

**A FRAMEWORK AND QUANTITATIVE METHODOLOGY FOR  
THE IDENTIFICATION OF COST-EFFECTIVE ENVIRONMENTAL  
POLICY FOR CIVIL AVIATION**

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The Academic Faculty

by

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**A FRAMEWORK AND QUANTITATIVE METHODOLOGY FOR  
THE IDENTIFICATION OF COST-EFFECTIVE ENVIRONMENTAL  
POLICY FOR CIVIL AVIATION**

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## LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

$\ddot{a}_{ni}$	Annuity Due
AEE	Federal Aviation Administration Office of Environment and energy
AEM	Eurocontrol's Advanced Emission Model
AERO-MS	Aviation Emissions and evaluation of Reduction Options - Modeling System
APMT	Aviation Portfolio Management Tool
ASPIRE	Asia and Pacific Initiative to Reduce Emissions
ATM	Air Traffic Management
ATS	Air Transportation System
$\beta$	Probability of survival mid point
C	Carbon
CAA	Clean Air Act
CAEP	Committee on Aviation Environmental Protection
CAFE	Corporate Average Fuel Economy
CBA	Cost-Benefit Analysis
CDM	Clean Development Mechanism
CEA	Cost-Effectiveness Analysis
CER	Certified Emissions Reductions
CH <sub>4</sub>	Tetrahydrocarbon (methane)
CO	Carbon Monoxide

CO <sub>2</sub>	Carbon Dioxide
CPI-U	Consumer Price Index for Urban Consumers
d	Aircraft depreciation rate
DOC	Direct Operating Cost
DoD	Department of Defense
DoE	Design of Experiments
Dp/F <sub>00</sub>	Emissions regulatory parameter, mass of emissions (Dp) divided by sea level static thrust (F <sub>00</sub> )
E3ME	Energy-Environment-Economy Model of Europe
EAC	Equivalent Annual Cost
EC	European Commission
EDS	Environmental Design Space
EMA	Exploratory Modeling and Analysis
EPA	U.S. Environmental Protection Agency
ERU	Emission Reduction Units
ETS	Emission Trading Scheme
EU	European Union
EUA	European Union Allowance
EU ETS	European Union Emission Trading Scheme
FAR	Federal Aviation Regulation
FB	Fuel burn
FESG	Forecasting and Economics Support Group
FL	Floor area

ft	Feet
$\gamma$	Probability of survival slope
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIACC	Group on International Aviation and Climate Change
GREAT	Global and Regional Environmental Aviation Tradeoff tool
Gt	Gigatons
HC	Hydrocarbons
i	Aircraft finance rate
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
IPPD	Integrated Product and Process Design
JI	Joint Implementation
kg	Kilograms
km	Kilometers
L/D	Lift to drag ratio
lb	Pounds
LCCs	Low Cost Carriers
m	meters
MDG	Modeling and Data base Group
mpg	Miles per gallon

MTOW	Maximum Takeoff Weight
MV	Metric Value
MZFW	Maximum Zero Fuel Weight
n	Years
NAMS	Nautical Air Mileage
NAP	National Allocation Plan
NAS	National Airspace System
NH <sub>3</sub>	Ammonia
NLL/S	Notional Limit Line(s)
nmi	Nautical miles
NRC	Non-Recurring Cost
NO <sub>x</sub>	Nitrous Oxide
O <sub>3</sub>	Trioxxygen (ozone)
OD	Origin-Destination
OEW	Operating Empty Weight
P	Payload
PC	Purchase Cost
PARTNER	Partnership for AiR Transportation Noise and Emissions Reduction
PED	Price Elasticity of Demand
PL	Payload
ppm	parts per million
PV <sub>scrap</sub>	Present value of scrapped item

Q	Quantity demanded
R	Range
R <sup>2</sup>	Coefficient of determination
RC	Recurring Cost
RF	Radiative Forcing
RPK	Revenue Passenger Kilometers
RPM	Revenue Passenger Miles
RTK	Revenue Tonne Kilometers
RTM	Revenue Ton Miles
SAR	Specific Air Range
SFC	Specific Fuel Consumption
SoPS	System-of-Policy-Systems
SoS	System-of-Systems
SoSE	System-of-Systems Engineering
SO <sub>x</sub>	Sulphur Oxide
SV	Scrap Value
TSFC	Thrust Specific Fuel Consumption
UL	Useful Load
UN	United Nations
US BTS	U.S. Bureau of Transportation Statistics
US FAA	U.S. Federal Aviation Administration
USD	United States Dollars
UT-LS	Upper Troposphere – Lower Stratosphere

VOC	Volatile Organic Compounds
W	Watts
x	Normalized metric value improvement

## SUMMARY

Public policy making is generally pursued as a “one policy at a time” process. Additionally, policy is often confined to national boundaries, even for global public issues. As such, legislation is often temporally and geographically dispersed. Despite this approach, many public policies are pursued with the intent of working concurrently to produce a desired behavior in the context of a larger, highly complex system. If we look at the civil aviation industry (which can be classified as a system-of-systems) public policy aimed at mitigating the emission of greenhouse gases, namely CO<sub>2</sub>, has been a major push throughout much of the world in recent years. With the passing of various emissions trading schemes throughout the world aimed at service providers, and in upcoming years with planned regulations on manufacturers, the mitigation of CO<sub>2</sub> into our atmosphere has been at the forefront of many civil aviation policy makers’ minds.

Compared to the relative wealth of information surrounding design in the context of system-of-systems there has been little research surrounding policy making in system-of-systems. Even recent pushes by select academics and policy makers have only addressed policymaking in system-of-systems from a conceptual level or under highly simplified system-of-systems architectures. While the adoption of a formal approach and lexicon for system-of-systems problems has been proposed by researchers, the specific inclusion of regulatory policies in system-of-systems is still largely absent or underdeveloped. Typically, there is no distinction between internal policies of an organization and exogenous policies coming through regulatory channels. Further,



researchers have yet to formally employ a standardized framework to regulatory policy problems in the context of a system-of-systems. As international regulatory bodies are calling on world States to identify and select “baskets of measures” to address CO<sub>2</sub> emissions from civil aviation, there is a growing recognition that doing so will require a framework for policy identification and selection. Despite this recognition, such a framework has yet to be established.

In order to address these issues in policy making, the following research develops a formal lexicon for public policy as a part of system-of-systems, and employs a formalized process to explore multiple established, planned, and potential policies in the context of the global civil aviation system. The following research defines system-of-systems characteristics, and provides a system-of-systems architecture for civil aviation based on previous work from academia. Existing architectures and lexicons are expanded to include regulatory policies that have often been treated as exogenous forcing functions in system-of-systems problems. This research addresses the obstacles documented in literature regarding the concurrent analysis of multiple policies throughout system-of-systems, by establishing a process for informed quantitative decision making to support concurrent CO<sub>2</sub> regulatory policy analysis and design in the civil aviation system-of-systems. The developed methodology allows policy makers to systematically identify effective policy space while maintaining the objectivity of the analyst.

# CHAPTER 1

## ENVIRONMENTAL CONCERNS OF THE AIR TRANSPORTATION INDUSTRY

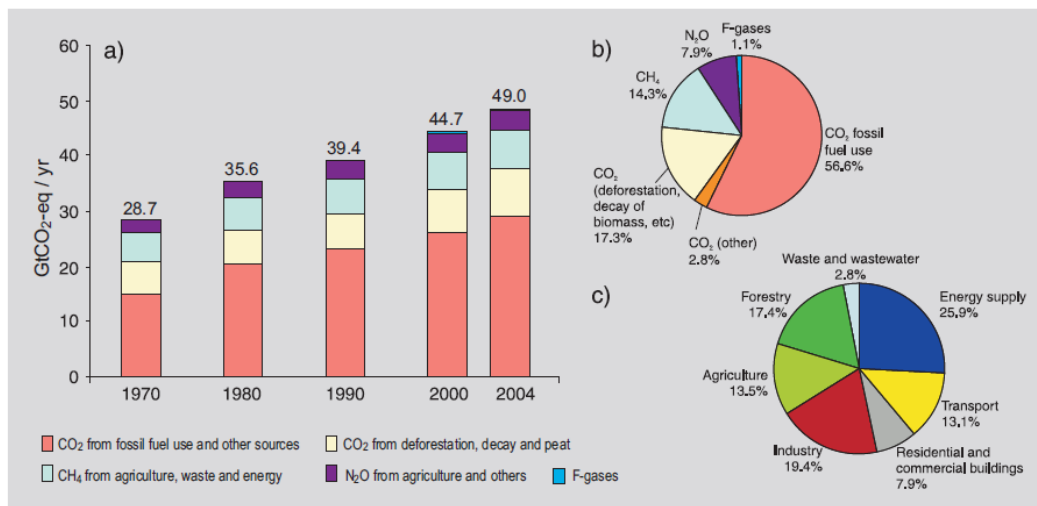
*“When we try to pick out anything by itself, we find it hitched to everything else in the universe.” – John Muir*

### 1.1 Introduction

Since the time of the Wright brothers’ first flight in 1903 aviation has grown to become one of the world’s most important transportation sources for both people and cargo. While the earth’s population was 1.6 billion in the year of that first flight, as of 2009 more than 2.3 billion passengers and 38 million tons of freight were utilizing the world’s airlines each year [1, 2]. This growth is certainly a strong indicator of continued progress in the civil aviation industry, however, there are environmental costs associated with such progress that are only recently being addressed.

