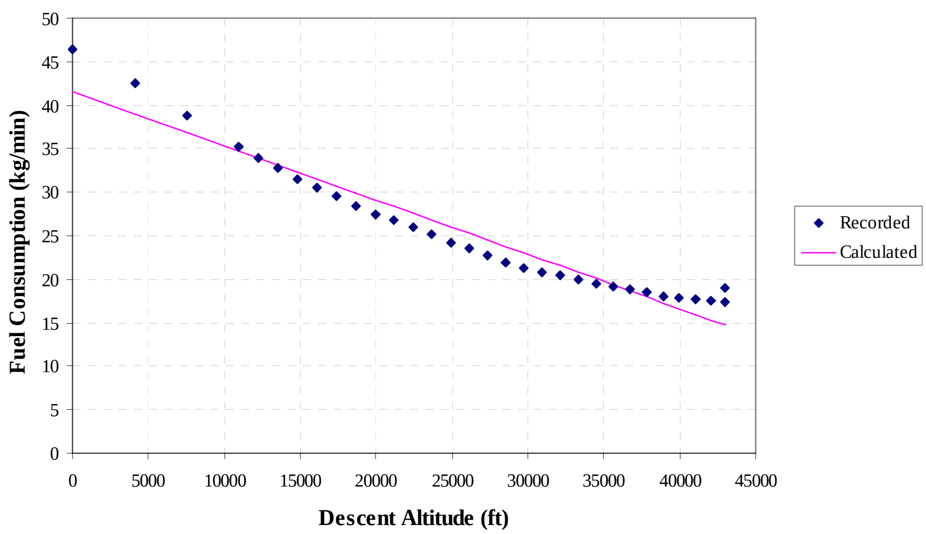

Figure 58: Descent Minimum Fuel Flow

5.5.1.3 BADA_THRUST

Similarly to the BADA_FUEL, the BADA_THRUST database contains coefficients that approximate the maximum available thrust of the engines as a function of altitude. In Figure 59 the recorded values and the approximation calculated using the coefficients are plotted. The coefficients used are shown in Table 18.

Table 18: BADA_THRUST Coefficients

Ctc1	Ctc2	Ctc3	Ctc4	Ctc5
668530	27407	4.00145E-10	0	0.00390094

The clump of points that is observed at an altitude of 10,000 ft is due to the fact that the mission analysis program has the FAR required limitation of 250 KTAS below that altitude.

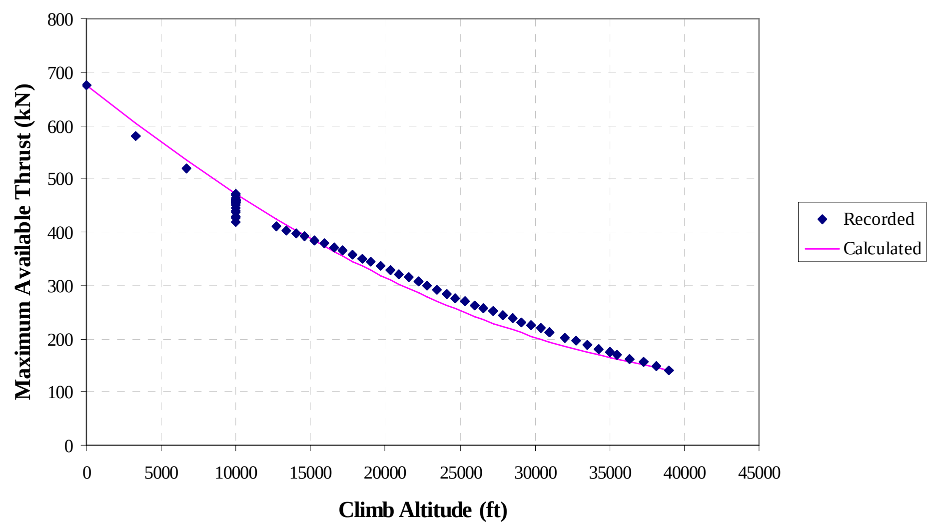

Figure 59: Maximum Available Climb Thrust

5.5.1.4 FLAPS

This database is similar to BADA_CONFIG in the sense that it contains aerodynamic data about the aircraft, but this data is presented in a different manner.

There are three coefficients in this table, COEFF_R, COEFF_CD, and COEFF_B. In this case, four configurations were used, full flap deployment for takeoff, part flap deployment for takeoff, clean configuration, and approach configuration. The resulting coefficients are shown in Table 19.

The trajectories performed by the aircraft for these four configurations are shown in Figure 60, along with the velocities along those trajectories. These parameters were used to calculate the coefficients that populate the database.

Table 19: FLAPS Takeoff Results

Parameter	Full TO	Part TO	Clean	Approach
Coeff_CD (knt/lb^1/2)	0.241966	0.241939	0.269992	0.240578
Rotation Speed (knots)	176.04	176.0204	196.4301	175.03
Coeff_B (ft/lb)	0.002735	0.002733	0.002731	0.00277688
Net Thrust (lbs)	158934.8	158934.8	158934.8	158934.8
Ground Roll (ft)	4821	4818	4814	4895

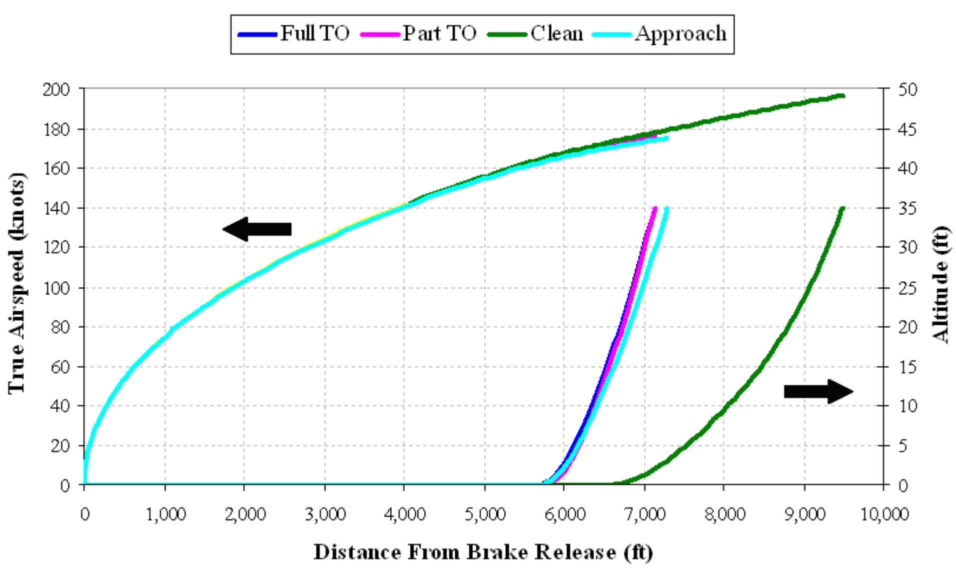

Figure 60: FLAPS Takeoff Trajectory and Velocity

5.5.1.5 THR_JET

This database contains coefficients that approximate the thrust of the aircraft for different flight conditions. Figure 61 and Figure 62 show the recorded values, along with the coefficients calculations, for take off and climb out.

Table 20: BADA_THRUST Coefficients

Condition	E	F	Ga	Gb	H
Max. Takeoff	97301.4	-114.693	0.297302	0	0
Climb Out	87743.42	-62.928	1.466424	-2.13E-05	0

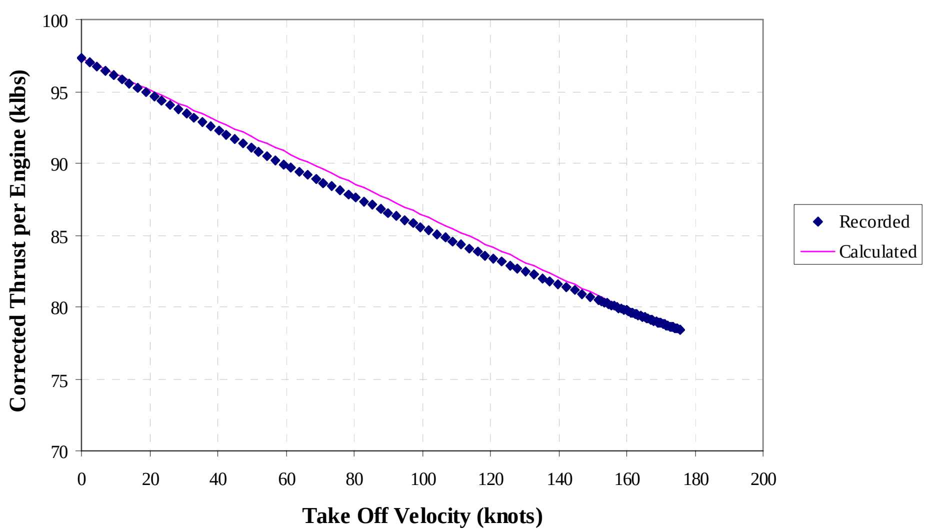

Figure 61: Takeoff Maximum Thrust

5.5.1.6 PROFILE

This database is composed of the takeoff gross weights for the aircraft for different mission ranges. In the case of the 300 passenger aircraft, the nine possible ranges, or profiles, are needed since the maximum range is greater than 6,500 nmi. The ranges were described in Table 5 and the resulting takeoff gross weights are shown in Table 21.

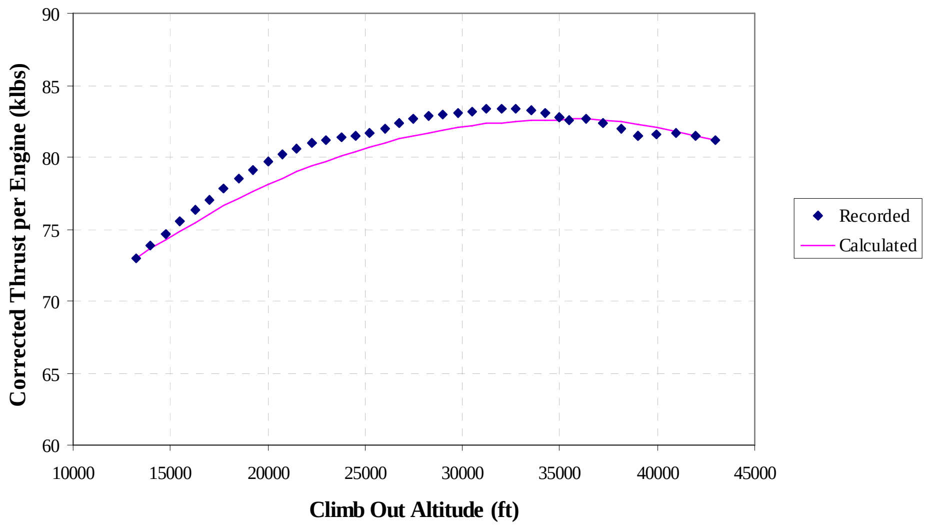

Figure 62: Climb Out Thrust

Table 21: Stage Number and Associated TOGW (lbs)

Stage Number	1	2	3	4	5	6	7	8	9
TOGW (lbs)	401,276	415,124	429,404	459,249	490,888	524,582	560,479	598,523	656,000

5.5.1.7 PROCEDUR

The PROCEDUR database contains information about the trajectory for the takeoff procedures defined as ICAO A, ICAO B, and STANDARD. These procedures were explained in CHAPTER 4 in detail. Figure 63 shows the ICAO A departure profile for different TOGW. Similarly, Figure 81, and Figure 82, shown in Appendix E, depict the ICAO B and STANDARD departure procedures for different takeoff gross weights, as defined in the profile section above.

5.5.1.8 PROF_PTS

Similarly to the PROCEDUR database, the PROF_PTS database contains information about specific procedures, but in this case it relates to the approach and landing procedure for maximum landing weight. Figure 64 shows the trajectory, thrust, and velocity for this aircraft for the approach and landing procedure.