Throughout the last two decades the impact of anthropogenic greenhouse gases (GHG) on global climate change has shaped much of the discourse regarding environmental policy. In large part, this is due to the recognition that “warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level [3].” Agencies such as the Intergovernmental Panel on Climate Change (IPCC) have shown that this warming of the planet is a result of the stark rise in global increases of GHG concentrations throughout the atmosphere. While there are a

number of GHGs that impact global climate, such as nitrogen oxides (NO<sub>x</sub>), methane (CH<sub>4</sub>), ozone (O<sub>3</sub>), and aerosols, the most abundant anthropogenic source of GHG throughout the atmosphere is carbon dioxide (CO<sub>2</sub>) [3]. As a result, many studies showing the growth in anthropogenic GHG concentrations will convert the effect of all gases to a CO<sub>2</sub> equivalent. This is the case in Figure 1.1, where the growth in global anthropogenic GHG emissions is shown for the period from 1970 to 2004 [4]. As is evident in (a) of this figure, GHG emissions have risen steadily since the 1970s, driven primarily by CO<sub>2</sub> emissions. From (b), the vast majority of this rise in CO<sub>2</sub> concentrations has been due to our dependence on liquid hydrocarbons, which certainly serve a critical role in the air transportation industry.



**Figure 1.1: Global Annual Emissions of Anthropogenic GHGs from 1970 to 2004 [4]**

In fact, while the effects of global warming cannot be isolated to any single point source, it's widely accepted that carbon dioxide in general is the most influential anthropogenic greenhouse gas. The global concentrations of CO<sub>2</sub> have risen since the pre-industrial era by almost 100ppm, from 280ppm in 1750 to 379ppm in 2005 [3]. This

trend in atmospheric concentrations of CO<sub>2</sub> far exceeds any natural ranges over the last 650,000 years, as verified by ice core samples [3]. Further, growth rates of CO<sub>2</sub> concentrations over the past 10 years (1995 to 2005 average of 1.9ppm/yr) have been larger than since the beginning of direct atmospheric measurements in the 1960s (1960 to 2005 average: 1.4ppm/yr), which indicates the potential for an even more exaggerated problem in the future [3]. Even if CO<sub>2</sub> emissions were to be maintained at near current levels, they would still lead to a nearly constant rate of increase in atmospheric concentrations for more than two centuries, approaching twice the pre-industrial concentration by the end of the 21<sup>st</sup> century [5].

These trends in global anthropogenic GHG emissions are certainly a cause for concern. Even if the continuous growth in emissions could be curbed to a sustainable level, the nature of CO<sub>2</sub> residence in the atmosphere would still lead to global rises in concentrations, and thus warming of the planet. While this may seem to be a bleak indicator for the future of our planet, a large number of studies have provided evidence that there is substantial economic potential for the mitigation of global GHG emissions in the coming decades that could offset or even reduce emissions below current levels [4]. As a result, the push in the scientific and policy communities must be in the exploration of the realm of possible measures to help mitigate GHG emissions.

## **1.2 Aviation and Climate Change**

As has been shown, the impact of climate change due to anthropogenic GHG emissions is a growing concern. This is especially true in the aviation industry where a substantial portion of the emissions occur at high altitudes. Due to this unique operating

environment, the impact of these emissions can often be greater than the same emissions released from the ground. As a result, there has been a call by a number of international and national regulatory bodies to impose controls on GHG emissions from commercial aviation.

### **1.2.1 Aviation Emissions**

Before addressing the role of aviation in anthropogenic climate change, the composition of aircraft emissions must first be understood. As with most transportation sources, the primary source of emissions in aviation are aircraft engines, where emissions are composed of approximately 70% CO<sub>2</sub>, slightly less than 30% water vapor, and less than 1% each of NO<sub>x</sub>, CO, SO<sub>x</sub>, VOC, particulate matter, and other trace compounds [1, 5]. In addition to the emissions coming directly from the engine, there are also a number of other sources of GHG throughout the aviation industry. These can be traced to land use changes, airport operations, contrail formation, manufacturing, and a large number of other activities related to the aviation industry [1].

As a result of this activity, aviation currently accounts for between 2% to 3% of the worldwide CO<sub>2</sub> emissions [3, 5-7]. While this may seem like an insignificant portion of worldwide CO<sub>2</sub> emissions, in 1992 alone the emissions of CO<sub>2</sub> by aircraft were at 0.14 Gt C/year, which can have a substantial effect on the global climate [5]. Further, one of the most worrisome trends throughout aviation is the projected growth in CO<sub>2</sub> emissions to around 3% to 4% per year in the coming decade [2, 5, 8]. This accelerated growth is projected to outpace growth in most other industries, and certainly in other sectors of

transportation. This is primarily due to the increased globalization of the planet and its people.

Complicating this issue is the fact that the bulk of aircraft emissions (approximately 90%) occur directly into the upper troposphere and lower stratosphere (UT-LS) region of the atmosphere, where aircraft cruise at heights of approximately 30,000 to 40,000 ft [1, 5]. This operating environment represents a relatively pristine portion of the atmosphere that is only episodically affected by weather events that can mix surface and stratospheric air [9]. As a result, CO<sub>2</sub> emitted into this region of the atmosphere has a residence time with a half-life of approximately 100 years [5, 10]. This long residence time and relatively stable portion of the atmosphere provides the ideal conditions for CO<sub>2</sub> emissions to become well mixed on a global scale. Subsequently, it is impossible to isolate the point sources of CO<sub>2</sub> pollution throughout the world. Despite this, studies by the IPCC, as well as a number of other agencies, have been able to produce estimates for CO<sub>2</sub> emissions from aviation through fuel sales, and have also been able to show scientifically that the impact of burning fossil fuels at altitude is approximately double that due to burning the same fuels at ground level [11]. Subsequently, if aviation emissions are allowed to grow at current rates, which outpace technological improvements, the impact of aviation on the global climate will continue to become more significant in the coming decades.

## 1.2.2 Effect on the Atmosphere

Given this knowledge of the emissions species coming from aviation, it is important to follow with an understanding of the overall effect on the atmosphere. Climate scientists have been able to show that carbon dioxide, water vapor, sulphur, and soot particles coming from aviation activities have a direct impact on the atmosphere that can lead to warming of the earth's surface [12]. These changes in the abundance of GHG throughout the atmosphere have a tendency to alter the energy balance of the climate system, in much the same way window panes alter the energy balance in a greenhouse. This energy balance of the global climate is generally measured through radiative forcing (RF), where the most influential contributors are CO<sub>2</sub>, NO<sub>x</sub>, aerosols, and increased cloudiness due to the formation of linear contrails and induced cirrus cloudiness [13]. Radiative forcing is ultimately a measure of the influence that a given GHG has in altering the incoming and outgoing energy in the earth's atmospheric system, and is measured in watts per meter squared (W/m<sup>2</sup>) with respect to a pre-industrial baseline established by the overall concentrations of GHG in the atmosphere in 1750 [5]. For these measurements, a positive RF tends to warm the surface of the earth, while negative RF has a cooling effect. As reported by the IPCC, there is a very high confidence that the net effect of human activities since 1750 has been one of global warming, with a net RF of +1.6 W/m<sup>2</sup> [3].

The IPCC has produced estimates of the relative contribution of each GHG that contributes to this warming and cooling of the planet. These estimates, based on a 2005 baseline, can be seen in Figure 1.2. As can be seen from this figure, and discussed

previously, the release of the long lived gases, such as CO<sub>2</sub>, are the primary contributors to global warming. As a result, the release of CO<sub>2</sub> due to aviation activities should be a primary concern for the global aviation industry as demand continues to increase. In fact, in 2005 the total RF from aviation was approximately 55 mW/m<sup>2</sup> with a 90% likelihood range, which accounts for 3.5% of the total anthropogenic forcing [6, 7, 13]. At this point, it should be evident that aviation, which accounts for 2% of CO<sub>2</sub> emissions and 3.5% of RF, has a greater relative effect on the atmosphere than other pollution sources. The continued growth of aviation emissions will make this trend more pronounced in the coming decades. As such, if the sustainability of earth's climate is to be addressed, the influence of aviation must not be ignored.

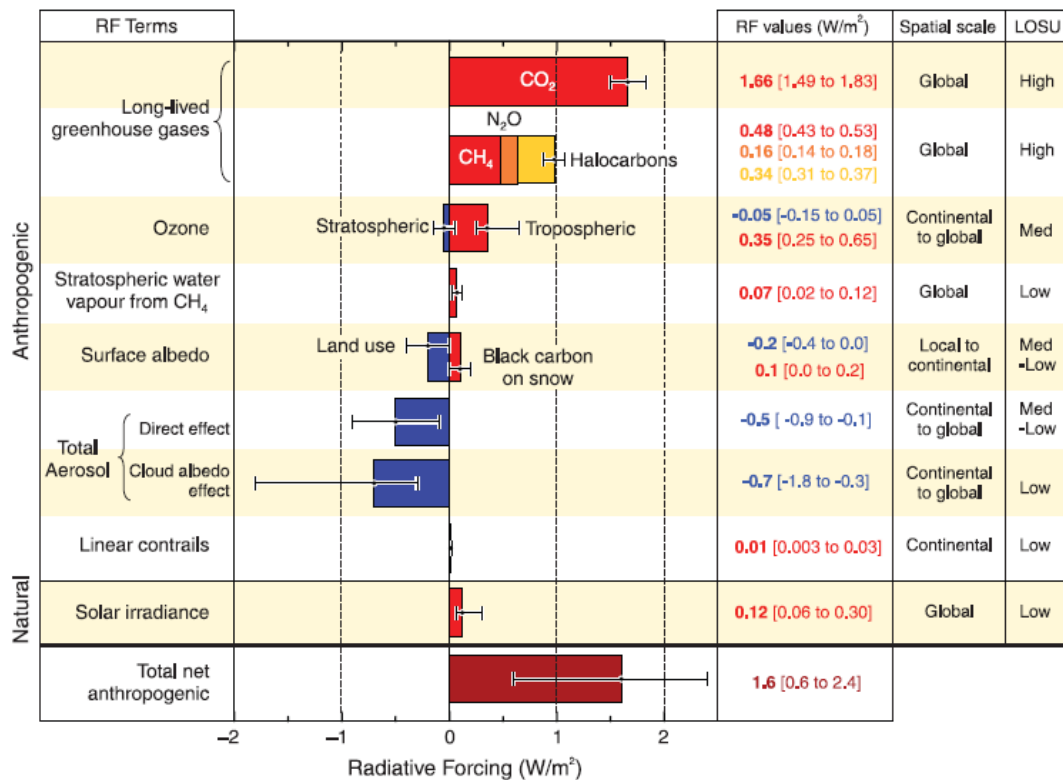


Figure 1.2: Global Average Radiative Forcing in 2005 [4]



### **1.2.3 Addressing Aviation's Impact on the Global Climate**

Given the importance of aviation's impact on the global climate, action must be taken in order to avoid catastrophic effects on our planet. Currently, there is broad concern that unless much more is done to reduce aviation emissions, the inherent demand growth will ultimately cancel out the work done to reduce emissions in other sectors [12]. This concern has permeated a number of government and non-government bodies, and spurred a wealth of research throughout the civil aviation industry. A number of recent reports have noted that reducing aircraft emissions can and should be accomplished on a global level through a variety means, including improvements in technologies, operations, the use of sustainable alternative fuels, and regulatory policy instruments [1, 2, 5, 6, 14-20].