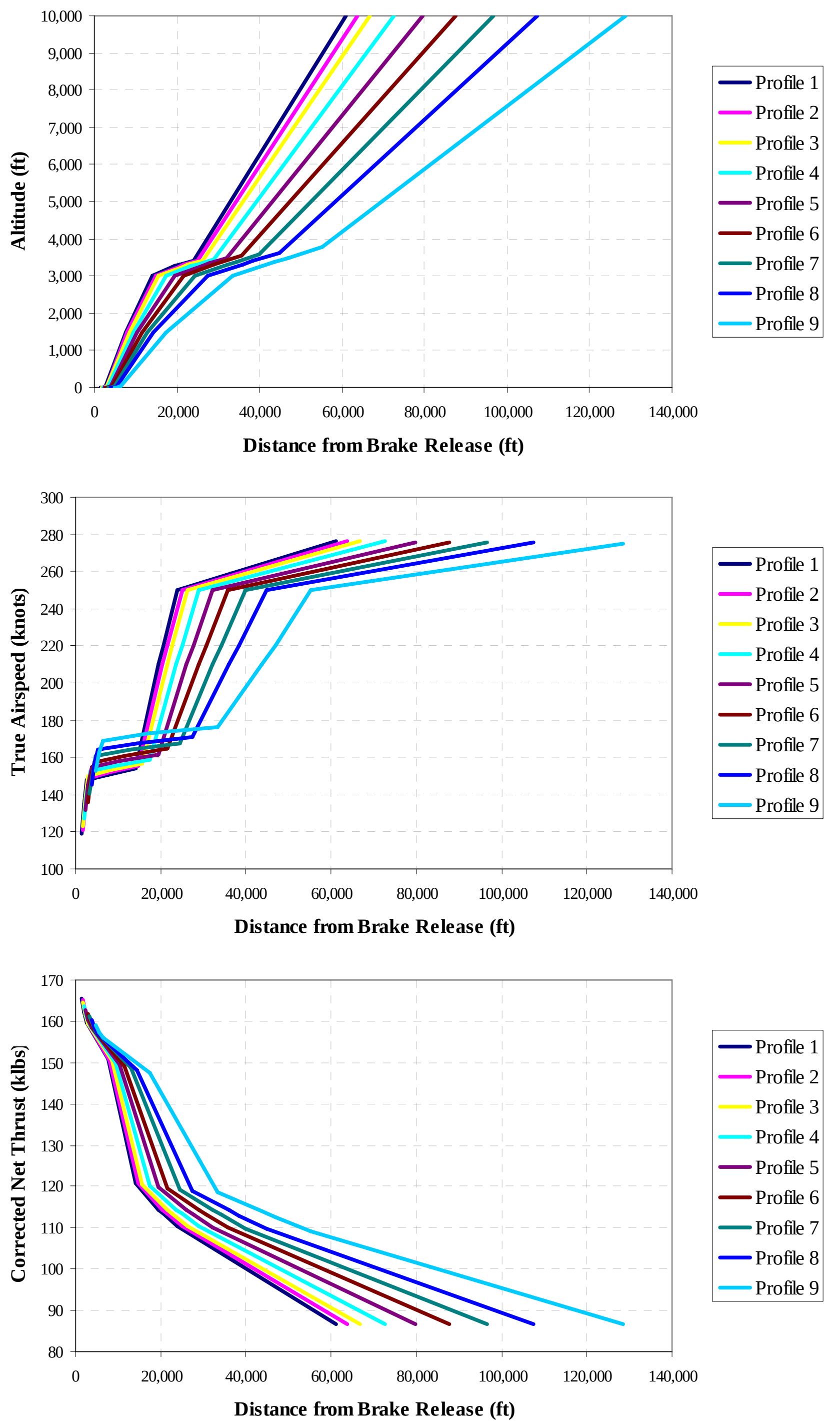

Figure 63: ICAO A Departure Procedures

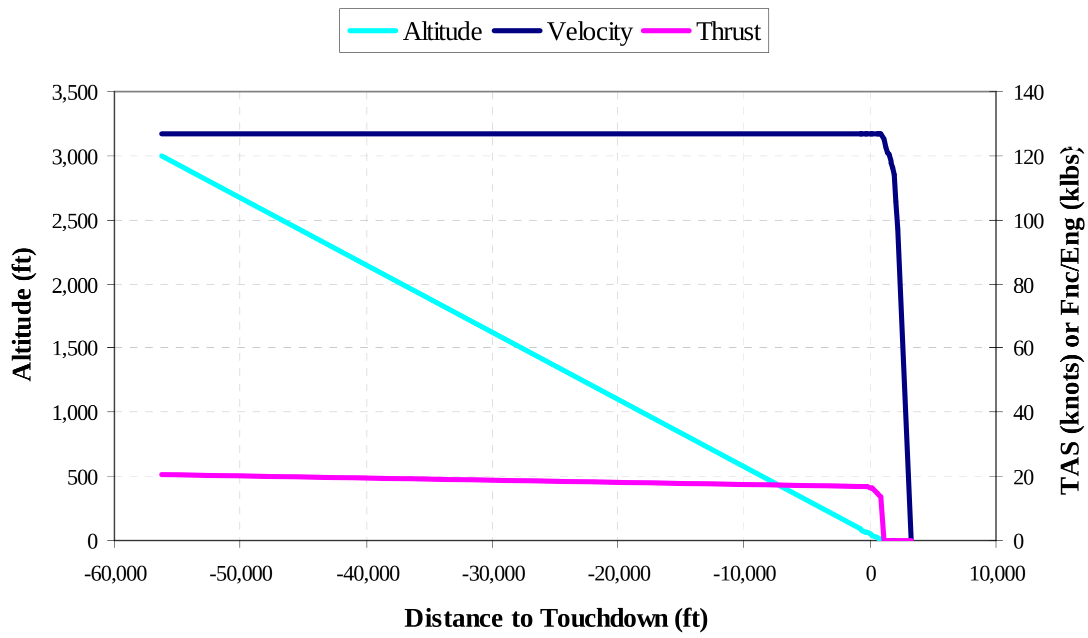

Figure 64: Landing Procedure for Maximum Landing Weight

5.5.1.9 Noise Data

The noise data provided to the AEDT is in the form of noise power distance curves. These curves provide the noise emitted, in terms of 4 different metrics, at different distances from the aircraft and at different power settings of the engine. The metrics provided are the Sound Exposure Level (SEL), the Effective Perceived Noise Level (EPNL), the maximum A-weighted level (max dBA), and the maximum tone corrected Perceived Noise Level (max PNLt). As with the rest of the databases, all of these parameters are provided in Appendix E, but a plot for the baseline case is given in Figure 65 for the SEL, for both approach and departure configurations.

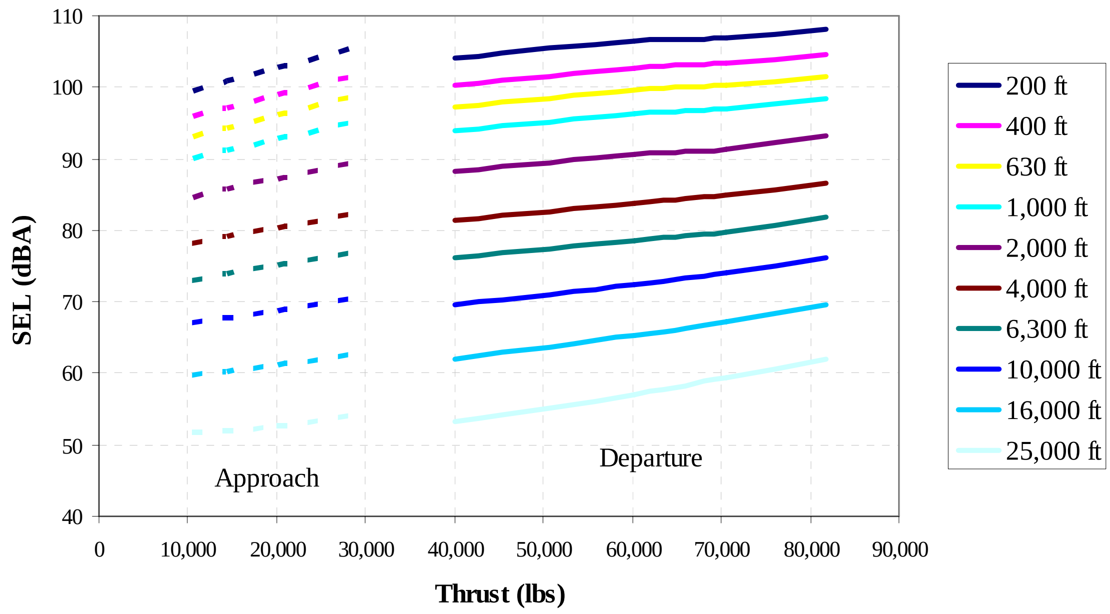

Figure 65: SEL NPD for Baseline Aircraft

5.5.2 Comparison of Baseline to Replacement Aircraft

The BADA_CONFIG database contains information about the aerodynamics of the aircraft. Since the aircraft itself is the same in all cases, this information is essentially the same for the 6 aircraft. The BADA_FUEL file, on the other hand, is quite different from one aircraft to the other. Figure 66 shows the difference of the replacement aircraft with respect to the baseline fuel consumption. Most of the replacement aircraft have lower fuel consumption than the baseline. This does not mean that they have a lower fuel burn for overall missions, the specific fuel consumption has to be calculated at cruise, and this figure only represents the fuel consumption for maximum power.

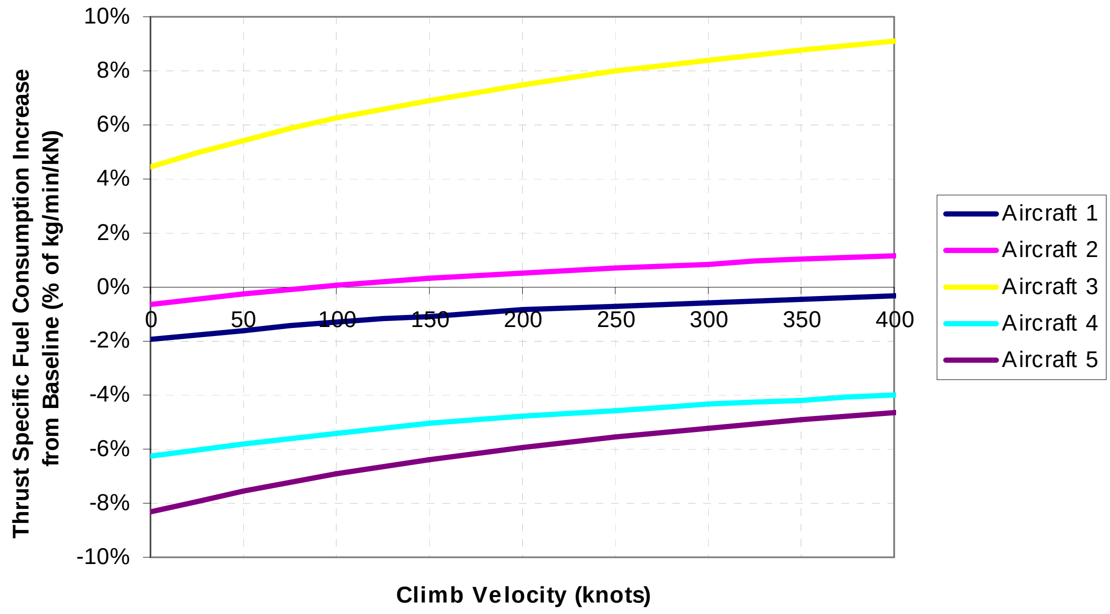

Figure 66: BADA_FUEL Comparison of Baseline and Replacement Aircraft (Max Climb Power)

If the cruise fuel consumption were to be used instead, the result would be Figure 67. In this figure, the representative fuel burn matches the results for a whole mission. The BADA_THRUST file also shows major differences between the different alternatives. Figure 68 shows the maximum thrust increase from the baseline value for different altitudes.

As with the BADA_CONFIG file, the FLAPS file represents the same aerodynamic data for all the configurations, except for the ground roll coefficient, which also depends on the takeoff maximum thrust. Figure 69 shows these ground rolls for the 6 aircraft, as calculated with the database coefficients.

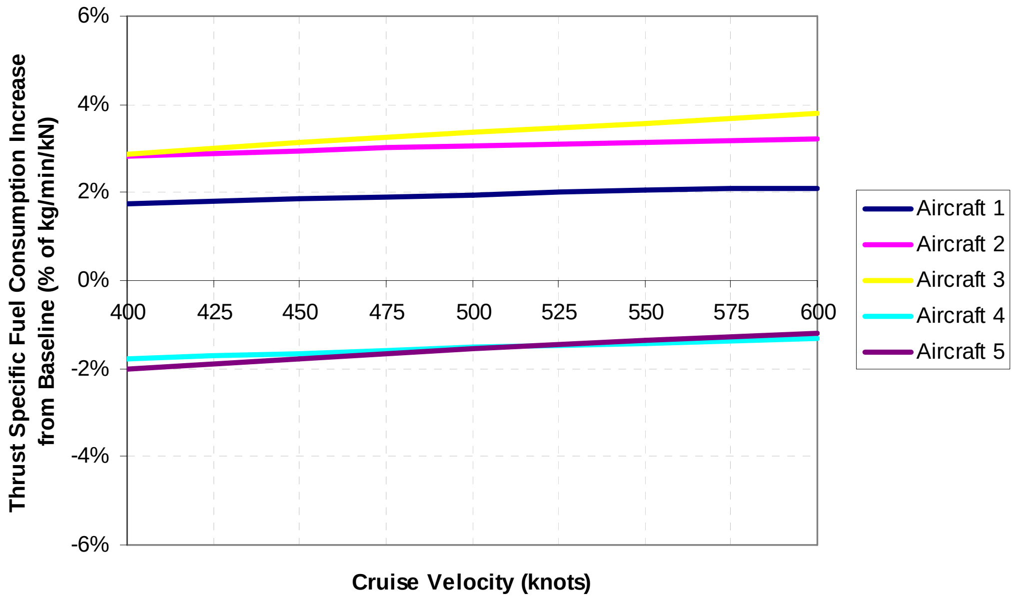

Figure 67: BADA_FUEL Comparison of Baseline and Replacement Aircraft (Cruise)

The emissions data used in the databases is the certification value for a LTO cycle, and those values were shown in Table 14.

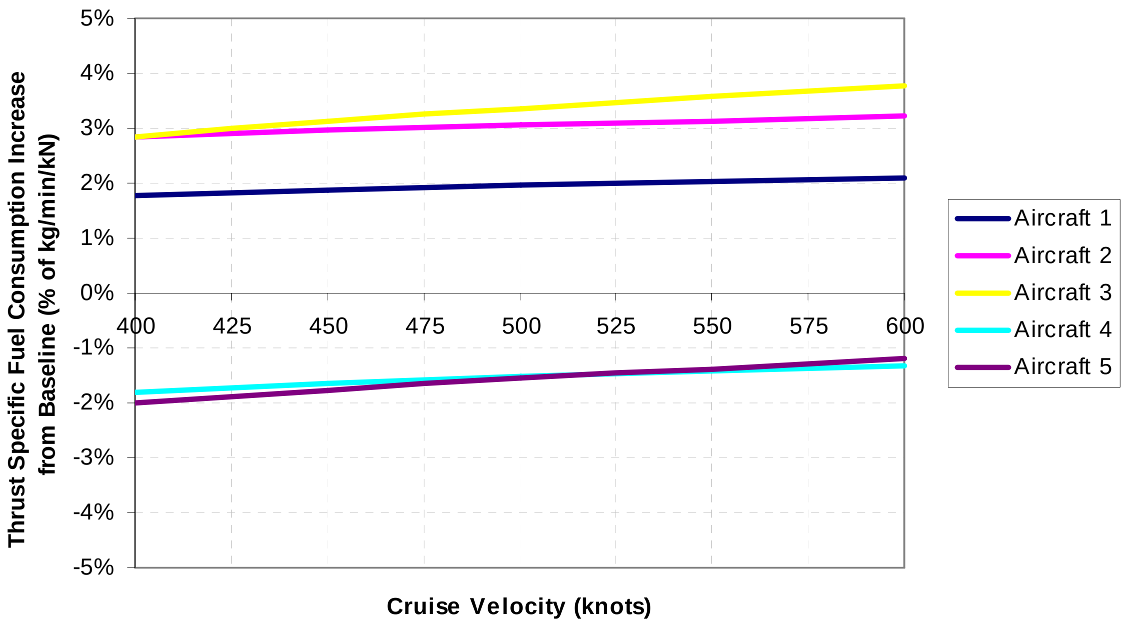

Figure 68: BADA_THRUST Comparison of Baseline and Replacement Aircraft

The noise produced by the aircraft is also different. In Figure 70 the SEL at 1,000 ft from the aircraft is shown. Both approach and departure configurations are depicted with their respective thrust. The results in the figure agree with the certification values shown in Table 14.

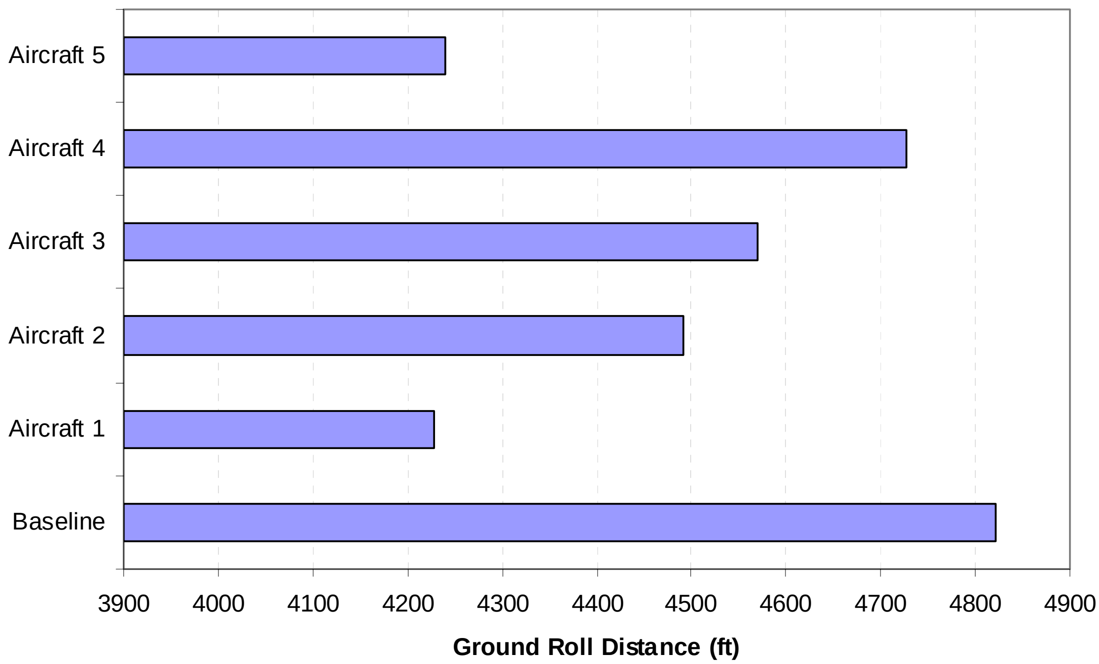

Figure 69: FLAPS Ground Roll Comparison of Baseline and Replacement Aircraft

This part of the experiment shows that the database entries created with the process proposed are consistent, and said process propagates the characteristics of the different aircraft to be used in other fleet analysis tools. The next step is the study of the effects of those coefficients on missions run through the fleet analysis tools. These tools include mission performance in terms of NOx and fuel burn, and noise in terms of footprints for takeoff and landing procedures.