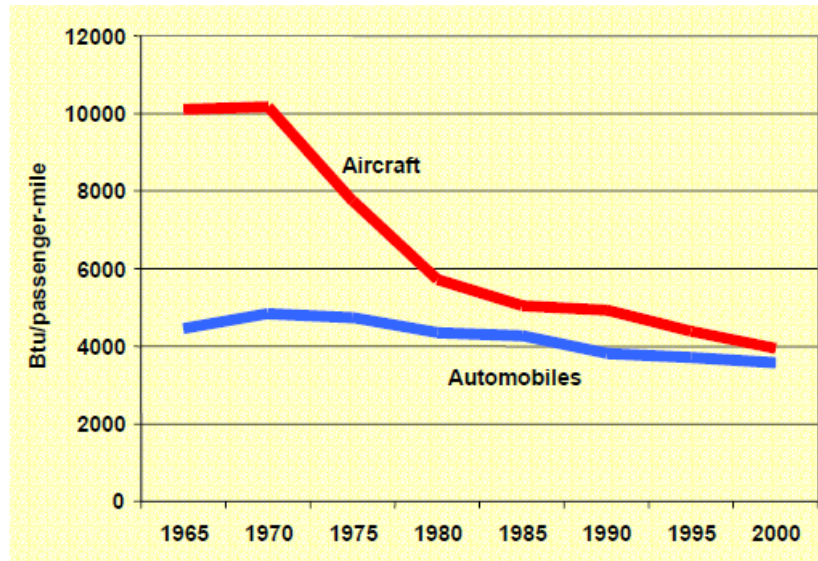
### **1.3 Trends in the Civil Aviation Industry**

To begin to understand how to accomplish such measures in aviation, there must first be an understanding of the trends throughout the civil aviation industry. In general, the dawn of the commercial jet age (1950s) spawned a significant amount of research and development, which has led to vast improvements in aircraft technologies and operational procedures. These improvements have typically been driven by the profit maximizing behaviors of the airline operators, for which fuel burn is tied directly to operating costs of the aircraft. As a result, CO<sub>2</sub> itself has been implicitly tied to the overall profitability of the aviation industry. Despite this fact, the widespread acceptance, and reliance on aviation for globalization, has led to even greater increases in demand than the inherent

increases in efficiency. The net effect has been one of continual increases in fuel use, and subsequent CO<sub>2</sub> emissions. Specific trends in technology, operations, and demand growth will be discussed here to provide a more complete view of the direction of civil aviation since the beginning of the commercial jet age. It should be noted that the trends described herein have motivated much of the policy discourse since the 1960's, which is further expanded upon in Chapter 2.

### **1.3.1 Technology is Improving**

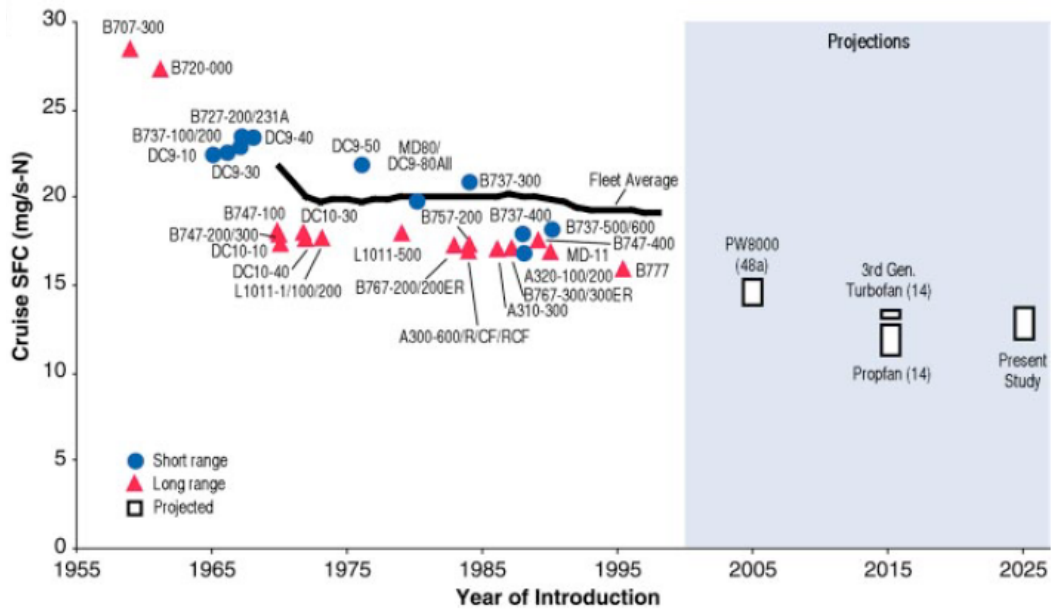
Since the beginning of the commercial jet age, technological advancement, driven by a desire to reduce operating costs, has significantly reduced aircraft fuel consumption and subsequently emissions. In fact, over the past 40 years, aircraft fuel efficiency has improved by almost 75% and the noise footprint has been reduced by 90% through improvements in airframe design, engine technologies, and constantly rising load factors [1, 5, 20]. These efficiency improvements are even more impressive when considered relative to other transportation sectors, such the automobile, which has seen energy efficiency increases on the order of only 20% over the same period [1]. This trend is highlighted by the U.S. Federal Aviation Administration (FAA) and reproduced in Figure 1.3. As can be seen here, since the late 1960's aviation efficiency has improved drastically through the integration of new technologies, especially on the engine and aerodynamics, with less evident trends on structural improvements.



**Figure 1.3: Relative Energy Efficiency of Automobiles and Aircraft [1]**

### 1.3.1.1 Engine Technology Improvements

While the basic geometry of commercial aircraft has largely remained the same since the dawn of the commercial jet age, improvements in engine efficiency have been quite drastic. Much of this improvement was initially realized prior to the 1970's due to the introduction of high bypass ratio engines [11]. The result of introducing high bypass ratio engines has been an increase in engine efficiency of approximately 40% over the 40 year period from 1960 to 2000, as measured by the cruise specific fuel consumption (SFC). This increase in engine efficiency corresponds to an average annual improvement of 1.5% [11]. These trends are highlighted by Lee through analysis of actual commercial aircraft, and the resulting improvements in SFC are shown in Figure 1.4.

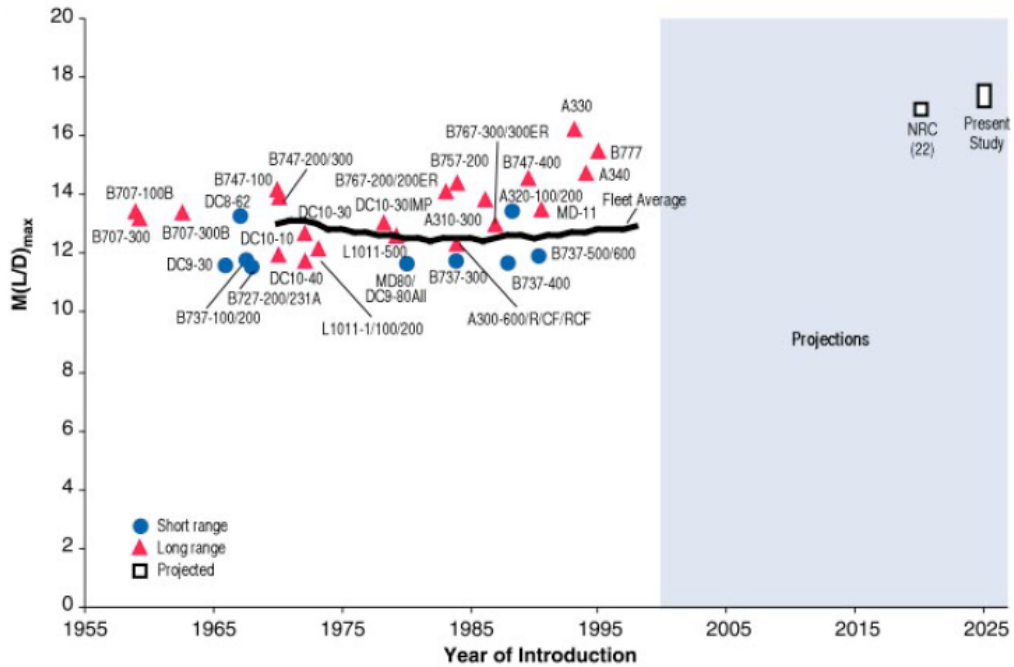


**Figure 1.4: Historical Improvements in Specific Fuel Consumption [11]**

The efficiency improvements in engines have been largely driven by the increase in bypass ratio, which means that engine diameters have become larger. As a result of increasing the engine diameter, the overall weight of the engine has increased substantially, as well as the aerodynamic drag [11]. As such, the overall increases in engine efficiency do not directly translate to improvements in overall aircraft efficiency. Despite this fact, other routes of engine efficiency have also been pursued, primarily by increasing the peak temperature within the engine leading to a more complete burn of the fuel. It should be noted though that this route is physically limited by materials and cooling technology, increasing pressure ratios, and improving engine component efficiencies [11].