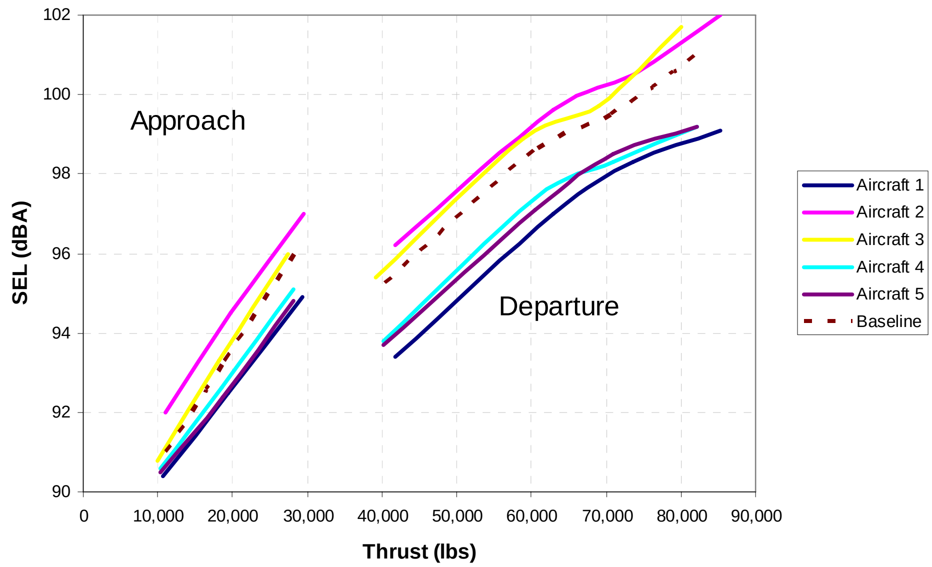

Figure 70: Noise Curve at 1,000 ft for Baseline and Replacement Aircraft

5.6 Effect of Proposed Process on Policy Making

In order to show the differences between using the actual technology response to the proposed process of replacement aircraft, aircraft from the two scenarios shown before are run through the fleet analysis tools. These tools are encompassed in the AEDT, described previously. This is a FAA tool that has been approved to be used by CAEP, so it will not be validated in this research work and treated as a black box, to which inputs are provided and outputs are obtained. The effect of utilizing the aircraft is measured in terms of the fuel burn and the NOx produced for a 7,873 nmi, and the noise footprint created for a takeoff procedure. In addition to the overall mission fuel burn and NOx, the partial emissions below 3,000 ft and below 1,000 ft is also recorded. They way in which a decision is made on how much a new stringency should reduce the existing limits is by assigning a dollar amount to the impact of introducing this stringency. As it was stated at the beginning of this work, this dollar amount is based on the fuel burn, NOx, and noise effects of a characteristic day of flights, for the whole fleet of world vehicles. A baseline case is run to show how each proposed stringency is different from it, in noise, NOx, and fuel burn. This process is recalled in Figure 71.

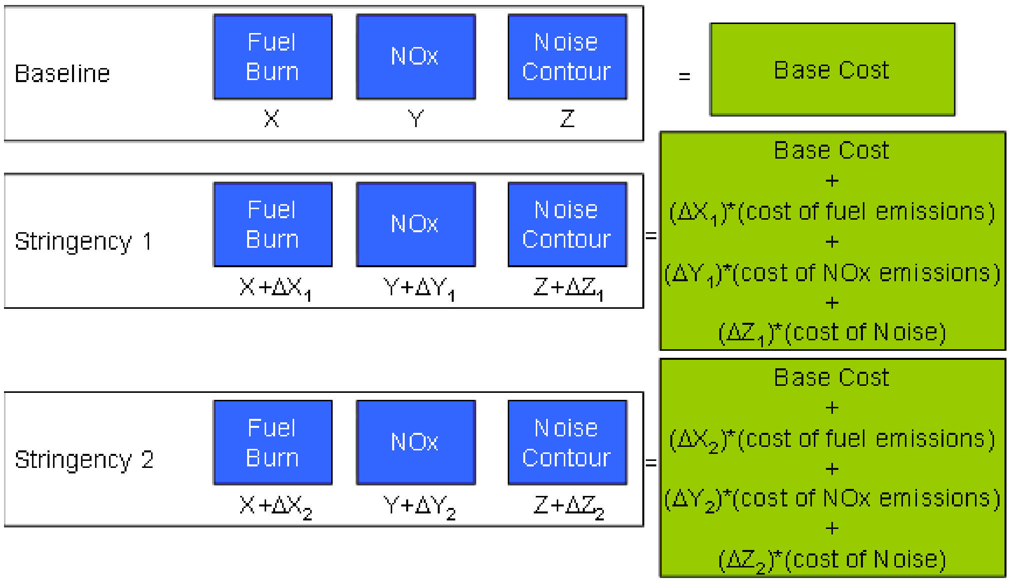

Figure 71: Example of Stringency Analysis

The current technology response assumes a constant 2% fuel burn penalty for those aircraft that do not meet a new stringency. This means that given two stringency levels in NOx, the effect in fuel burn will be the same, and also, there will be no change in the noise with respect to the baseline. If, on the other hand, the proposed method of using replacement aircraft were to be used, the results would vary drastically. First, there would be a physical connection between the NOx reduction needed and the fuel burn effects. And second, there would be an effect on the noise too. The following example shows, with the aircraft created in the previous sections, the differences between the current process and the proposed herein.

First, the certification results from the replacement aircraft that are used in the fleet analysis tool are recalled in Table 22. In addition, the characteristics of the baseline aircraft as they would be seen with the required technology response are shown.

Table 22: Selected Aircraft Performance Characteristics

Aircraft	% Fuel Increase	% NOx Above CAEP/6	Cumulative Noise Increase
Baseline	0.00	1.53	0
Base + Technology Response	2.00	Whatever necessary	0
Scenario 1 Aircraft 1	0.42	-1.33	-1.02
Scenario 2 Aircraft 4	6.66	-12.82	-5.58
Scenario 2 Aircraft 5	0.85	-3.89	-5.19

The results of running the vehicles through the fleet tools are depicted in the following figures. Figure 72 shows the noise footprint created by the baseline aircraft during a takeoff procedure. The units on this graph, and the consecutive one, are feet for the vertical and horizontal directions and the contours are those of sound exposure level (SEL) in dB, separated by intervals of 10 dB.

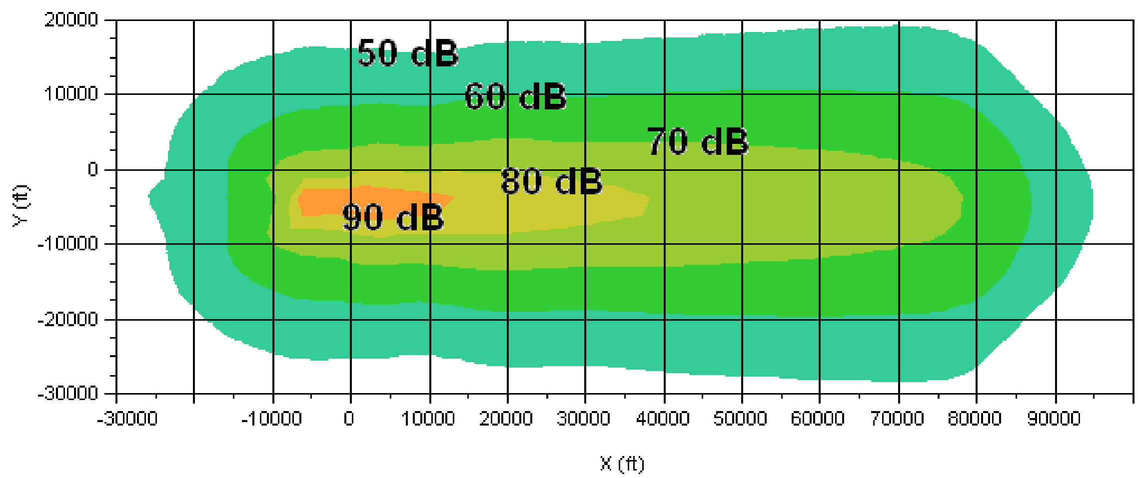

Figure 72: Baseline Vehicle Noise Footprint

The technology response aircraft would have the same noise footprint since no effect is assumed for the NOx reduction. The footprints for the used aircraft are shown in the following pictures. The footprint for the aircraft from scenario 1 is shown in Figure 73. This figure shows very little improvement over the baseline aircraft footprint, but this result is expected, since the new aircraft is only one decibel quieter than the baseline.

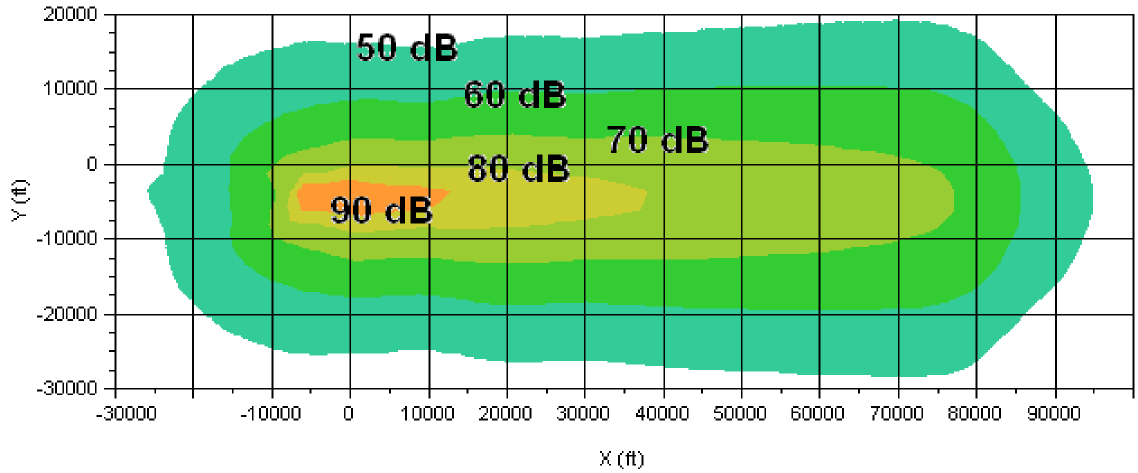

Figure 73: Scenario 1 Aircraft Noise Footprint

The aircraft propagated from scenario 2, the complete engine overhaul, are aircraft 4 and 5. A much greater difference occurs if the baseline noise footprint is compared to that of those two aircraft, depicted in Figure 74 and Figure 75. It is easily seen that the decrease in cumulative noise, over 5.5 dB for aircraft 4 and 5.1 for 5, from the baseline to the new aircraft, is propagated to the noise footprints, in terms of the area covered by each contour. The area covered by the 60 dB interval was calculated to show the differences between the aircraft chosen. These areas are listed in Table 23.

Table 23: Areas Covered by 60 dB Noise Contour

Aircraft	Baseline	Scenario 1 Aircraft 1	Scenario 2 Aircraft 4	Scenario 2 Aircraft 5
Area Covered (nmi^2)	74.88	72.48	67.84	68.8

The differences in the areas covered by the footprints are consistent with the noise certification levels shown above.

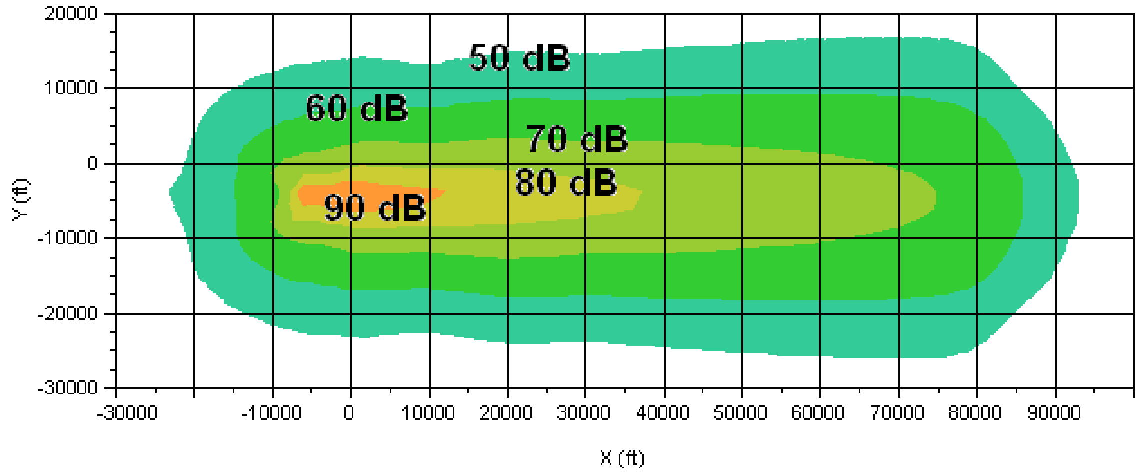

Figure 74: Scenario 2 Aircraft 4 Noise Footprint

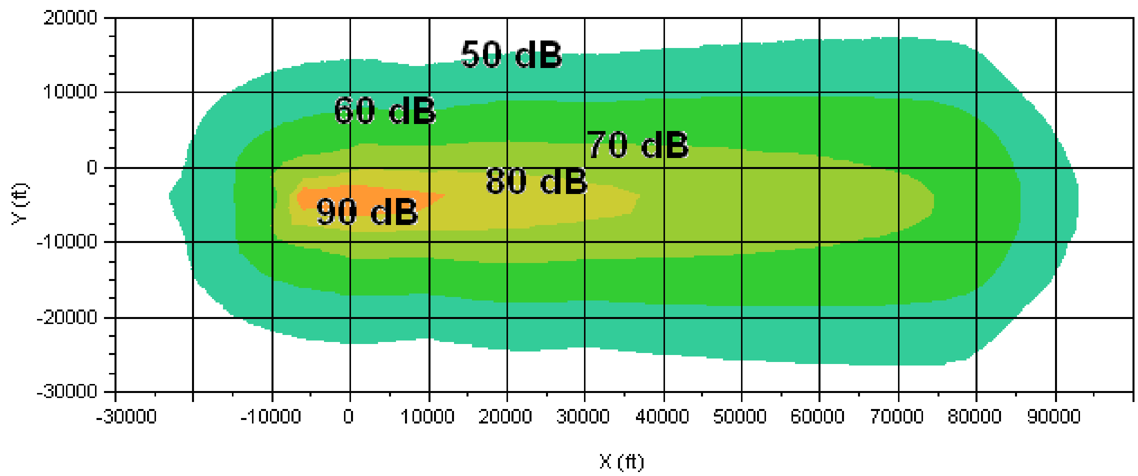

Figure 75: Scenario 2 Aircraft 5 Noise Footprint

The fuel burn and NOx emitted for the baseline vehicle in mission defined above are listed in Table 24. The following figures depict the change in both fuel and NOx emitted by the other three aircraft.

Table 24: Baseline Vehicle Mission Results

	Overall	Below 3,000 ft	Below 1,000 ft
Fuel burn (lbs)	218,205	2,816	1,798
Nox (lbs)	4,689.5	97.0	58.88

Figure 76 and Figure 77 show the results for the 3 vehicles used, from the mission mentioned before, in terms of the fuel burn, and NOx emissions, for the overall mission, below 3,000 ft, and below 1,000 ft, as they compare to the baseline values. The results obtained are consistent with the results listed above in Table 22. The results of the baseline vehicle with the technology response applied to it vary depending on the stringency scenario being studied. The fuel burn will always be 2% below that of the baseline and the NOx will be whatever it is required to meet said stringency.

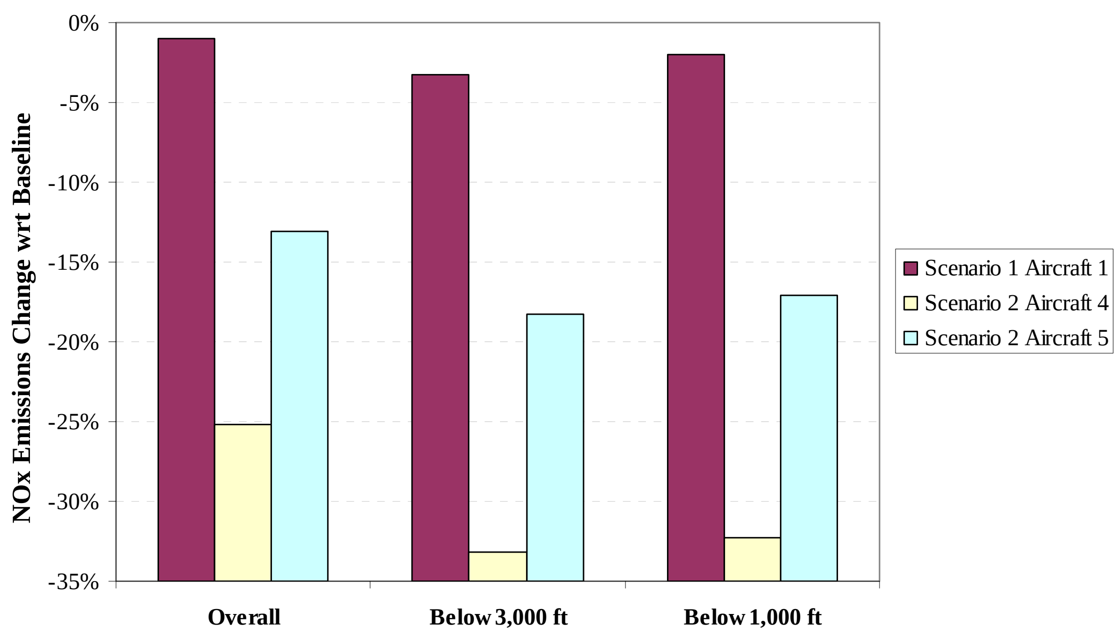

Figure 76: NOx Emissions Results wrt Baseline

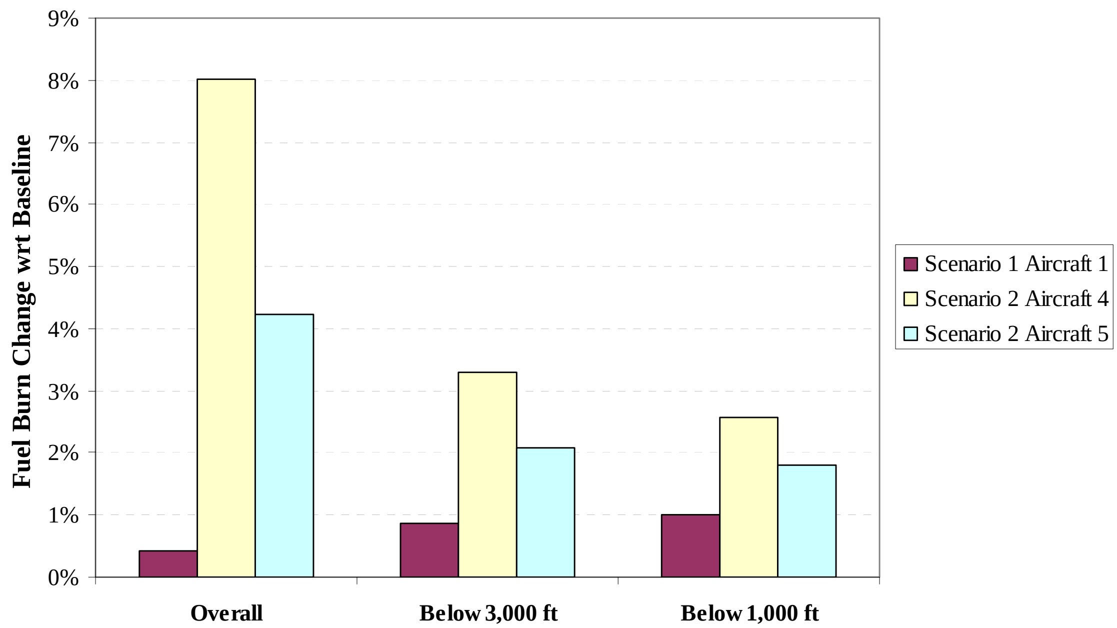

Figure 77: Fuel Used Results wrt Baseline

For aircraft 1, from scenario 1, the change is minimal, in comparison to the baseline. Again, this result was expected, since the chosen aircraft only improves the NOx from the baseline by less than 2 %. A similar pattern is seen on the fuel burn, only decreased by less than a percentage point in all six areas. As with the noise contours, it is aircraft 4 the one with the greatest differences from the baseline. In the NOx emissions, the new aircraft produces a reduction of almost 13% below CAEP/6 levels, and this reduction is even bigger for the overall mission. Aircraft 5 is between aircraft 1 from the first scenario and aircraft 4 from the second. It produces a reduction in NOx not as big as aircraft 4, but the penalty in fuel burn is also not as significant.

Up to this point, this example proves that the connectivity to the AEDT is operational and the characteristics of the chosen aircraft can be propagated to the fleet analysis tool. The data created in this simulation proves that the current technology response is not the proper way to approach the problem.

If a policy maker were to look at these numbers, different conclusions would be reached, depending on which technology response was used. Using the current technology response, the effect of implementing any NOx reduction would be the NOx reduction itself and a 2% fuel burn increase for those vehicles that could not meet the stringency. For larger reductions, the benefits would only increase by the amount of NOx not emitted, there would be no effect on the fuel used. On the other hand, if the new proposed technology response is used, depending on what level of reduction is required, the effect on noise and fuel used can be differentiated clearly. What this example shows is that the current technology response is only susceptible to the NOx reduction, since the fuel burn is always constant at 2%, and there is no noise associated with it. The new technology response, characterized by the replacement aircraft, can provide a more transparent relationship between NOx, noise, and fuel burn.

Summarizing, the actual technology response only provides a one-way view of the tradeoffs. The process itself is not flawed, as long as the policy maker has information about the three key measures simultaneously. In addition, the constant fuel burn penalty assumption does not provide enough insight, and it is only by linking the physics of the aircraft and the engine to the environmental effects that the true tradeoffs can be observed. The process delineated here provides policy makers with more transparent information, and knowledge in more areas than what was provided before. This allows them to create policies that would be more beneficial and that are more achievable at the same time.

CHAPTER 6. CONCLUSIONS AND FUTURE WORK

The motivation for improving the state of the art in terms of environmental policy making comes from the primordial mission of policy making itself: to provide a better life for all people. Aviation has improved the quality of life around the planet making it possible to transport goods and people in a faster more efficient way over far distances. But this improvement does not come at a cheap price: the usage of fossil fuels fills the atmosphere with toxic waste that increases health problems and damages the environment as a whole. In addition to the gases produced, noise is a key concern in areas surrounding airports. This noise can cause major health issues and should not be taken lightly either.

It was mentioned at the beginning of this work that its main objective was to develop a process to improve actual policy-making procedures in terms of aviation environmental effects. The area that this research focuses on is the interdependencies between noise, NOx and fuel burn at the aircraft level, and how their propagation to the fleet affects policy making. The current process lacks transparency in the area of linking the fundamental aircraft and engine characteristics to the environmental key measures sought to reduce, in this case, noise, NOx emissions, and fuel burn, and it only provides a constant relationship between NOx emissions and fuel burn. On another area of the existing practice, aircraft and engine manufacturers are required to provide detailed performance about their products, but a detailed procedure by which this information has to be created does not exist. Addressing these deficiencies is the core of this research work.

The research questions proposed in the first chapter define the gaps existing in the current policy making process with respect to aviation environmental protection. This process is outlined in Figure 78 [Ref. 29]. As it was stated in the Approach section, CHAPTER 4, the contributions of this research work are confined to the AC Data box, on the bottom of the figure. This particular area provides the rest of the tools with the aircraft performance information used for the different stringency analyses.

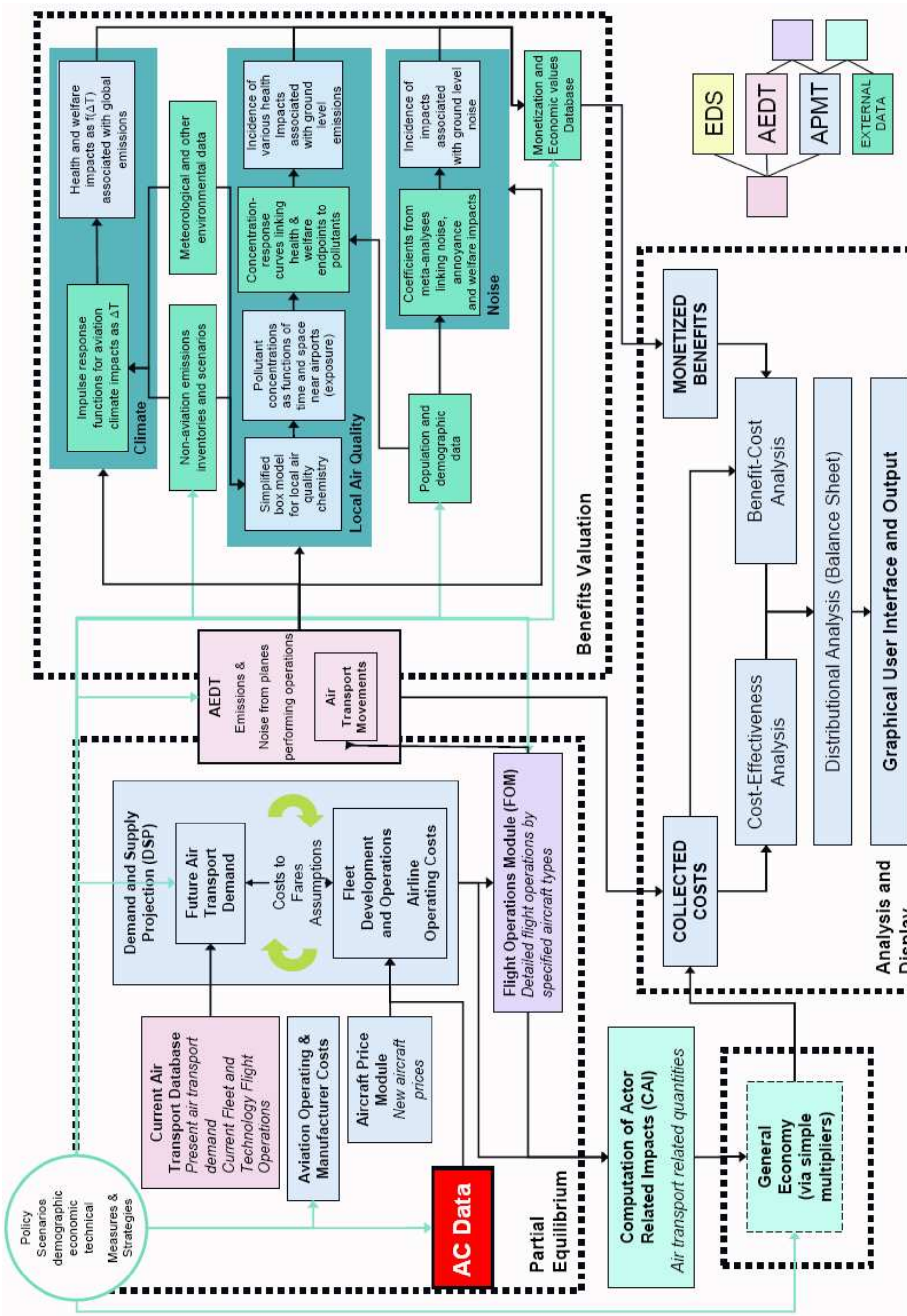

Figure 78: CAEP Policy Making Process Flow of Data [Ref. 29]

The research questions were determined based on observations made on the current practices in the CAEP process. This process was described in the CAEP/6 Information Paper 13, and it has the objective to analyze the effect of implementing different policy scenarios, in terms of their efficiency and ultimate economic costs. This analysis is done utilizing a series of tools that model the environmental effects of the aircraft currently in the international fleet. The analysis of the different policies is done by setting an implementation timeframe, and a stringency level, in the case of IP13 this stringency is in the LTO NOx emissions level. Depending on the level of stringency, some of the existing aircraft would not meet said level. Those aircraft would have to be modified to meet the new standards, in order to be kept flying. These modifications could be in any part of the aircraft or engine, anything that would make it meet the stringency level. But modifying the aircraft to meet the new regulation would most likely affect the performance in other areas of the aircraft, such as noise or fuel burn. But the current process only allows for a constant fuel burn penalty for cases where the existing aircraft is very far away from meeting the proposed regulation, and there is no penalty in the noise produced in any case. Based on this process, a number of observations were made, and the subsequent questions that arose from them are recalled here:

- Observation A. Current technology response does not provide physical relations between NOx and fuel burn, due to competitive issues between companies.

  Research Question A.1. What are the physical aircraft and engine characteristics that contribute to the environmental key measures?

  Research Question A.2. Can these physical attributes be determined utilizing non-proprietary, public domain data and tools?

Research Question A.3. How can the traceability of the data be assured?

- Observation B. Current technology response assumes a constant fuel burn penalty for any NOx reduction.

  Research Question B.1. Is the assumption of constant fuel burn penalty appropriate for the technology response?

  Research Question B.2. If not, how can it be improved?

- Observation C. Current technology response only connects NOx emissions and fuel burn, leaving noise outside the area of study.

  Research Question C.1. Can the physical interdependencies of NOx, fuel burn, and noise be established using physics based modeling tools?

  Research Question C.2. What assumptions can be made or have to be made?

- Observation D. There does not exist a clear process for the calculation of BADA and SAE AIR 1845 coefficients.

  Research Question D.1. Can a process be created to delineate the calculation of the coefficients to populate the BADA and AIR 1845 databases?

Using these questions, background research was performed to determine possible ways of answering them. These alternatives were defined in the hypotheses shown in CHAPTER 3. There are two main processes that were developed as a solution to the problems mentioned above: the creation of a technology response that would physically link noise, NOx, and fuel burn, and the determination of the coefficients that represent an aircraft in the databases used in the fleet analysis tools. The first of these processes can be further reduced into three hypotheses:

Hypothesis 1. The technology responses cannot be assumed to be constant due to the complexity of aircraft and engines interactions, and the interdependencies between noise, NOx, and fuel burn.