### **1.3.1.2 Aerodynamic Efficiency Improvements**

In addition to improvements on the engine, technological improvements are also impacting the aerodynamic efficiency quite substantially. Throughout the commercial jet age aerodynamic efficiency has increased by approximately 15%, corresponding to an average increase of 0.4% per year over the period [11]. This trend can be observed directly through analysis of the lift to drag ratio (L/D) of commercial aircraft, which is considered a measure of overall aerodynamic efficiency. The historical L/D of commercial jet aircraft is shown in Figure 1.5 below [11]. As can be seen, there is a general trend of increasing L/D, especially for long haul aircraft. This increase in aerodynamic efficiency has been largely driven by better wing design and improved engine-airframe integration, which has been enabled through more advanced computational and experimental design tools and methods [5, 11, 21].

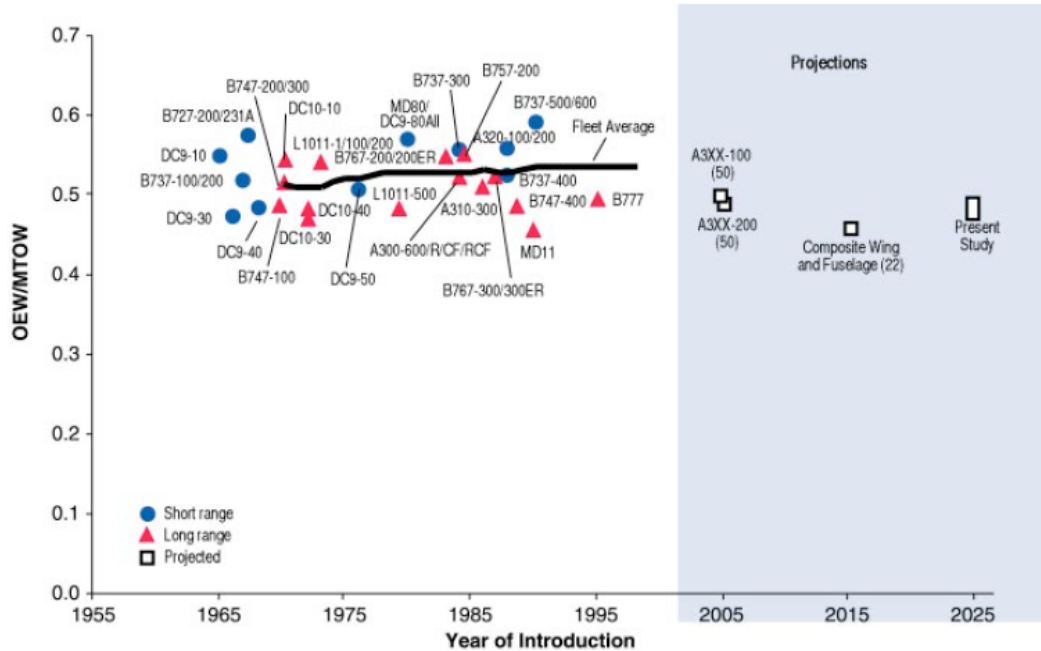


**Figure 1.5: Historical Improvements in L/D [11]**

### 1.3.1.3 Structural Efficiency Improvements

While the historical improvements in engine and aerodynamic efficiency throughout the years have been readily apparent, improvements in structural efficiency are less evident. The overall structural efficiency is a measure of the necessary structural weight to the overall weight of the aircraft. As such, it can be measured through a proxy ratio of the operating empty weight to the maximum takeoff weight. The historical trends of this measure for actual aircraft are demonstrated by Lee, and shown in Figure 1.6 below [11]. As can be seen, the trend has been relatively flat throughout the commercial jet age. Despite this fact, current advancements in composite materials and their integration throughout the airframe will likely change this trend to begin to see decreases

in OEW/MTOW. This is demonstrated to some extent by Lee in his projections of future aircraft, which are also shown in Figure 1.6 [11].



**Figure 1.6: Historical Improvements in OEW/MTOW [11]**

### 1.3.1.4 Fleet Efficiency Lags Aircraft Efficiency

The trends in technological efficiency improvements shown thus far have been isolated to specific aircraft throughout commercial aviation. However, it should be noted that in order to assess future aviation fuel consumptions and emissions it's important to consider the delay between technology introduction and full implementation throughout the fleet [11]. While the overall efficiency of individual aircraft may improve quite drastically from one generation to the next, this is not typically the case for the entire fleet in the same time frame. The reason is due to the time necessary to retire and purchase new aircraft for the commercial aviation fleet. This fleet evolution typically

creates a lag in technology introduction on the order of a decade [11]. As such, it will generally take 10-15 years for commercial aviation's fleet to reach the same fuel efficiency as the newly introduced aircraft. This is mentioned here because it's important to understand that there will be a lag between newly introduced aircraft and overall fleet efficiency improvements.

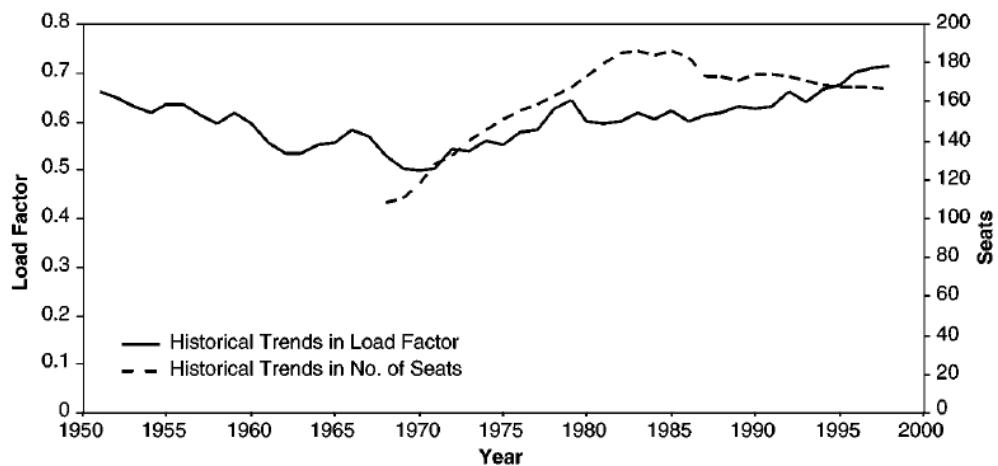
In general though, it's expected that this trend of constant improvements will continue into the future through the incorporation of more advanced aerodynamic technologies, weight reductions, new engine designs, and advanced control systems [22].

### **1.3.2 Operational Efficiency is Improving**

As with technological improvements, airlines have a vested interest in the reduction of operating costs through operational efficiency measures. As such, there has been considerable effort throughout civil aviation's history to create more efficient movements with aircraft. These improvements have been facilitated through better meteorological information, which has now become available in the cockpit in real time, allowing optimized flight planning and shorter routing to occur [1]. As a specific application of such improvements, the International Civil Aviation Organization (ICAO) under the United Nations (UN) has been pursuing improvements in air traffic management (ATM) by focusing on the Global ATM Operational Concept, which will potentially achieve interoperable global air traffic management [2]. The hope is to provide optimum economic operations and environmental sustainability, while maintaining the safety and national security requirements.



Additionally, further improvements have been possible through the development of yield management tools that have allowed airlines to dramatically increase load factors and per-aircraft capacity [1, 11]. In fact, the load factor on domestic and international flights operated by US carriers alone have climbed 15% between 1960 and 2000, albeit entirely occurring after 1970 [11]. This increase in load factor corresponds to an average of 1.1% growth per year since 1970, and is likely to continue until the overall load factor reaches approximately 0.85, or 85% of full capacity [23]. Generally, these trends are attributed to widespread deregulation of the U.S. national airspace system (NAS) and global air travel liberalization, which ultimately gave rise to the hub-and-spoke transportation systems largely implemented today [11, 24]. The historical trends in load factor and per-aircraft capacity are shown below in Figure 1.7. Increases in both of these measures of operational efficiency can be readily observed starting around 1970 as aforementioned.



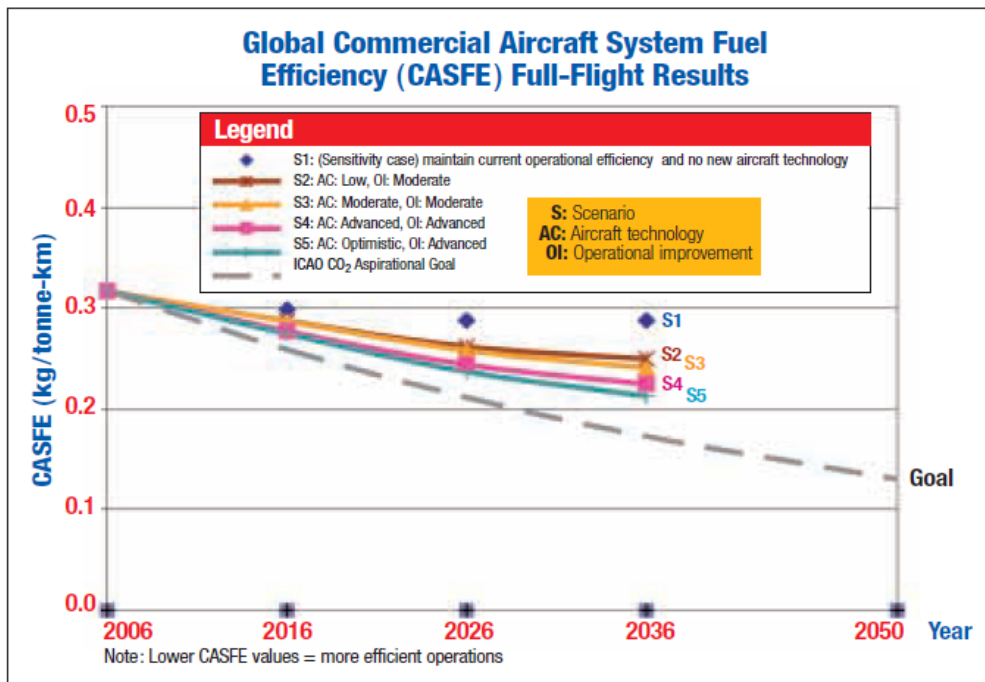
**Figure 1.7: Historical Trends in Load Factor and Seating Capacity [11]**

Despite these improvements in the operational efficiency of airlines, it is estimated that as much as 18% of fuel is still wasted [5, 25]. As such, the potential exists to reduce emissions further with inherent economic incentives. This has led organizations such as the IPCC to note that improvements in air traffic management (ATM) and other operational procedures have the potential to further reduce fuel burn by approximately 8% to 18% in the coming decades [5]. The vast majority of these improvements will come from the implementation of advanced ATM procedures, which are anticipated to be fully incorporated in civil aviation in the next 20 years. Looking even further into the future, concepts such as formation flight could also be incorporated into the air transportation system given sufficient proof that safety would not be compromised. Formation flight has been shown to have the potential for significant induced drag reductions on the order of 30-40% depending on the formation and speed, which could lead to additional fuel savings not currently being considered [26]. Subsequently, there are a number of additional operational efficiency improvements that can be made to the air transportation system.