Hypothesis 2. The technology responses can be created as replacement aircraft that would substitute the ones that do not meet a required stringency requirement.

Hypothesis 3. The replacement aircraft can be chosen as a subset of the Pareto optimal from a complete space exploration. The maximization of the minimum Euclidean distances between the selected points can be used as the criterion for choosing this subset.

Proving these hypotheses true is the purpose of the research effort. In order to do so, the processes mentioned above were developed. The first process was created to quantify the tradeoffs between the environmental key measures, noise, NOx, and fuel burn, at the aircraft level. The second process is the creation of the procedure to populate the databases used for fleet analyses with the coefficients that define a particular aircraft and engine combination. These two processes are shown graphically linked together in Figure 79.

Each of the individual steps of both processes was explained in CHAPTER 4. In this section, only a brief reminder of each of the steps will be given .The first step involves the determination of the environment that would link the fundamental airframe and engine characteristics to the noise, fuel burn, and emissions produced by an aircraft. There are a number of tollgates that any environment that desires to be used must go through, in order to be approved to be used.

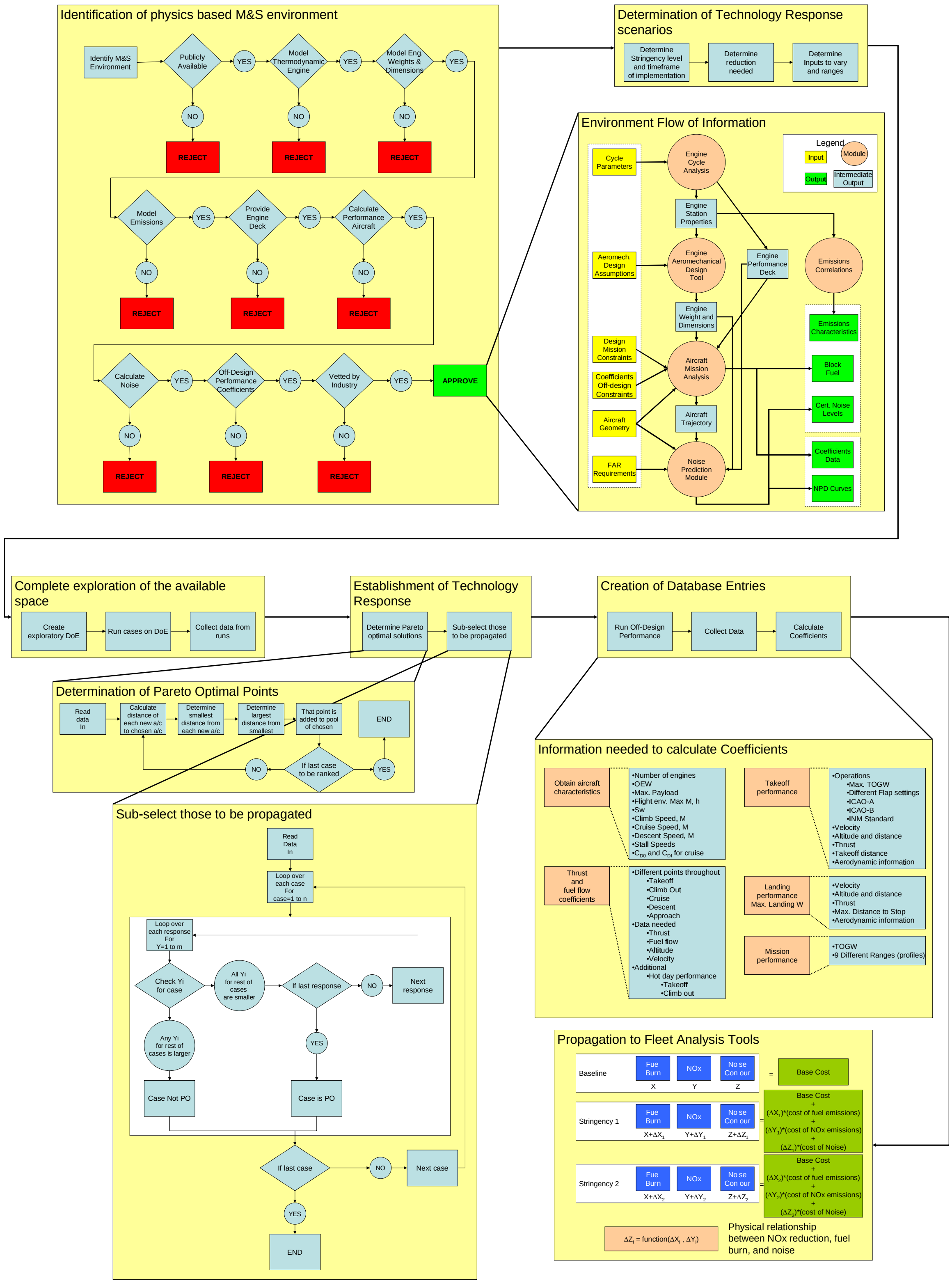

Figure 79: Process for the Quantification of Interdependencies between Environmental Metrics

The second step involves the determination of the inputs and ranges of those inputs, to be varied in the third step, the space exploration. These inputs and ranges are dependent on the scenario, or stringency level, being studied. The fourth step is the determination of the actual technology response, as the Pareto optimal aircraft, from those calculated during the space exploration. After the Pareto aircraft are determined, a sub-selection must take place, in order to reduce the overall number of vehicles to be propagated. This is done utilizing the *maxmin* algorithm. Once the vehicles are prepared, the process to calculate the database coefficients is follows, to populate those databases with the coefficients that represent the chosen aircraft.

The environment identified as suitable for this process was EDS, an evolution of the UEET/VSP work, being developed for the FAA. This environment was used to demonstrate that the assumption of constant fuel burn penalty assumed in the current technology response used by CAEP was proven to be inefficient, but a solution was proposed. This solution was the determination of the technology response, using the process mentioned above. The technology response can be created utilizing the concept of Pareto optimality and with a complete space exploration. The independent variables are chosen as the engine and aircraft characteristics, while the technology level can be set to state of the art or even future technologies. Performing a complete space exploration of the independent variables and their effect on the key measures, the feasible space can be obtained. The Pareto optimal concept comes into play to determine the limits of this space, which represent the area where trade-offs are to be made. This Pareto front is what can be used as the technology response since it represents the achievable limits for any technology level, and shows the interdependencies that exist between the key measures.

Once the Pareto front is determined, not all the aircraft in it can be chosen for usage in fleet analysis tools, due to limited computational resources. A method was proposed to slim down the number of options without sacrificing the shape of the technology response. This method uses the *maxmin* algorithm to select a subset of points, out of the Pareto optimal, that represent the front, covering it completely, and at the same time being different from existing aircraft. Once these aircraft are chosen, they need to be entered into the database of the fleet analysis tools, so that they can be used for stringency scenario studies. A process was created to determine what the entries into the database need to be, depending on the performance characteristics of the particular aircraft. This process requires a set of parameters that define the aircraft's performance, and different takeoff and landing procedures to be accomplished. The process was proven to propagate the characteristics of the aircraft to the fleet analysis tool. This connectivity, joined with the linkage between the physical characteristics of the aircraft and engine with the environmental measures, makes the process herein proposed an improvement over the actual technology response procedure used in the current policy making process.

Answering the research questions posed at the beginning of this document was said to be one of the main objectives of the research work herein shown. The first set of questions were those pertaining to the observation of the lack of physical relations between the key measures, due to the proprietary nature of the data that individual companies would have to provide. The answer to these questions was shown to be the utilization of a physics based modeling and simulation environment to link the fundamental characteristics of the aircraft and engine to the environmental metrics. This linkage ensures that the data provided by this environment can be vetted and validated.

The second and third set of questions dealt with the current technology response used by CAEP for their policy scenario analyses. A better alternative was shown, with the creation of a process to calculate a new technology response, individual to a class of vehicles, that not only showed that the constant fuel burn penalty was inappropriate, but it provided the tradeoffs between the three. The fourth question was answered with the creation of the process to populate an entry into the databases that are used for CAEP's policy scenario analyses, to represent a particular aircraft/engine combination.

Based on the results shown in the previous chapter, there are different conclusions that can be reached. First, the interdependencies between noise, NOx emissions, and fuel burn need to be addressed concurrently. It was also proven that a physics based environment, when properly integrated, can provide information about those interdependencies, and their linkage to fundamental aircraft and engine characteristics. And this linkage can be used to create a technology response that would determine the feasible limits for a given technology level. This technology response would provide policy makers with more transparent information that would in turn help them understand the physics behind the tradeoffs that exist between noise, NOx, and fuel burn.

Based on the time and resources available for this research work, not all the desired goals were reached. One of the first aspects that should be addressed to continue this work is the expansion of the aircraft classes to include more of the existing vehicles. At the same time, the ability to explore new technologies, at different stages of development, can result in improved vision of feasible limits. This could prove beneficial in setting policy that needs to be implemented in the medium term future. The new technologies need not be reduced to individual aspects of the aircraft and engine, such as the use of composites or a new combustor, but new overall airframes and engines, such as blended-wing bodies, or geared fans, or even electric propulsion. Another area that would need to be expanded is a process to determine the Pareto optimal points utilizing some form of optimizer, so that computational resources are better utilized. The actual process of finding the Pareto optimal points through the use of a space filling design of experiments has the potential to not find the actual limits. Since there is a level of randomness in the creation of the DoE, for cases where the number of variables is large, the potential exists to ignore areas of the space where Pareto points could exist. A possible solution is the linkage of an optimizer to the Pareto algorithm, so that the optimizer would perform a structured search of the space for the Pareto optimal points. This has been addressed by the Multi-Objective Genetic Algorithms (MOGA). One key aspect that is missing from the current formulation is the economic one. The cost of production of the aircraft, as well as the utilization cost of the aircraft by the airlines, should be addressed by the policy makers when considering new policy. The ability to produce an estimate of these costs should be included in future developments.

Ultimately, the proposed process for the quantification of the interdependencies between noise, NOx, and fuel burn, provides a vast improvement over current practices. The proposed technology response has a direct link to the physical attributes of the aircraft and engine, while providing a global vision of the tradeoffs between the environmental key measures. In addition, the process delineated to populate the databases that are used for global fleet studies helps promote consistency in the databases. This uniformity in the process allows the communication of the data to be more open, without risking the proprietary nature of the real data. At the same time, the union of the database population process and the new technology response creation allows for the propagation of the tradeoffs between noise and emissions at the aircraft level to the fleet level, thus providing policy makers with a truer representation of the capabilities of the current state of the art.

APPENDIX A. ALGORITHM TO OBTAIN PARETO OPTIMAL POINTS

The algorithm developed to identify the Pareto optimal points was based on the definition of Pareto optimality; that is points for which there cannot be further improvement in any direction without deteriorating any of the other areas. The data points were positioned on a spreadsheet in column form, in which each row represented a different point in a multidimensional space. Each column was then the value of that point in each of the areas of interest, which included the input values. The algorithm starts by determining whether the column is to be used or not, and whether its value is to be maximized or minimized. Then, it moves the columns to be used to a new temporary worksheet and the actual algorithm starts. It moves point by point and compares it to the rest of them, and determines whether it is dominated, that is, if any improvement can be made in any response without hurting some other, and at the end, it assigns a value of 1 to the non-dominated and 0 to the dominated. Figure 80, shows the flow diagram of this algorithm.

<u>Main Algorithm</u>

```
Sub pareto_calculator()
Dim i, j, k, metrics, cases, m, domined(10000), tmp
metrics = Worksheets("chars").Cells(4, 3).Value
cases = Worksheets("chars").Cells(5, 3).Value
For i = 1 To cases
    domined(i) = 1
    Next i
k = 0
For i = 1 To metrics
    If (Worksheets("chars").Cells(2, i).Value = 0) Then GoTo break1
k = k + 1
    For j = 1 To cases
        Worksheets("tmp").Cells(j, k).Value = Worksheets("Input").Cells(j + 1, i).Value *
Worksheets("chars").Cells(2, i).Value
        Next j
```

```
break1:
    Next i
m = Worksheets("chars").Cells(6, 3).Value
For i = 1 To cases - 1
    For j = 1 + 1 To cases
        a = 0
        b = 0
        For k = 1 To m
            If Worksheets("tmp").Cells(i, k).Value <= Worksheets("tmp").Cells(j, k).Value
Then
                a = a + 1
                End If
            If Worksheets("tmp").Cells(i, k).Value < Worksheets("tmp").Cells(j, k).Value
Then
                b = b + 1
                End If
            Next k
        c = 0
        d = 0
        For k = 1 To m
            If Worksheets("tmp").Cells(i, k).Value >= Worksheets("tmp").Cells(j, k).Value
Then
                c = c + 1
                End If
            If Worksheets("tmp").Cells(i, k).Value > Worksheets("tmp").Cells(j, k).Value
Then
                d = d + 1
                End If
            Next k
        If (a >= m) Then
        If (b > 0) Then
            domined(i) = 0
            GoTo break2
        End If
        End If
        If (c >= m) Then
        If (d > 0) Then
            domined(j) = 0
        End If
        End If
        Next j
break2:
    Next i
Worksheets("PF").Cells(1, 1).Value = Worksheets("Input").Cells(1, 1).Value
Worksheets("PF").Cells(1, 2).Value = "Pareto"
For i = 1 To cases
    Worksheets("PF").Cells(i + 1, 1).Value = Worksheets("Input").Cells(i + 1, 1).Value
    Worksheets("PF").Cells(i + 1, 2).Value = domined(i)
    Next i
End Sub
```

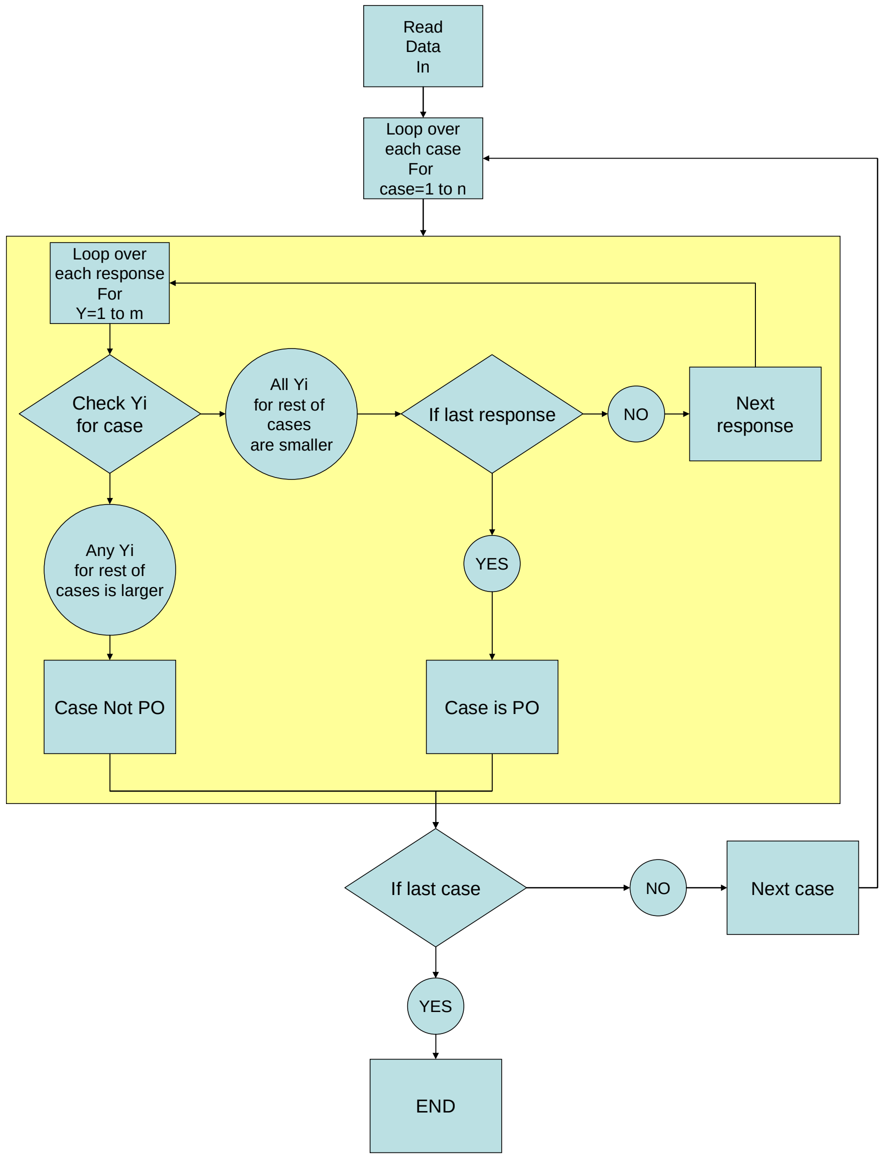

Figure 80: Pareto Calculator Flow Diagram

APPENDIX B. ALGORITHM TO RANK ALTERNATIVES BASED ON MAXIMIZATION OF MINIMUM DISTANCE

This algorithm ranks a series of alternatives depending on the euclidean distance they have in the multi-dimensional space created with the existing already chosen alternatives. The first step is to calculate the distances of each point to the existing elements in the pool of already chosen cases. Each point has to be represented by one parameter, and that is the distance that exists between that point and the closest of the already chosen points. Those distances are compared from all the alternatives, and the largest is chosen to join the pool. The process is then repeated, but the point chosen is no longer used as an alternative, but as a member of the existing pool. This can be done for any number of points to be selected, or for all of them, if the overall ranking needs to be found.

Main Algorithm

```
Sub get_the_points()
existing_ac = Worksheets("Data").Cells(4, 11).Value
new_ac = Worksheets("Data").Cells(3, 11).Value
km = Worksheets("Data").Cells(5, 11).Value
n = Worksheets("Data").Cells(6, 11).Value
ReDim pos(new_ac, km), ex_ac(existing_ac, km), chosen(existing_ac + n, km), distance(new_ac, new_ac + existing_ac), min_distance(new_ac, 2), order(new_ac)

'Import the data
'Existing Aircraft
For i = 1 To existing_ac
    For j = 1 To km
        ex_ac(i, j) = Worksheets("Data").Cells(8 + i, 15 + j).Value
        chosen(i, j) = ex_ac(i, j)
    Next j
Next i

'New Aircraft
For i = 1 To new_ac
    For j = 1 To km
        pos(i, j) = Worksheets("Data").Cells(8 + i, 10 + j).Value
    Next j
```

```
Next i

'Start Main Loop
For i = 1 To n
'Calculate distance of each of the new aircraft to aircraft in the chosen fleet
    For j = 1 To new_ac
    min_distance(j, 1) = 1000
        For k = 1 To existing_ac + i - 1
            distance(j, k) = 0
            For l = 1 To km
                distance(j, k) = distance(j, k) + (pos(j, l) - chosen(k, l)) ^ 2
            Next l
            distance(j, k) = (distance(j, k)) ^ 0.5
        If min_distance(j, 1) > distance(j, k) Then
            min_distance(j, 1) = distance(j, k)
            min_distance(j, 2) = k
        End If
        Next k
    Next j

'Find largest minimum distance
max_dist = 0
    For j = 1 To new_ac
        If max_dist < min_distance(j, 1) Then
            max_dist = min_distance(j, 1)
            chos = j
        End If
    Next j

'Add aircraft to chosen pool and Export Results back to Spreadsheet
    chosen(existing_ac + i, 0) = chos
    Worksheets("Data").Cells(1 + i, 1).Value = chos
    For k = 1 To km
        chosen(existing_ac + i, k) = pos(chos, k)
        Worksheets("Data").Cells(1 + i, 1 + k).Value = pos(chos, k)
    Next k
Next i
End Sub
```

APPENDIX C. INPUTS TO ENVIRONMENT

Table 25: Inputs to the Environment

DoE Variable	Description	Units	300 Pax (B777 200ER w/ GE90 94B)	300 Pax 2 (B777 200ER w/ PW4090)
ADP_Alt	Aero Design Point altitude	ft	35000	35000
ADP_MN	Aero Design Point Mach number		0.8	0.8
AITEK	Aerodynamic Efficiency Factor		1.95	1.9
Bld3_LH	Bleed 3 length	in	7.04	4.80
BurnerTime	Burner residence time	sec	0.009	0.0095
BurnerV	Burner velocity	ft/sec	75	75
BypBld_A_Out	Bypass Bleed outlet/inlet area ratio		1	1
Core_Nozz_LDratio	Core nozzle length to diameter ratio		0.27	0.27
Cust_Bleed	Customer Bleed		3.93	3.805
d_Burn_dP	Burner pressure drop		0.0399	0.0579
d_Burn_eff	Burner efficiency		0.997	0.997
D_Bypass_A_Out	Bypass Duct outlet/inlet area ratio		1	1
D_Bypass_dP	Bypass Duct pressure drop		0.018	0.015
D_HPT_LPT_dP	HPT to LPT duct pressure drop		0.0095	0.0121
D_HPT_LPT_LH	HPT to LPT duct length to heigth ratio		2.9685	0.7500
D_LPC_HPC_dP	LPC to HPC duct pressure drop		0.008299	0.008709
D_LPC_HPC_LH	LPC to HPC duct length to heigth ratio		2.8221	4.9000
D_LPT_Nozz_A_Ou	LPT to Core Nozzle Duct outlet/inlet area ratio		0.95	0.95
D_LPT_Nozz_dP	LPT to Core Nozzle duct pressure drop		0.007858	0.007807
D_LPT_Nozz_LH	LPT to Core Nozzle duct length to heigth ratio		0.216	0.05
D_Split_C_dP	Splitter pressure drop		0.0102	0.006504
D_Split_C_LH	Splitter length to heigth ratio		0.07821054	0.07
Ext_Ratio	Extraction ratio at Aero Design Point		1.08197719	1.1565
Fan_AR_Fact	Aspect ratio factor applied to fan blades and		1	1
Fan_Deff	Fan efficiency delta at Aero Design Point		-0.003179	-0.004375
Fan_Duct	Length of duct from rear fan blade to splitter	%	0.4155	0.2

DoE Variable	Description	Units	300 Pax (B777 200ER w/ GE90 94B)	300 Pax 2 (B777 200ER w/ PW4090)
Fan_Dutip	Fan tip speed delta at Aero Design Point	ft/sec	35.57	186.67
Fan_HtoT	Fan hub to tip ratio		0.3	0.337
Fan_OutIn_RR	Fan outlet radius to inlet radius ratio		1	1
Fan_SM	Fan stall margin at Aero Design Point	%	27.92	25.74
Fan_SpecW	Fan specific flow at Aero Design Point	lbs/ft2	42.75	44.76
FCDI	Induced Drag Factor		1.182	0.850
FCDO	Profile Drag Factor		0.804	0.855
Flat_dTs	Flat rated thrust temperature	oF	27	27
FPR	FPR at Aero Design Point		1.58	1.67288
HPC_A_Out	HPC outlet/inlet area ratio		0.1083	0.1888
HPC_AR_Fact	Aspect ratio factor applied to HPC blades and		1	1
HPC_Deff	HPC efficiency delta at Aero Design Point		0.016631	-0.0059
HPC_Dutip	HPC tip speed delta at Aero Design Point		-64.32	200.33
HPC_FSPRmax	Maximum HPC 1st stage PR		1.582	1.478
HPC_HtoT	HPC hub to tip ratio		0.477	0.69
HPC_NcDes	HPC corrected speed at Aero Design Point	%	0.966216	0.955263
HPC_SM	HPC stall margin at Aero Design Point	%	17.60	16.70
HPC_SolidityFact	Solidity factor applied to HPC blades and		0.944	1
HPC_SpecW	HPC specific flow at Aero Design Point		31.3692	34.9947
HPCPR	HPCPR at Aero Design Point		20.03	11.96
HPT_AR_Fact	Aspect ratio factor applied to fan blades and		1	1
HPT_ChargeEff	HPT chargeable cooling factor		0.40954	0.989
HPT_eff	HPT polytropic efficiency at Aero Design		0.925	0.891
HPT_FlowCoeff	HPT Flow Coefficient		1.1157	1.004
HPT_Load	HPT Loading		0.93	0.97
HPT_Mn_out	HPT Exhaust Mach Number		0.3079	0.3866
HPT_NonChargeEff	HPT non-chargeable cooling factor		1.8651	1.1867
HPT_OutIn_RR	HPT outlet radius to inlet radius ratio		0.98	0.98
HPT_SolidityFact	Solidity factor applied to HPT blades and		0.98	1

DoE Variable	Description	Units	300 Pax (B777 200ER w/ GE90 94B)	300 Pax 2 (B777 200ER w/ PW4090)
HPX	Horsepower Extraction	HP	250	250
k_CdBypNozz	Bypass Nozzle Flow Coefficient		1.210	1.511
k_CdCoreNozz	Core Nozzle Flow Coefficient		1.225	1.977
LPC_A_Out	LPC outlet area	ft2	0.746	0.583
LPC_AR_Fact	Aspect Ratio factor applied to LPT blades and		1	1
LPC_Deff	LPC efficiency delta at Aero Design Point		0.017691	0.01238
LPC_FSPRmax	Maximum LPC 1st stage PR		1.12	1.16
LPC_HtoT	LPC hub to tip ratio		0.805	0.745
LPC_OutIn_RR	LPC outlet radius to inlet radius ratio		0.82	1.0438
LPC_SM	LPC stall margin at Aero Design Point	%	33.302	16.925
LPC_SolidityFact	Solidity factor applied to LPC blades and		1	1
LPC_SpecW	LPC specific flow at Aero Design Point		26.307	25.852
LPCPR	LPCPR at Aero Design Point		1.2603	1.352726
LPT_AR_Fact	Aspect ratio factor applied to LPT blades and		1	1
LPT_ChargeEff	LPT chargeable cooling factor		0.8838	1.362
LPT_eff	LPT polytropic efficiency at Aero Design Point		0.938	0.897
LPT_FlowCoeff	LPT Flow Coefficient		5.448	7.1
LPT_Load	LPT Loading		1.7	1.28
LPT_Mn_out	LPT Exhaust Mach Number		0.2977	0.403
LPT_NonChargeEff	LPT non-chargeable cooling factor		1.43	2.256
LPT_OutIn_RR	LPT outlet radius to inlet radius ratio		0.8	1.064
LPT_SolidityFact	Solidity factor applied to LPT blades and		0.944	1
PCT_NOx	Percentage NOx for combustor swap	%	1001	0
Plug_LDratio	Plug length to diameter ratio		4	4
RE1	Design Reynolds number for fan and LPC		388966.66	383114
RE2	Design Reynolds number for HPC		311925.98	420692
T4max	Maximum T4 (set at Takeoff)	oR	3450	3332
TCHT	Thickness-chord ratio for the horizontal tail		0.0890	0.0938
TCVT	Thickness-chord ratio for the vertical tail		0.0923	0.0986

DoE Variable	Description	Units	300 Pax (B777 200ER w/ GE90 94B)	300 Pax 2 (B777 200ER w/ PW4090)
TO_Alt	Takeoff altitude	ft	0	0
TO_MN	Takeoff Mach number		0.25	0.25
TO_Thrust	Takeoff thrust target	lbs	78400	23351.5
TOC_Alt	Top of Climb Altitude	ft	35000	35000
TOC_MN	Top of Climb Mach number		0.85	0.8
TOC_Thrust	Top of Climb thrust target	lbs	19600	5250
TOC_Wratio	Mass flow ratio of Top of climb to Aero		1.0356	1.0240
TOC1	Wing Thickness to chord (1)		0.1239	0.1434
TOC2	Wing Thickness to chord (2)		0.1040	0.1113
TOC3	Wing Thickness to chord (3)		0.083256	0.081635

APPENDIX D. PARETO AIRCRAFT FOR 300 PASSENGER EXAMPLE

Table 26: Pareto Aircraft for 300 Passenger Example

Aircraft Number	Extraction Ratio	FPR	HPCPR	LPCPR	TOC Thrust	TOC Wflow ratio	TO Thrust	% Fuel Increase	% NOx Above CAEP/6	Cumulative Noise Increase
Baseline	1.0819771	1.58	20.03255	1.2603	19600	1.035	78400	0	1.58	0
1	1.010	1.550	15.500	1.850	22000.0	1.020	78000.0	0.47	-6.12	-3.97
2	1.055	1.550	9.000	2.500	20000.0	1.020	78000.0	3.85	-11.79	-3.91
3	1.055	1.550	9.000	2.500	22000.0	1.020	82000.0	6.66	-12.82	-5.58
4	1.055	1.550	15.500	1.850	22000.0	1.020	80000.0	0.62	-5.08	-4.61
5	1.055	1.550	22.000	1.200	20000.0	1.020	80000.0	-0.58	-1.73	-1.25
6	1.100	1.550	9.000	2.500	18000.0	1.020	78000.0	1.78	-9.67	-2.61
7	1.100	1.550	9.000	2.500	18000.0	1.020	80000.0	2.21	-9.29	-2.62
8	1.100	1.550	9.000	2.500	18000.0	1.020	82000.0	2.67	-8.90	-2.79
9	1.100	1.550	9.000	2.500	20000.0	1.020	78000.0	3.98	-12.47	-4.36
10	1.100	1.550	9.000	2.500	20000.0	1.020	80000.0	3.92	-11.74	-4.60
11	1.100	1.550	9.000	2.500	20000.0	1.020	82000.0	4.19	-10.84	-4.81
12	1.100	1.550	9.000	2.500	22000.0	1.020	78000.0	6.00	-14.38	-5.30
13	1.100	1.550	9.000	2.500	22000.0	1.020	80000.0	6.26	-14.01	-5.55
14	1.100	1.550	9.000	2.500	22000.0	1.050	78000.0	2.96	-10.78	-3.75
15	1.100	1.550	15.500	1.200	18000.0	1.020	78000.0	3.01	-11.93	0.81
16	1.100	1.550	15.500	1.200	18000.0	1.020	80000.0	3.35	-11.60	0.59
17	1.100	1.550	15.500	1.200	18000.0	1.020	82000.0	3.29	-11.24	0.43
18	1.100	1.550	15.500	1.200	20000.0	1.020	78000.0	5.08	-14.64	-0.49
19	1.100	1.550	15.500	1.200	20000.0	1.020	80000.0	5.33	-13.93	-0.77
20	1.100	1.550	15.500	1.200	20000.0	1.020	82000.0	5.63	-13.14	-1.08
21	1.100	1.550	15.500	1.200	20000.0	1.050	78000.0	2.77	-11.40	1.50
22	1.100	1.550	15.500	1.200	20000.0	1.050	80000.0	2.72	-11.00	1.36
23	1.100	1.550	15.500	1.200	22000.0	1.020	78000.0	7.59	-16.49	-1.33
24	1.100	1.550	15.500	1.200	22000.0	1.020	80000.0	7.83	-16.10	-1.63
25	1.100	1.550	15.500	1.200	22000.0	1.020	82000.0	8.10	-15.68	-1.98