### **1.3.3 Technological and Operational Efficiency Forecasting**

ICAO has been able to use these trends in technological development and operational efficiency to produce estimates of future civil aviation fuel efficiency. Figure 1.8 provides an overview of those results extending fuel burn efficiency out to 2036 [2]. A fixed technology and operational baseline is provided for benchmarking, which is often referred to in literature as a business as usual case. Additionally, four cases of operational and technological improvement scenarios are assessed relative to ICAO goals for CO<sub>2</sub>

emissions. As can be seen, even optimistic aircraft technologies and advanced operational concepts will not fully address the goals set forth. Generally, this difference in operational and technological fuel burn improvements and international goals is referred to as a CO<sub>2</sub> gap, and is the direct result of demand growth. Addressing this gap will ultimately be necessary for the health of the global climate, and is of paramount concern for policymakers in civil aviation.



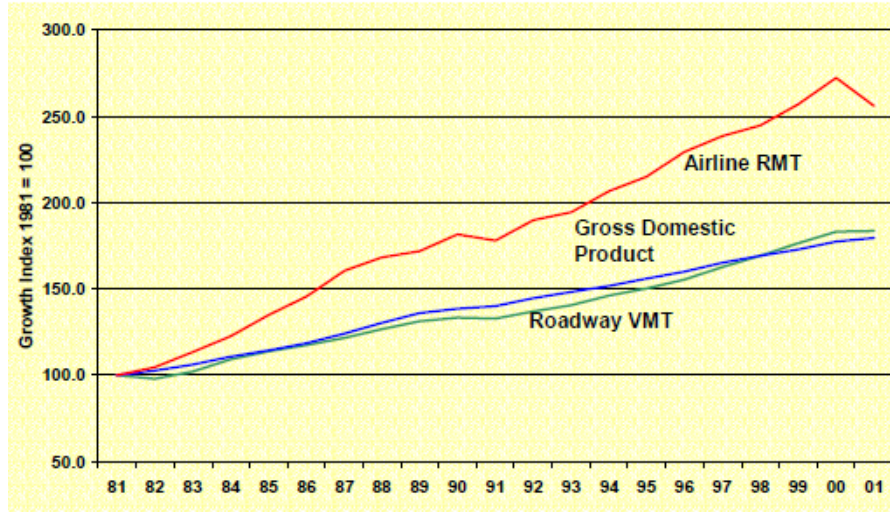
**Figure 1.8: ICAO Commercial Aircraft System Fuel Efficiency (CASFE) for Technology and Operational Improvements [2]**

### 1.3.4 Aviation Demand Growth Overshadows Inherent Improvements

As aforementioned, as aviation grows in popularity and the world moves toward a global society, the demand for civil aviation continues to grow without bounds. This is producing greater emissions of CO<sub>2</sub> every year from civil aviation. In fact, the IPCC

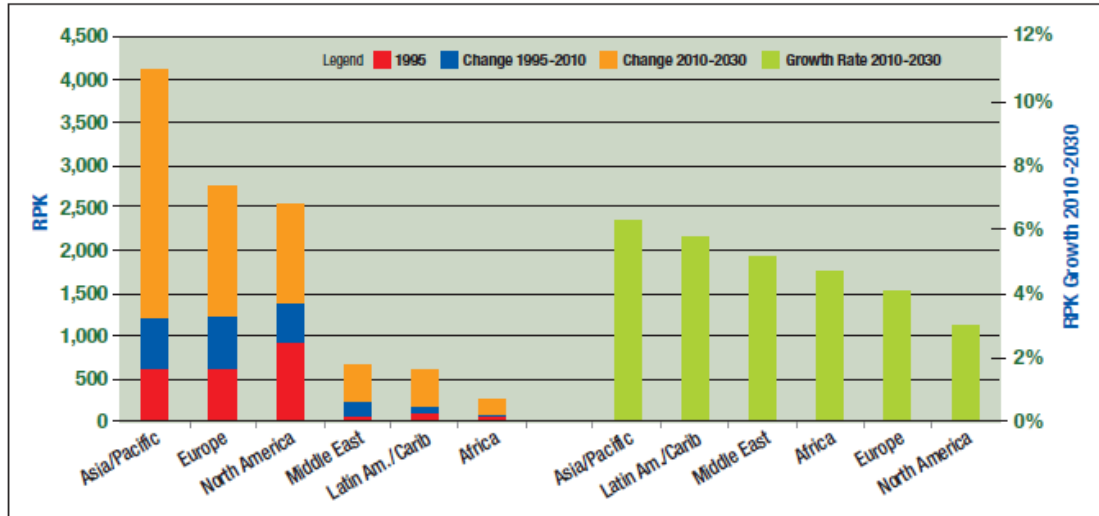
notes that “although improvements in aircraft technologies and in the efficiency of the air traffic system will bring environmental benefits, these will not fully offset the effects of the increased emissions resulting from the projected growth in aviation [5].” In large part this observation is a result of the rapid growth of aviation in the past several decades, where aviation has been growing faster than other modes of transportation and is expected to continue to outpace them in the future.

This rapid growth in aviation has been attributed to a 21.5% increase in population, a 32% increase in the labor force, and a 90% increase in gross domestic product (GDP) between 1980 and 2000 according to the U.S. Bureau of Transportation Statistics (US BTS) and Federal Aviation Administration (FAA) [1, 27]. Another important factor that has contributed to this trend in recent years has been the emergence of Low Cost Carriers (LCCs), which refer to their low operating cost basis. These new entrants to the civil aviation market have had a dramatic impact on air traffic growth in all parts of the world [2]. In fact, in analyzing Figure 1.9, it can be seen that the airline growth index, measured through revenue miles travelled (rmt) has actually outpaced both the GDP and vehicle miles travelled (vmt) by a considerable margin over the last few decades. These trends provide a good indication that aviation demand is growing much faster than most other markets, especially other transportation industries. As such, the relative impact of aviation compared to other transportation sectors is likely to grow exponentially in the coming decades.



**Figure 1.9: Aviation Growth 1981 to 2001 [1]**

Analyzing more specific data on aviation demand growth, it can be seen that passenger traffic, expressed as a revenue passenger kilometer (RPK), has grown since 1960 at nearly 9% per year, which is almost 2.4 times the average GDP growth rate [5]. While this growth rate has slowed in recent years, reaching an average of 5.3% per year between 2000 and 2007 [11, 13], many estimates put growth in global passenger traffic at about 5% per year in the coming decades [2, 5]. This growth in demand is expected to stay at such a high level due to the increased development of the Asia/Pacific region, specifically in China and India. This expectation can be seen quite clearly in the ICAO passenger traffic forecast provided in Figure 1.10. Obviously, this overall growth rate of 5% per year will likely outpace the expected improvements in efficiency of approximately 3% per year, as projected by ICAO [2].



**Figure 1.10: ICAO Passenger Traffic Forecast [2]**

Another sector of the aviation industry that is likely to play a more significant role in the future is cargo air transportation. As consumer markets are becoming more global in nature, the need to quickly and efficiently transport large quantities of goods continues to rise. Subsequently the growth in cargo transportation will outpace that of passenger transportation, with a likely growth of approximately 6.1% per year over the next 20 years according to the Committee on Aviation Environmental Protection (CAEP). The trends in freighter traffic from ICAO's CAEP can be observed in Figure 1.11. The growth rate of 6.1% per year corresponds to the most likely scenario for freighter traffic in their traffic and fleet forecasts.