Aircraft Number	Extraction Ratio	FPR	HPCPR	LPCPR	TOC Thrust	TOC Wflow ratio	TO Thrust	% Fuel Increase	% NOx Above CAEP/6	Cumulative Noise Increase
26	1.100	1.550	15.500	1.200	22000.0	1.050	78000.0	4.41	-13.18	-0.03
27	1.100	1.550	15.500	1.200	22000.0	1.080	78000.0	2.31	-10.61	2.84
28	1.100	1.550	15.500	1.850	20000.0	1.020	78000.0	-1.36	-0.08	-3.90
29	1.100	1.550	15.500	1.850	22000.0	1.020	78000.0	0.55	-7.60	-4.48
30	1.100	1.550	15.500	1.850	22000.0	1.020	80000.0	0.88	-5.84	-4.84
31	1.100	1.550	15.500	1.850	22000.0	1.020	82000.0	0.85	-3.89	-5.19
32	1.100	1.550	22.000	1.200	20000.0	1.020	78000.0	-0.76	-4.46	-1.04
33	1.100	1.550	22.000	1.200	20000.0	1.020	80000.0	-0.41	-2.61	-1.46
34	1.100	1.550	22.000	1.200	20000.0	1.020	82000.0	-0.44	-0.66	-1.88
35	1.100	1.550	22.000	1.200	22000.0	1.020	78000.0	1.27	-9.90	-1.70
36	1.100	1.550	22.000	1.200	22000.0	1.020	80000.0	1.58	-8.68	-2.10
37	1.027	1.551	12.367	1.671	20383.1	1.044	80291.9	2.51	-10.20	0.04
38	1.069	1.556	13.369	1.589	21762.8	1.038	81917.2	3.34	-11.49	-2.19
39	1.050	1.559	14.565	1.626	21252.3	1.039	78058.4	0.70	-8.63	-2.02
40	1.051	1.581	17.361	1.398	20965.6	1.030	78609.3	0.53	-6.32	-0.77
41	1.083	1.570	17.260	1.523	21101.8	1.022	79379.2	0.30	-5.79	-2.54
42	1.087	1.560	13.921	1.646	20187.4	1.052	79010.9	-0.17	-6.84	-0.07
43	1.092	1.555	11.216	1.936	20167.9	1.055	78140.7	1.04	-9.46	-0.31
44	1.022	1.555	13.432	1.557	20840.5	1.048	78025.1	2.28	-10.22	0.16
45	1.066	1.550	20.679	1.283	21131.7	1.037	78992.0	-1.10	-0.77	-1.79
46	1.065	1.574	18.943	1.308	20622.2	1.042	78915.7	-0.97	-0.92	0.07
47	1.079	1.583	15.008	1.382	21136.8	1.026	79719.2	3.42	-12.04	-0.37
48	1.087	1.574	12.612	1.506	21257.4	1.025	78748.3	5.81	-13.71	-1.83
49	1.078	1.564	9.999	2.398	20355.1	1.027	78791.7	2.13	-8.77	-3.16
50	1.085	1.556	12.998	1.923	18591.5	1.032	80810.0	-0.40	-2.38	-1.59
51	1.073	1.573	13.948	1.794	19549.8	1.048	78739.9	-1.26	-0.20	0.24
52	1.076	1.575	14.504	1.717	20139.5	1.040	79818.0	-0.50	-1.76	-1.14
53	1.084	1.586	12.399	1.931	18693.4	1.022	78506.4	0.05	-4.51	-0.93
54	1.022	1.576	15.325	1.843	21877.7	1.022	79056.1	0.22	-3.00	-3.51
55	1.092	1.563	11.744	2.109	18448.6	1.033	78469.3	-0.50	-3.10	-1.35

APPENDIX E. DATABASE ENTRIES OF CHOSEN PARETO AIRCRAFT

AIRCOMBO

```
EQUIP_ID,ENG_ID,ACFT_ID,HELO_ID,ENG_MOD_ID,UID
,,pax300-1,,16,97k-1
,,pax300-2,,16,98k-2
,,pax300-3,,16,105k-3
,,pax300-4,,16,106k-4
,,pax300-5,,16,88k-5
,,pax300-6,,16,101k-6
,,pax300-7,,16,101k-7
```

AIRCRAFT

```
ACFT_ID,ACFT_DESCR,WGT_CAT,OWNER_CAT,ENG_TYPE,NOISE_CAT,NOISE_ID,NUMB_ENG,THR_RESTOR,MX_G
W_TKO,MX_GW_LND,MX_DS_STOP,COEFF_TYPE,THR_STATIC
pax300-1,pax300-97k,H,C,J,3,EDS-97-1,2,N,654173,460000,5355.06,J,97301.4
pax300-2,pax300-98k,H,C,J,3,EDS-98-2,2,N,659978,460000,5354.99,J,98835.2
pax300-3,pax300-105k,H,C,J,3,EDS-105-3,2,N,701891,460000,5354.66,J,105166
pax300-4,pax300-106k,H,C,J,3,EDS-106-4,2,N,705643,460000,5354.77,J,106134
pax300-5,pax300-88k,H,C,J,3,EDS-88-5,2,N,667687,460000,5355.14,J,88636.8
pax300-6,pax300-101k,H,C,J,3,EDS-101-6,2,N,659770,460000,5354.86,J,101353
pax300-7,pax300-101k,H,C,J,3,EDS-101-7,2,N,675428,460000,5354.71,J,101707
```

BADA_ACFT

```
BADA_ID,NUM_ENG,ENG_TYPE,WAKE_CAT,MANUF_DESC,MASS_REF,MASS_MIN,MASS_MAX,MASS_PAYLD,MASS_G
RAD,FENV_VMO,FENV_MMO,FENV_ALT,FENV_HMAX,FENV_TEMP,WING_AREA,COEFF_CLBO,BUFF_GRAD,COEFF_C
M16
Z1,2,J,H,EDS,222.657,137.611,296.726,56.9255,0,350,0.871,43000,43000,0,427.804,0,0,0
Z2,2,J,H,EDS,224.444,139.516,299.359,56.9255,0,350,0.871,43000,43000,0,427.804,0,0,0
Z3,2,J,H,EDS,232.649,146.342,318.371,56.9255,0,350,0.871,43000,43000,0,427.804,0,0,0
Z4,2,J,H,EDS,232.867,146.375,320.073,56.9255,0,350,0.871,43000,43000,0,427.804,0,0,0
Z5,2,J,H,EDS,224.626,138.027,302.856,56.9255,0,350,0.871,43000,43000,0,427.804,0,0,0
Z6,2,J,H,EDS,224.606,140.01,299.265,56.9255,0,350,0.871,43000,43000,0,427.804,0,0,0
Z7,2,J,H,EDS,228.447,143.607,306.367,56.9255,0,350,0.871,43000,43000,0,427.804,0,0,0
```

BADA_APF

```
BADA_ID,CO_CODE_1,CO_CODE_2,CO_NAME,AC_VERSION,ENGINE,MASS_RANGE,CL_CAS_1,CL_CAS_2,CL_MAC
H,CR_CAS_1,CR_CAS_2,CR_MACH,DE_MACH,DE_CAS_2,DE_CAS_1
Z1,***,**,Default-Company,1,EDS-
97k,LO,332.63,359.936,0.84,332.63,359.936,0.84,0.84,332.652,263.291
Z1,***,**,Default-Company,1,EDS-
97k,AV,332.63,359.936,0.84,332.63,359.936,0.84,0.84,332.652,263.291
Z1,***,**,Default-Company,1,EDS-
97k,HI,332.63,359.936,0.84,332.63,359.936,0.84,0.84,332.652,263.291
```

```
Z2,***,**,Default-Company,2,EDS-
98k,LO,332.63,359.936,0.84,332.63,359.936,0.84,0.84,333.895,264.255
Z2,***,**,Default-Company,2,EDS-
98k,AV,332.63,359.936,0.84,332.63,359.936,0.84,0.84,333.895,264.255
Z2,***,**,Default-Company,2,EDS-
98k,HI,332.63,359.936,0.84,332.63,359.936,0.84,0.84,333.895,264.255
Z3,***,**,Default-Company,3,EDS-
105k,LO,332.63,359.936,0.84,332.63,359.936,0.84,0.84,337.493,268.006
Z3,***,**,Default-Company,3,EDS-
105k,AV,332.63,359.936,0.84,332.63,359.936,0.84,0.84,337.493,268.006
Z3,***,**,Default-Company,3,EDS-
105k,HI,332.63,359.936,0.84,332.63,359.936,0.84,0.84,337.493,268.006
Z4,***,**,Default-Company,4,EDS-
106k,LO,332.63,359.936,0.84,332.63,359.936,0.84,0.84,338.21,268.584
Z4,***,**,Default-Company,4,EDS-
106k,AV,332.63,359.936,0.84,332.63,359.936,0.84,0.84,338.21,268.584
Z4,***,**,Default-Company,4,EDS-
106k,HI,332.63,359.936,0.84,332.63,359.936,0.84,0.84,338.21,268.584
Z5,***,**,Default-Company,5,EDS-
88k,LO,332.63,359.936,0.84,332.63,359.936,0.84,0.84,333.78,263.874
Z5,***,**,Default-Company,5,EDS-
88k,AV,332.63,359.936,0.84,332.63,359.936,0.84,0.84,333.78,263.874
Z5,***,**,Default-Company,5,EDS-
88k,HI,332.63,359.936,0.84,332.63,359.936,0.84,0.84,333.78,263.874
Z6,***,**,Default-Company,6,EDS-
101k,LO,332.63,359.936,0.84,332.63,359.936,0.84,0.84,333.266,263.871
Z6,***,**,Default-Company,6,EDS-
101k,AV,332.63,359.936,0.84,332.63,359.936,0.84,0.84,333.266,263.871
Z6,***,**,Default-Company,6,EDS-
101k,HI,332.63,359.936,0.84,332.63,359.936,0.84,0.84,333.266,263.871
Z7,***,**,Default-Company,7,EDS-
101k,LO,332.63,359.936,0.84,332.63,359.936,0.84,0.84,335.338,266.085
Z7,***,**,Default-Company,7,EDS-
101k,AV,332.63,359.936,0.84,332.63,359.936,0.84,0.84,335.338,266.085
Z7,***,**,Default-Company,7,EDS-
101k,HI,332.63,359.936,0.84,332.63,359.936,0.84,0.84,335.338,266.085
```

BADA_CONFIG

```
BADA_ID,PHASE,NAME,VSTALL,COEFF_CD0,COEFF_CD2
Z1,CR,N/A,166.544,0.0119782,0.0592831
Z1,TO,N/A,144.97,0.0408948,0.0430555
Z1,IC,N/A,166.549,0.0595733,0.0592831
Z1,AP,N/A,130.084,0.0463962,0.0592831
Z1,LD,N/A,97.56,0.0861868,0.0436541
Z2,CR,N/A,166.62,0.0120411,0.0593733
Z2,TO,N/A,144.97,0.0409948,0.0430555
Z2,IC,N/A,166.625,0.0612442,0.0593733
Z2,AP,N/A,130.271,0.0462363,0.0593733
Z2,LD,N/A,97.56,0.0862868,0.0436541
Z3,CR,N/A,168.746,0.0123987,0.0593172
Z3,TO,N/A,144.97,0.041504,0.0430237
Z3,IC,N/A,168.752,0.0753193,0.0593172
Z3,AP,N/A,130.69,0.046918,0.0593172
```

```
Z3,LD,N/A,97.56,0.0867847,0.0436595
Z4,CR,N/A,169.093,0.0122865,0.0593024
Z4,TO,N/A,144.97,0.0412933,0.0430611
Z4,IC,N/A,169.099,0.076358,0.0593024
Z4,AP,N/A,130.778,0.0467606,0.0593024
Z4,LD,N/A,97.56,0.0865847,0.0436595
Z5,CR,N/A,167.497,0.0118967,0.0593305
Z5,TO,N/A,144.98,0.0407948,0.0430555
Z5,IC,N/A,167.503,0.0636167,0.0593305
Z5,AP,N/A,129.83,0.0461597,0.0593305
Z5,LD,N/A,97.56,0.0860868,0.0436541
Z6,CR,N/A,166.57,0.012186,0.0593033
Z6,TO,N/A,144.98,0.0411948,0.0430555
Z6,IC,N/A,166.575,0.0614809,0.0593033
Z6,AP,N/A,130.358,0.046638,0.0593033
Z6,LD,N/A,97.56,0.0864847,0.0436595
Z7,CR,N/A,167.105,0.0123451,0.0593588
Z7,TO,N/A,144.97,0.0413933,0.0430611
Z7,IC,N/A,167.11,0.0663857,0.0593588
Z7,AP,N/A,130.637,0.0466982,0.0593588
Z7,LD,N/A,97.56,0.0866847,0.0436595
```

BADA_FUEL

```
BADA_ID,COEFF_CF1,COEFF_CF2,COEFF_CF3,COEFF_CF4,COEFF_CFCR
Z1,0.465792,421.468,45.5404,86232.4,0.946009
Z2,0.452734,407.595,45.8428,87549,0.949423
Z3,0.462745,424.401,48.7912,99519.8,0.974472
Z4,0.468957,423.505,53.2288,92250.6,0.970808
Z5,0.49282,401.629,46.5232,89233,0.900038
Z6,0.44225,417.903,44.8752,94095.1,0.976593
Z7,0.432536,405.038,46.7047,101789,0.98123
```

BADA_THRUST

```
BADA_ID,COEFF_TC1,COEFF_TC2,COEFF_TC3,COEFF_TC4,COEFF_TC5,COEFF_TDL,COEFF_TDH,DES_ALT,COE
FF_TAPP,COEFF_TLD,DESC_CAS,DESC_MACH
Z1,669530,28240.7,3.88E-10,0,0.00390094,0.07,0.07,15000,0.09,0.4,310,0.84
Z2,668658,28206.6,3.90E-10,0,0.0040575,0.07,0.07,15000,0.09,0.4,310,0.84
Z3,688524,33858.5,2.51E-10,0,0.00452955,0.07,0.07,15000,0.09,0.4,310,0.84
Z4,697420,32858.6,2.72E-10,0,0.00409069,0.07,0.07,15000,0.09,0.4,310,0.84
Z5,667150,30144.9,3.48E-10,0,0.00273006,0.07,0.07,15000,0.09,0.4,310,0.84
Z6,661941,29965.5,3.41E-10,0,0.00445353,0.07,0.07,15000,0.09,0.4,310,0.84
Z7,662413,37530.6,1.82E-10,0,0.00460616,0.07,0.07,15000,0.09,0.4,310,0.84
```