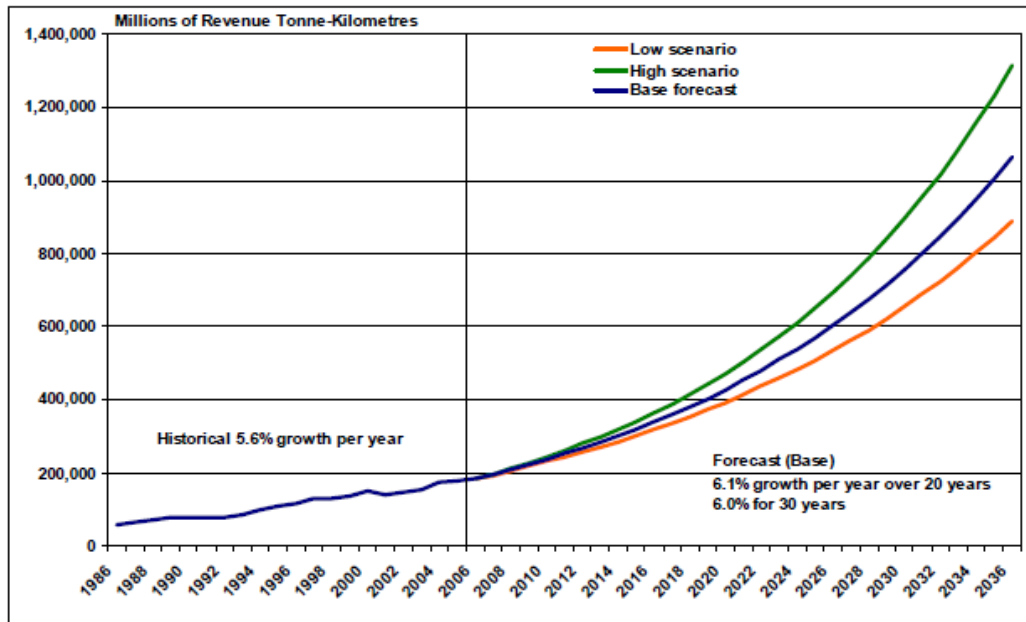
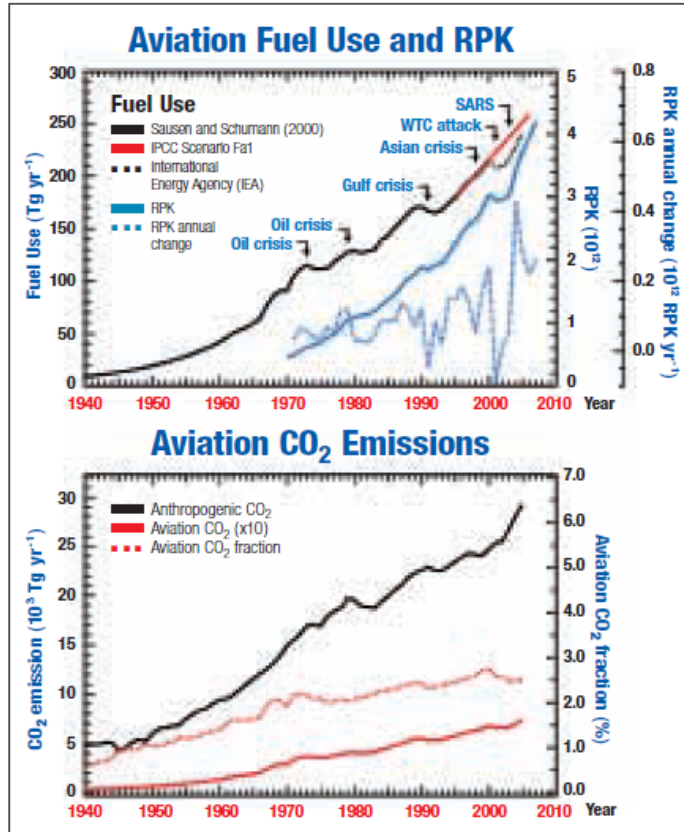


Figure 1.11: ICAO Freighter Traffic Forecast [23]

### 1.3.5 Summary of Efficiency Trends throughout the Civil Aviation Industry

Given the historical trends in technology, operations, and demand growth throughout the history of commercial aviation, it should be evident that the overall effect has been ever increasing fuel use and CO<sub>2</sub> emissions. This has certainly been the case, as reported by ICAO, and reproduced in Figure 1.12. As can be seen in this figure, even with a history of technological and operational improvements, significant increases in demand have led to continual increases in aviation fuel use. In addition to the increase in overall fuel use, the fraction of CO<sub>2</sub> emitted from aviation compared to all other sources has also been on the rise.



**Figure 1.12: Summary of Aviation Fuel Use and CO<sub>2</sub> Emissions Over Time [2]**

As a result of these historical trends in aviation fuel use, it's expected that medium-term mitigation of aviation CO<sub>2</sub> emissions can come from improved fuel efficiency, however, such improvements will not fully offset demand growth [2]. Subsequently, future projections of global aviation fuel consumption and efficiency through 2050 reveal fuel efficiency improvements over the period on a per flight basis, while in absolute terms an emission gap will persist relative to necessary emissions limits to achieve sustainability [2, 23]. This emissions gap is the direct result of demand growth outpacing expected technological and operational efficiency measures being considered. Subsequently there are two general paths that would need to be followed in order to close



the emissions gap, and mitigate the harmful effects of GHG emissions from civil aviation.

The first, and most obvious, path forward to help close this emissions gap is to push for greater increases in technological and operational efficiency than is currently expected. This would likely require a mixed approach to efficiency improvements from aircraft manufacturers as well as airline owners and operators. Pushing technological advancements would necessitate increased expenditures in research and development from aircraft manufacturers, while improving operational efficiency in the short term would likely increase the complexity of airlines' operational strategies. Given the additional cost and complexity of such an approach, it seems unlikely that these increasing rates of improvement will occur independent of intervention from outside bodies.

Alternatively, closing the emissions gap can also be accomplished by curbing demand growth to levels at or below expected technological advancement, accounting for the lag between fleet efficiency and aircraft efficiency. With that said, a reduction in demand growth for commercial aviation is unlikely to occur given the historical trends and future forecasts aforementioned. As such, realistically reducing demand growth would have to occur by outside intervention as well, likely through creating a real price for CO<sub>2</sub> and other GHG emissions from civil aviation.

Ultimately, closing the emissions gap in civil aviation will likely come from a mixed approach, pushing efficiency improvements while at the same time limiting

demand growth. Since neither is likely to occur without direct intervention, addressing this emissions gap will need to come from external mechanisms to the aviation industry, namely the integration of regulatory policy measures.

#### **1.4 The Growing Importance of Regulatory Policy in Civil Aviation**

Recent efforts to mitigate the climate change impacts of civil aviation have looked toward regulatory policy as an answer. Despite this more recent concern for aviation's impact on our environment, it should be noted that regulation in commercial aviation has only come about historically as a result of immediate concern or annoyance [28]. This fact will be explored more thoroughly in the Chapter 2, where it will be shown that from a regulatory perspective action is only taken once the potential for harm is occurring or imminent.

Due to the fact that concern about the impact of aviation on climate change is a relatively new phenomenon, it lags more than a decade behind concerns about emissions in the vicinity of airports, and more than two decades behind noise impacts [28]. This is evident in the fact that the first report to consider aviation's effect on the global environment was the 1999 IPCC special report titled "Aviation and the Global Atmosphere" [5]. As was noted previously, due to the long persistence of CO<sub>2</sub> in the atmosphere, this delay in addressing climate concerns in aviation can be highly problematic for longer term environmental effects. It has been widely discussed by international regulatory bodies that significant lead time is required for prevention of climate change [5, 10], and yet we are only beginning to address these concerns.

In addition to this late entry addressing these environmental concerns, other issues associated with making regulatory decisions in the face of immediate concerns exist. When regulation is pursued to address immediate concerns, the resulting regulations are difficult to generalize, often aimed at meeting a singular environmental goal, and the potential to be disruptive to other policies or market mechanisms is sometimes poorly explored. These policy mechanisms are generally pursued one at a time, are geographically dispersed, and there is no standard framework on which to assess interaction among various policy measures. So, while regulatory policy aimed at mitigating CO<sub>2</sub> in civil aviation may push the technological and operational efficiency of the aviation industry, there is little evidence to suggest they will impact demand growth and thus lead to lower CO<sub>2</sub> emissions in the industry as a whole.

Despite the issues associated with regulatory policy throughout civil aviation's history, a number of policy options to reduce emissions beyond inherent market incentives exist. Typically, these emissions reduction policies fall into one of three basic policy schemes including: command-and-control policy, market-based measures, and voluntary agreements, each of which will be discussed here. While groups such as the IPCC and ICAO have considered many of these mechanisms in their analysis of the future of civil aviation, many of these approaches have not been fully investigated or tested in commercial aviation [5]. Further, the assessment of interactions between multiple implemented policies addressing a singular goal, such as CO<sub>2</sub>, has yet to be accomplished on an aviation system wide level.

A more thorough discussion of aviation specific policies is included in the Chapter 2. The following discussion however, will highlight the basic mechanisms of each type of policy scheme, as well as the benefits and challenges generally associated with each approach.

### **1.4.1 Command and Control Policy**

Command and control policy mechanisms are those in which governments require or prohibit specific actions [29]. Typically this is manifested through a strict rule that must be met regardless of the situation for a firm or consumer. For instance, in the U.S., command and control policies exist in environmental policy, such as the Corporate Average Fuel Efficiency (CAFE) standards for automobile manufacturers. In these standards, a strict requirement exists for all automotive manufacturers. Each of these manufacturers must meet or exceed the standard, or they face high fines and possible exclusion from the U.S. market [30]. As is the case for CAFE standards, if sufficient resources are available for monitoring and enforcement, these approaches can be quite effective.

However, it has been noted throughout literature that when governments are unable to offer such monitoring, when environmental damage comes from hard to detect sources, and when the need is to encourage innovation rather than prohibit action, these command and control approaches are often less effective than other potential measures [14, 29, 31, 32]. Additionally, due to the lack of flexibility for regulated entities to decide

how to best meet their emissions reduction targets, these types of regulations tend to be less cost effective than other market based measures [7].

As such, the strength of command and control policy is the ability to achieve a stated goal through a well-defined course of action. By specifying a strict rule set to abide by, regulatory bodies are able to achieve these goals with very little uncertainty. However, this level of government control provides very little flexibility for the entities being regulated, and offers no incentives for further regulation beyond a stated goal. Subsequently, command and control policy is typically only effective in relatively homogeneous markets where regulatory bodies can provide significant oversight.

For a more complete discussion of the results of command and control policy, such as CAFE Standards, please refer to Appendix A.