ENG_EMIS

```
ENGINE,UID,COMBUSTOR,RATED_OUT,MANUFACT,TEST_FROM,TEST_TO,UA_RWF_TO,UA_RWF_CO,UA_RWF_AP,U
A_RWF_ID,RWF_TO,RWF_CO,RWF_AP,RWF_ID,CO_REI_TO,CO_REI_CO,CO_REI_AP,CO_REI_ID,HC_REI_TO,HC
_REI_CO,HC_REI_AP,HC_REI_ID,NOX_REI_TO,NOX_REI_CO,NOX_REI_AP,NOX_REI_ID,SN_TO,SN_CO,SN_AP
,SN_ID,OUT_OF_SER,SOURCE,BYPASS_RATIO,PRESSURE_RATIO,NOTES,TFMTF
```

```
EDS-97k,97k-1,EDS-1,432.818,EDS,,
,3.48994,2.85039,0.912934,0.274,3.52483,2.88745,0.931192,0.3014,0,0,0,0,0,0,0,0,56.696,41
.539,17.151,6.211,0.499,0.499,0.499,0.499,F,EDS,8.7877,39.156,,TF
EDS-98k,98k-2,EDS-2,439.641,EDS,,
,3.46565,2.84297,0.912733,0.273752,3.50031,2.87993,0.930988,0.301127,0,0,0,0,0,0,0,0,54.5
15,40.508,16.984,6.101,0.499,0.499,0.499,0.499,F,EDS,9.4826,38.412,,TF
EDS-105k,105k-3,EDS-3,467.804,EDS,,
,3.69807,3.06946,0.977794,0.270421,3.73505,3.10936,0.997349,0.297463,0,0,0,0,0,0,0,0,34.7
02,28.275,12.079,5.026,0.499,0.499,0.499,0.499,F,EDS,10.0942,34.233,,TF
EDS-106k,106k-4,EDS-4,472.108,EDS,,
,3.78662,3.13511,1.01083,0.310179,3.82449,3.17587,1.03104,0.341197,0,0,0,0,0,0,0,0,26.632
,23.239,10.74,4.488,0.499,0.499,0.499,0.499,F,EDS,10.9088,28.299,,TF
EDS-88k,88k-5,EDS-5,394.276,EDS,,
,3.27865,2.69256,0.87224,0.271687,3.31143,2.72756,0.889685,0.298856,0,0,0,0,0,0,0,0,30.38
8,25.528,12.282,4.473,0.499,0.499,0.499,0.499,F,EDS,8.566,28.299,,TF
EDS-101k,101k-6,EDS-6,450.839,EDS,,
,3.4264,2.83316,0.905177,0.257927,3.46066,2.86999,0.923281,0.283719,0,0,0,0,0,0,0,0,63.32
3,46.331,17.41,5.651,0.499,0.499,0.499,0.499,F,EDS,9.9518,43.628,,TF
EDS-101k,101k-7,EDS-7,452.413,EDS,,
,3.36205,2.79885,0.893527,0.260327,3.39567,2.83524,0.911398,0.28636,0,0,0,0,0,0,0,0,52.22
6,39.877,16.275,5.216,0.499,0.499,0.499,0.499,F,EDS,10.7427,43.628,,TF
```

EQUIPMNT

```
ACCODE,ENG_MOD_ID,AC_NAME,SIZE_CODE,DESIG_CODE,USAGE_CODE,HELICOPTER_FLAG,AIR_TAXI_FLAG,E
URO_GRP_CODE,NUM_ENGS,ENG_LOC_CODE,MAX_RANGE,INTRO_YEAR,ENG_TYPE_CODE,BADA_ID
pax300-1,,EDS-pax300-1,H,C,P,0,0,JL,2,W,,,J,Z1
pax300-2,,EDS-pax300-2,H,C,P,0,0,JL,2,W,,,J,Z2
pax300-3,,EDS-pax300-3,H,C,P,0,0,JL,2,W,,,J,Z3
pax300-4,,EDS-pax300-4,H,C,P,0,0,JL,2,W,,,J,Z4
pax300-5,,EDS-pax300-5,H,C,P,0,0,JL,2,W,,,J,Z5
pax300-6,,EDS-pax300-6,H,C,P,0,0,JL,2,W,,,J,Z6
pax300-7,,EDS-pax300-7,H,C,P,0,0,JL,2,W,,,J,Z7
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FLAPS

```
ACFT_ID,OP_TYPE,FLAP_ID,COEFF_R,COEFF_C_D,COEFF_B
pax300-1,D,CLEAN,0.0796178,0.242851,0.00178777
pax300-1,D,F1,0.0805802,0.217641,0.00179028
pax300-1,D,F2,0.0830565,0.217616,0.00178904
pax300-1,A,F-APP,0.107875,0.216392,0.00181757
pax300-2,D,CLEAN,0.0796813,0.242556,0.00177287
pax300-2,D,F1,0.0805802,0.217248,0.00177537
pax300-2,D,F2,0.0831255,0.217248,0.00177414
pax300-2,A,F-APP,0.107875,0.216042,0.00180262
pax300-3,D,CLEAN,0.0799361,0.240824,0.00171344
pax300-3,D,F1,0.000421745,0.215257,0.00171591
pax300-3,D,F2,0.0831947,0.215329,0.0017147
pax300-3,A,F-APP,0.107991,0.214242,0.00174285
pax300-4,D,CLEAN,0.0798722,0.240528,0.00170268
pax300-4,D,F1,0.0806452,0.215113,0.00170511
pax300-4,D,F2,0.0831255,0.21516,0.00170392
pax300-4,A,F-APP,0.107991,0.214065,0.00173157
```

```
pax300-5,D,CLEAN,0.0795545,0.24251,0.00184435
pax300-5,D,F1,0.0803213,0.216859,0.00184705
pax300-5,D,F2,0.08285,0.216908,0.00184572
pax300-5,A,F-APP,0.107643,0.215782,0.00187655
pax300-6,D,CLEAN,0.0798085,0.242508,0.0017554
pax300-6,D,F1,0.0806452,0.217159,0.00175788
pax300-6,D,F2,0.0831947,0.217159,0.00175666
pax300-6,A,F-APP,0.107991,0.215965,0.0017849
pax300-7,D,CLEAN,inf,0.241834,0.0017427
pax300-7,D,F1,0.0806452,0.216185,0.00174522
pax300-7,D,F2,0.0831947,0.216245,0.00174398
pax300-7,A,F-APP,0.107991,0.215138,0.00177276
```

noise_grp

```
NOISE_ID,THRSET_TYP,MODEL_TYPE,SPECT_APP,SPECT_DEP,SPECT_AFB
EDS-97-1,L,I,7011,7021,0
EDS-98-2,L,I,7012,7022,0
EDS-105-3,L,I,7013,7023,0
EDS-106-4,L,I,7014,7024,0
EDS-88-5,L,I,7015,7025,0
EDS-101-6,L,I,7016,7026,0
EDS-101-7,L,I,7017,7027,0
```

NPD_curv

```
NOISE_ID,NOISE_TYPE,OP_MODE,THR_SET,L_200,L_400,L_630,L_1000,L_2000,L_4000,L_6300,L_10000,L_16000,L_25000
EDS-97-1,S,A,28093.9,105.5,101.6,98.6,95.2,89.4,82.3,76.8,70.4,62.7,54.2
EDS-97-1,S,A,18547.4,102.5,98.7,95.9,92.6,87,80.2,74.9,68.6,61.1,52.6
EDS-97-1,S,A,10228.4,99.7,96.1,93.3,90.1,84.8,78.3,73.2,67.1,59.9,51.8
EDS-97-1,S,D,81826.9,108.2,104.5,101.5,98.4,93.1,86.7,81.9,76.2,69.5,62.1
EDS-97-1,S,D,70643.9,107,103.3,100.3,97,91.4,84.9,79.8,74,67.1,59.4
EDS-97-1,S,D,60279.2,106.4,102.6,99.6,96.3,90.7,83.8,78.6,72.4,65.2,57.1
EDS-97-1,S,D,40095.2,104.1,100.2,97.3,94,88.3,81.5,76.1,69.6,61.9,53.3
EDS-97-1,M,A,28093.9,107.8,99.5,94.5,89.3,77.5,67.9,60.7,52.5,43,33
EDS-97-1,M,A,18547.4,104.7,96.5,91.7,83.8,75.6,66.2,59.2,51.3,42.2,32.3
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PROF_PTS

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PROFILE

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Plots for Procedur file for Baseline Aircraft

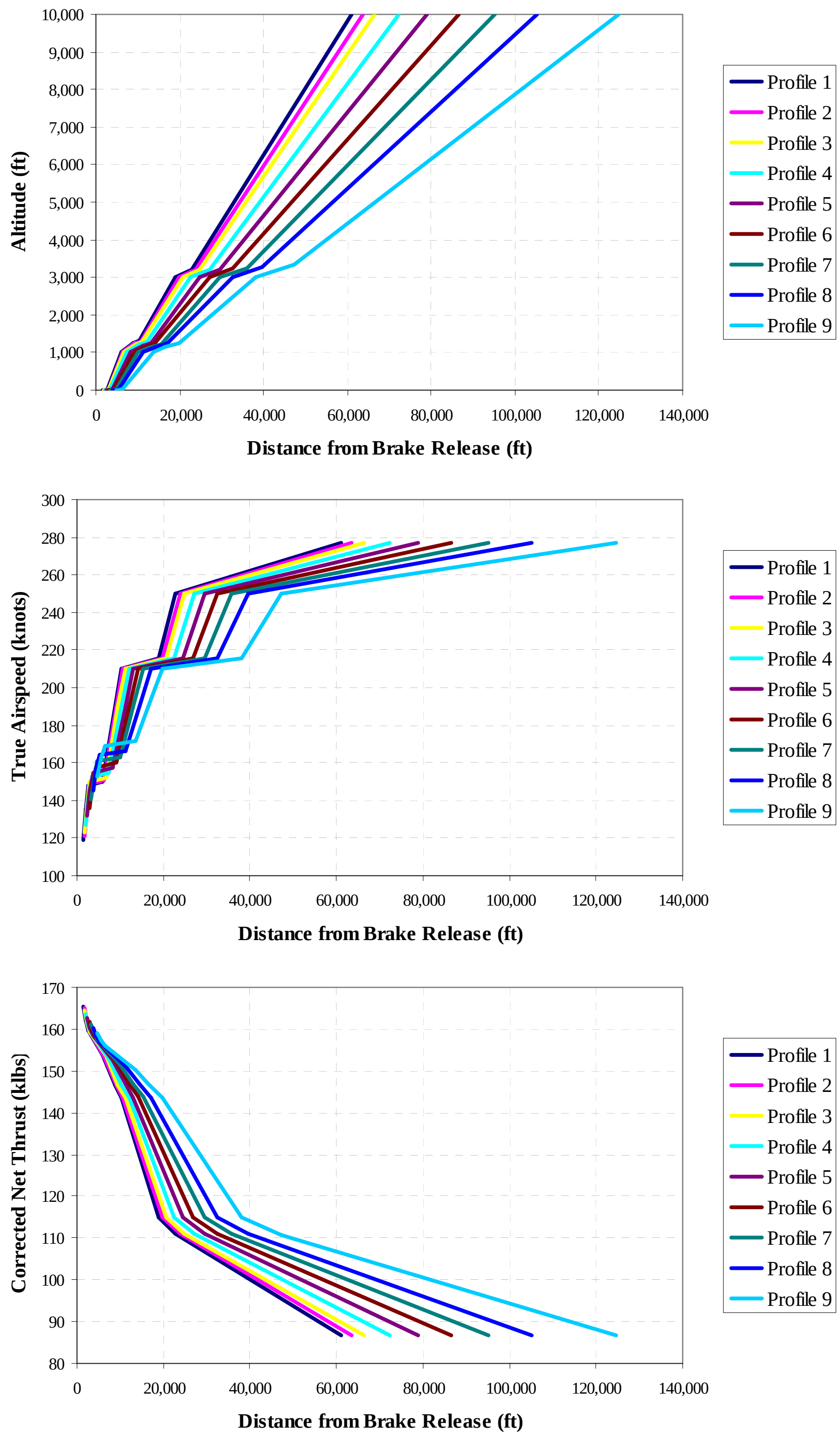

Figure 81: ICAO B Departure Procedures

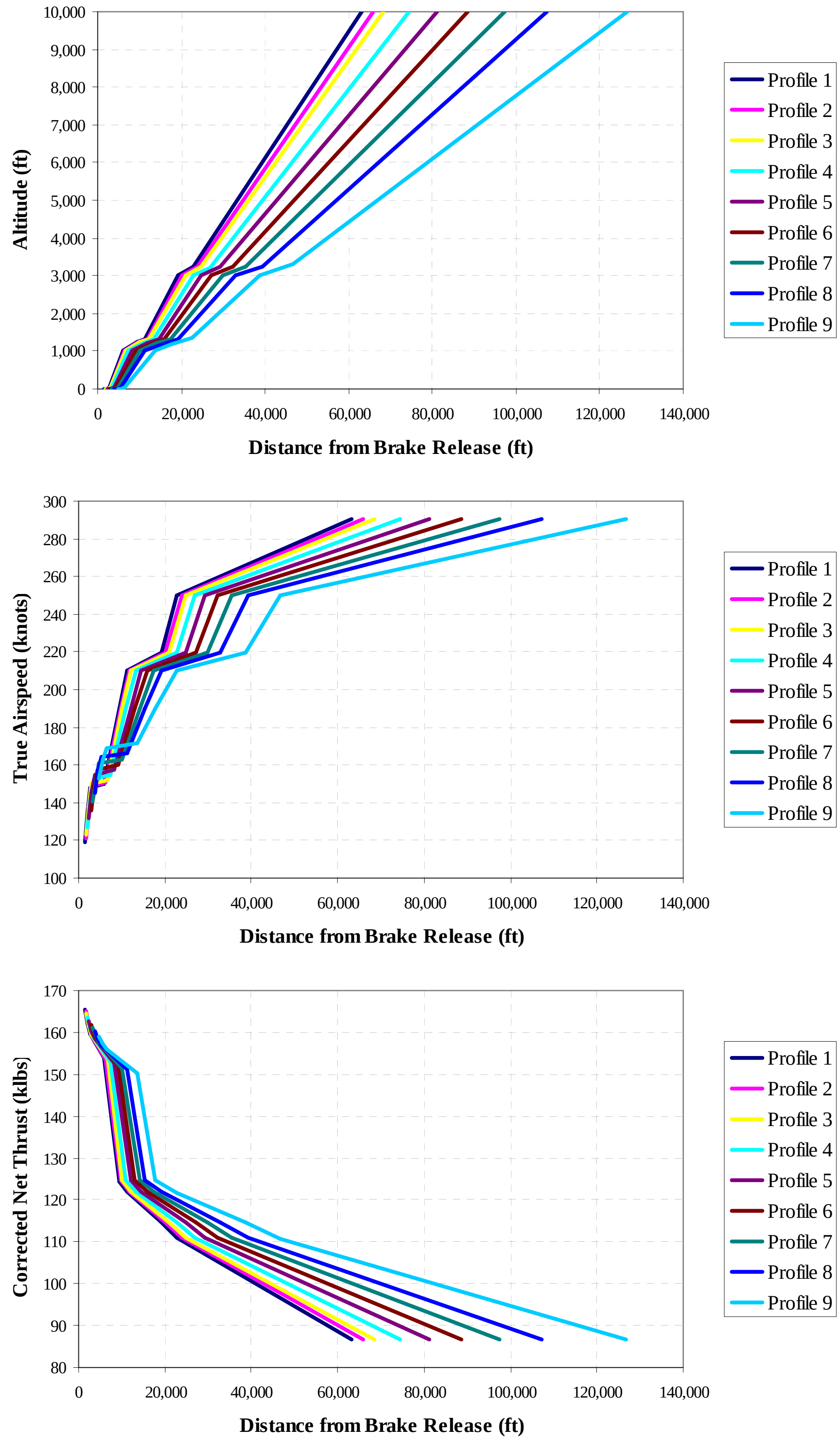

Figure 82: STANDARD Departure Procedures

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