#### **1.4.2 Market Based Measures**

Market based measures are those policies that provide an economic incentive for change. These options typically include environmental levies, such as charges and taxes, and emissions trading. The perceived benefit of such approaches is the potential to encourage technological innovation and improve efficiency, including the reduction of demand for air travel, which is a necessity for overall reductions in CO<sub>2</sub> emissions [2, 5]. It has been mentioned throughout the most recent IPCC assessment report released in 2007, that policies that provide a real or implicit price of carbon could create incentives for both producers and consumers to significantly invest in low GHG products, technologies, and processes [2, 33]. Further, researchers in regulatory policy, such as

Elinor Ostrom, have argued that financial instruments can provide incentives to achieve emissions reduction targets [29]. Ultimately, what is being indicated through economic research is that these market based approaches to policy are more likely to provide a balance between the costs and benefits of achieving GHG reductions. That being said, due to the more decentralized control of these mechanisms, there is greater uncertainty regarding how the goals set forth are achieved.

The following discussion will highlight both emissions trading and taxes, offering some examples of each policy scheme implemented in the U.S.

#### **1.4.2.1 Trading and Offsetting**

While trading and offsetting market based mechanisms provide incentives for environmental improvement, they can be quite varied in how they are implemented. Currently, one of the most popular schemes for market based policy mechanisms is through the establishment of trading and offsetting, which is also often referred to as cap and trade policy. GHG emissions trading and offsetting was initially introduced as a part of the Kyoto Protocol in 1997, which provided three distinct mechanisms to do so [2, 34]:

1. **Emissions Trading:** Developed countries may transfer Kyoto units to, or acquire units from, another developed country.
2. **Clean Development Mechanism (CDM):** This project-based mechanism involves credits generated from the implementation of emission reduction projects or from afforestation and reforestation projects in developing countries.

3. **Joint Implementation (JI):** A project based mechanism where one developed country can invest in a project that reduces emissions or enhances sequestration in another developed country, receiving credits for the emissions reduction.

The ideas surrounding trading and offsetting have become core tenets of a number of current regulatory policy mechanisms, with one of the most widely discussed globally being the European Union's Emission Trading Scheme (EU ETS). A more thorough examination of the EU ETS is provided in 2.4.2.2, as it pertains directly to commercial aviation. However, trading and offsetting policy mechanisms have been implemented in the U.S. as well in recent decades. In fact, one of the most celebrated domestic environmental policies is the U.S. EPA's Acid Rain Program established under the Clean Air Act of 1990 [35]. In order to provide a more complete understanding of this cap and trade policy in the domestic U.S. the following discussion is provided.

#### ***1.4.2.1.1 Clean Air Act of 1990***

Arguably one of the most influential cap and trade programs implemented globally was the U.S. Acid Rain program created under Title IV of the Clean Air Act of 1990. The amendments implemented in the CAA of 1990 were specifically aimed at reducing the sulfur dioxide (SO<sub>2</sub>) and nitrogen oxide (NO<sub>x</sub>) emissions from electric utility generators [36]. In order to accomplish this objective, a permanent cap was set on SO<sub>2</sub> emissions from utility companies at about half of the annual emissions occurring in 1980 [35, 36]. Additionally, one of the core tenets of this market-based approach to environmental regulation was the unrestricted trading of emission allowances by utility

companies. Each allowance ultimately represents one ton of SO<sub>2</sub> emissions released from a plant's smokestack, and they are issued based on the set cap and a relative measure of market presence [35]. If a given utility generator expects to emit more SO<sub>2</sub> than available allowances permit, it must purchase allowances on an open market or implement technologies to control emissions. It is this flexibility in compliance that has been cited as a harbinger for efficient, inexpensive innovation in the U.S. coal power generation market. In fact, it has been noted in literature that the CAA of 1990 did not necessarily lead to "more innovation", but rather produced "more environmentally-friendly innovation" [37].

The result of this cap and trade policy was ultimately a substantial reduction in acid deposition in the environment. This quite obviously occurred due to the fact that the patents granted during the 1990s showed significant improvement in the efficiency of the scrubbers removing pollutants from coal power producers [37]. In fact, it has been shown that the rate of decline of acid deposition in the environment has accelerated since Phase I of the 1990 CAA was implemented in 1995, and as of 2005 emissions reductions totaled more than 7 million tons of SO<sub>2</sub> from power plants, reaching almost 41% below 1980 levels [35, 38]. As a result, it's quite apparent that this type of market-based cap and trade policy has been shown to be effective at reaching substantial environmental goals.

In addition to meeting environmental goals, one of the most widely discussed aspects of market-based policies is the potential to meet environmental objectives at a lower cost than through traditional command and control approaches. Interestingly, the regulation of emissions from coal fired power plants occurred under a command and



control regime prior to 1990, so the economic impacts of the two distinct policy mechanisms can be compared directly. What has been identified in literature is that the research and development for scrubbers performed under the command and control period did not result in a cleaner environment, but just in a lower compliance cost for the utilities [37]. It has been evident throughout implementation of this policy that the market-based approach has allowed for greater flexibility in how utility generators comply with the law, leading to more efficient and inexpensive mitigation of emissions. Despite this success, there has been some criticism of cap and trade policy in literature due to the uncertainty and volatility of allowance price created in an open trading market [39].

In the end, what the CAA of 1990 was able to demonstrate was that for power producers, previous command and control policy incentivized innovation that lowered the cost of installing and operating scrubbers, while market-based policy produced a real cost of emissions incentivizing real improvements on the efficiency of the scrubbers at removing the pollutant species targeted [36, 37]. In the context of commercial aviation, some direct comparison can occur regarding aircraft owners and operators. If policy only dictates the types of aircraft that could be employed (command and control) then air carriers could be incentivized to utilize only those that lower the cost of operations without a direct link to any specific pollutant species. However, if a real cost is associated with a pollutant species, then it is likely that air carriers would be incentivized to reduce emissions in the most efficient manner possible.

### 1.4.2.2 Taxes and Levies

Another widely discussed, although rarely implemented market based policy mechanism, is environmental levies, which include environmentally focused taxes and other charges. While some nations throughout the world have already imposed fuel taxes on domestic air services [40], direct taxation of the aviation industry is often a contentious issue [41-45]. Despite this political controversy, the idea is widely discussed among policymakers and the organizations they represent, especially in response to the current urgency to address environmental protection [2, 28]. In large part, this consideration is a result of the acceptance among economists and policymakers that emissions taxes are generally a more economically efficient policy tool to address GHG emissions than other policies, including trading and offsetting schemes [2, 7, 8]. The reasoning behind such claims is illustrated by the U.S. Government Accountability Office in a 2009 report where it's noted that higher fuel prices would make the costs of low-emissions technologies relatively cheaper and would likely encourage their development [7]. However, the overall impact of these environmental levies is dependent on worldwide participation, since the existence of lower taxes in a given region could lead to a "race to the bottom". As such, most studies considering the implementation of environmentally effective levies recognize the need to consider them in the context of an international framework [5, 46].

Ultimately, both trading and offsetting schemes as well as environmental levies work from the same principle, which is to create a real price for emissions. While trading and offsetting tends to be viewed as more politically feasible [39], current legislation

exists throughout the U.S. that specifies a direct tax on gasoline sales. Typically, these taxes vary from state to state, however, they have all been shown to have a real impact on consumer demand for gasoline, and thus overall emissions of CO<sub>2</sub> [47]. As such, they have proven to be an effective mechanism to curb consumer demand, and mitigate overall GHG emissions. Despite this fact, there have often been concerns raised regarding this form of environmental levy as being a regressive policy [48]. That is, a policy which has a disproportionate effect on less affluent members of society. While it's recognized that this concern exists, research has shown that the disproportionate effects of such a tax in the U.S. have been less regressive than initially thought [49].

#### **1.4.2.3 Summary of Market-Based Measures**

In the end, the market-based policy measures discussed here operate in fundamentally the same capacity. That is, they create a real cost for GHG emissions in order to reduce demand, spur innovation, and incentivize new technology adoption. Given this, there are a number of differences between trading and offsetting schemes and environmental levies. While the previous discussion implicitly covers these differences, Table 1.1 is provided to summarize the main advantages and disadvantages of each approach in order to more explicitly highlight the underlying differences.

**Table 1.1: Comparison of Trading and Offsetting with Taxes and Levies**

	<b>Trading and Offsetting</b>	<b>Taxes and Levies</b>
<b>Advantages</b>	<ul style="list-style-type: none"> <li>• Creates a real price for emissions</li> <li>• Provides a known emission cap</li> <li>• Allows flexibility in meeting goals</li> <li>• Incentivizes technology investment</li> </ul>	<ul style="list-style-type: none"> <li>• Creates a real price for emissions</li> <li>• Incentivizes technology investment</li> <li>• Produces real impact on consumer demand</li> </ul>
<b>Disadvantages</b>	<ul style="list-style-type: none"> <li>• Uncertain compliance cost</li> <li>• Potential volatility in allowance market</li> <li>• May produce disproportionate effects on entities</li> </ul>	<ul style="list-style-type: none"> <li>• May be regressive</li> <li>• Creates uncertain emission totals</li> </ul>

### **1.4.3 Voluntary Agreements**

In addition to these market based policy mechanisms, there are also a number of voluntary agreements currently being explored in order to address GHG emissions reductions in aviation. These voluntary agreements are measures that are taken in the absence of relevant regulatory obligations, or those that extend beyond existing obligations. Typically, these types of agreements occur in the presence of “win/win” situations where environmental and economic progress coincide [40]. Currently a number of these voluntary arrangements are in place throughout the world, including the Asia and Pacific Initiative to Reduce Emissions (ASPIRE); GHG emissions targets set between Transport Canada and the Air Transport Association of Canada; negotiated agreements among airlines, air traffic control, government and manufacturers in Romania; and voluntary emissions trading schemes in Japan and New Zealand [2]. Despite this perceived progress addressing GHG emissions on a voluntary basis, behavior changes are

only likely to occur so long as everyone involved benefits from the reductions. As such, it's anticipated that such behavior changes may occur through increased public awareness of climate change, but government intervention to encourage further change will still be necessary [39]. This is certainly the case in the face of situations where emissions reductions do not align with economic progress.

### **1.5 Assessing Policy Interaction in Civil Aviation**

While a number of environmentally focused policies are being agreed upon throughout the aviation industry, one area that still remains relatively unexplored among policymakers is the assessment of policy interdependencies and interaction. That is not to say that it has not been considered though, as there is recognition among policymakers that taking on climate change mitigation will affect a number of policy areas [39]. Given the complexity of the civil aviation industry as an integrated system with tradeoffs and interdependencies, it is highly likely that no single solution will adequately address CO<sub>2</sub> mitigation throughout the entire industry. As a result, a number of policies must be pursued concurrently, and their interaction with one another and the civil aviation industry must be understood.

Currently, the U.S. is pursuing a mix of solutions including advanced quiet, clean, and energy efficient aircraft technologies and alternative jet fuels, to the implementation of environmentally focused operational procedures and market measures [50]. Similarly, EU member States have been invited to voluntarily submit action plans outlining their “baskets of measures” and actions to reduce international aviation CO<sub>2</sub> emissions through Resolution A37-19 with ICAO as the reporting body [51]. Ultimately, the implicit

assumption occurring in both the U.S. and the EU is that each region will know best how to meet their share of the global CO<sub>2</sub> emissions targets. While regulatory bodies such as ICAO have pointed out that when selecting policy mixes, the interdependencies between environmental effects and policies ought to be considered, there has been no established framework on which to accomplish this assessment [52]. Despite this fact, as of 2010, the Group on International Aviation and Climate Change (GIACC) under ICAO has outlined the basket of measures to address CO<sub>2</sub> mitigation, and called on EU member States to begin their selection process [52, 53]. ICAO invited voluntary submission of national action plans (NAP) to the GIACC by June of 2012, and has since made a number of those submissions public [54]. Despite providing some guidance for submission of these action plans, the result from each UN member state is often quite divergent, and there is little indication that international goals are recognized or addressed in the national plans submitted [55-71]. That being said, the publicly available NAPs do prove quite useful in identifying policies addressing CO<sub>2</sub> mitigation that are common to a number of regions. Two of the most widely discussed policies are a new aircraft certification standard and various trading and offsetting schemes.

Based on the evidence surrounding policy mix identification and selection from U.S. and international regulatory bodies, it is quite apparent that the approach is accomplished on a case by case basis. It's unclear that the emergence of regionally specific policies addressing CO<sub>2</sub> will work toward the same internationally accepted CO<sub>2</sub> goals, and further how they may impact other policies not currently being considered, such as CO<sub>2</sub> taxes and levies. At the heart of this issue is the lack of a formalized process

to analyze the potential policy design space in the context of the global civil aviation system. Due to the inherent complexity of this system, policy is currently only discussed in isolation, and typically under highly aggregated models of system behaviors. By making policy decisions in this environment we risk over-constraining the industry, creating a patchwork of regional policies, and introducing policies that exhibit feedback on one another and the civil aviation system, potentially creating adverse emergent behaviors. This particular issue is the crux of the following research, which is intended to answer the following question.

*How can the knowledge of policy tradeoffs and interdependencies be used to help meet internationally established goals?*

## **1.6 Addressing the Need**

While it's clear that the primary need in aviation is to address the continually growing CO<sub>2</sub> emissions to provide a sustainable civil aviation system, a number of more specific issues regarding this pursuit have been identified in literature. ICAO has been the international body leading the charge in the study of options for limiting GHG emissions; however, they have not yet been able to devise or have chosen not to publicly formalize a suitable framework for implementing effective mitigation policies concurrently [4]. This is unfortunate since making sound decisions for investments in future technologies requires a stable international regulatory framework based on dependable scientific knowledge [2]. Further, with the GIACC recommendation that EU member States establish their own baskets of measures to address CO<sub>2</sub> mitigation, the absence of such a framework could make coordination more difficult, create distortion among competition,

and create unnecessary burdens for compliance [53]. Unfortunately, the reality of effectively addressing CO<sub>2</sub> emissions in civil aviation will require complex institutional arrangements, with redundancies nested in many layers. It is well understood that simple strategies for CO<sub>2</sub> mitigation that rely exclusively on a single market level, centralized command and control, or that eliminate redundancies in the name of efficiency will fail [29]. Thus, the linking of regional and local emissions policy must be the road forward. This must be pursued cautiously as there is little experience in linking emissions trading schemes or other policies [2].

Despite the lack of a standard policy analysis framework on which to make decisions, a number of policy options exist, including policies that set a price on emissions, market based measures, regulatory standards, and funding for research and development that can help reduce CO<sub>2</sub> emissions for commercial aviation [7]. Additionally, there is agreement and a great deal of evidence that supports the view that a wide variety of national policies and instruments can be employed to create the incentives for mitigation action, and that each region of the world (member state) will be able to best decide how to meet international emissions goals [33]. Ultimately, their applicability and effectiveness will depend on regional circumstances and an understanding of their interactions.

From the following discussion, it is quite evident that the mitigation of CO<sub>2</sub> in civil aviation is a primary concern for policymakers throughout the world. As it's unlikely that technology or operational efficiency alone will provide the necessary reductions in fuel use to stabilize GHG emissions from aviation, the only feasible course



of action is to pursue a range of mitigation measures. These measures will likely come in the form of internationally agreed upon aircraft CO<sub>2</sub> standards, emissions trading schemes, and potential environmental levies. However, due to the current approach to policymaking it's likely that various states throughout the world will pursue their own mix of policy options in order to best meet CO<sub>2</sub> targets without a standard framework on which to assess interactions throughout the civil aviation industry.

The purpose of this research will be to establish a formalized process that will serve as the needed policy analysis framework to allow policymakers to make informed decisions based on quantitative data of the civil aviation industry. This process will be exploratory in nature, in order to provide a basis to understand the full realm of possible consequences of regulatory policies and their interactions. The intent is to account for the interaction of policies, and provide a more open policy design space throughout the policymaking process. In addition to this primary goal, an expansion of the lexicon upon which regulatory policy can be discussed will also be pursued. The purpose of expanding this lexicon will be to provide a common language that can be used to discuss regionally specific policy and track potential interaction in a global context. Based on analysis of current literature and submitted NAPs, this research will focus on two distinct policies widely discussed throughout the world. Those policies are a new certification standard aimed at increasing aircraft efficiency, and emissions trading schemes which will provide a real cost for CO<sub>2</sub> emissions. In order to demonstrate the usefulness of formalizing a quantitative, concurrent policy analysis process, implementation within the domestic U.S. will serve as the geographic region of study. The hope is to provide evidence of success

that could then be applied to other regions of the world, ultimately helping to inform future versions of UN member states' NAPs.

## **CHAPTER 2**

### **CURRENT PROGRESS ON DEFINING AND ADDRESSING CO<sub>2</sub> MITIGATION**

Given the need to provide a framework for the quantification and scientific analysis of environmental policy tradeoffs in civil aviation, the problem that CO<sub>2</sub> represents for commercial aviation must first be addressed. Following this, a discussion of the structure of the civil aviation system will be provided. Additionally, policymaking in the context of commercial aviation will be addressed, and the inherent uncertainty regarding both policy and the physical system will be discussed. Provided with this background on the problem of CO<sub>2</sub> policy in civil aviation, the foundations for exploratory modeling proposed to address this need will be covered, in addition to suitable policy analysis frameworks that can be employed.

#### **2.1 Defining the CO<sub>2</sub> Problem in Civil Aviation**

In order to establish an effective policy analysis framework that can account for multiple mitigation measures nested at different levels of a complex system, an understanding of the type of problem CO<sub>2</sub> mitigation represents is first necessary. From a conceptual perspective, the problem can be stated as follows: the atmosphere represents a finite resource of clean air, as we externalize the costs associated with civil aviation activities through the emission of CO<sub>2</sub> we deplete this finite resource. While this may seem to be a gross simplification of the problem, it serves to show that our CO<sub>2</sub> emissions are the result of the cost of polluting being lower than the cost of removing those pollutants before they reach the atmosphere. As we continue to put these pollutants into

the atmosphere there may be a point in time when our pristine environment no longer exists in its useful state, and catastrophic climate impacts can occur. In this way, the problem of CO<sub>2</sub> emissions in civil aviation can be viewed as a tragedy of the commons problem, where the atmosphere represents our global commons. There has been a great deal of discussion regarding these problems in the social sciences, and their relevance to pollution, including GHG emissions, is widely accepted [72].

In addition to being a tragedy of the commons problem, the focus of this policy analysis framework is to assist the global civil aviation industry as a whole to meet very aggressive emissions goals. The air transportation system represents a highly complex system, with heterogeneous, geographically distributed, component systems working together to perform functions that could not be anticipated by a single system alone. It will be shown that this structure is typically classified as a system-of-systems (SoS). Subsequently, the mitigation of CO<sub>2</sub> throughout civil aviation can be characterized more specifically as a system-of-systems tragedy of the commons. For more information regarding tragedy of commons please refer to Appendix B.

## **2.2 Tragedy of the Commons as a System-of-Systems (SoS)**

It should be noted that many of these tragedy of the commons involve a number of systems or actors operating cooperatively in a hierarchical structure, producing aggregate effects at a level that cannot be predicted by the analysis of a single system or actor alone. Generally, these system structures are referred to in academic literature as complex systems or systems-of-systems depending on the criteria by which they act. In the canonical example of the shared pasture land, the individual herdsman can be thought

of as a system, as can the pasture itself. The community or village in which these systems interact could then be considered a higher level system. As was illustrated in the previous sections, while each component system (herdsman) maximized individual utility, the result for the higher level system (community) was ruin.

In analyzing tragedy of the commons problems, it is observed that many (including the civil aviation industry) can be classified as system-of-systems problems. The following discussion will provide a background on system-of-systems, including a definition and criteria by which they can be categorized. In doing so, it will be shown that the civil aviation system can be classified as a SoS, and further that regulatory policy in the civil aviation system is an integral part of the SoS structure.

### **2.3 System-of-Systems Background**

The numerous definitions provided by researchers in the field of system-of-systems engineering (SoSE) can create some confusion around such an abstract concept as SoS. As a basis for understanding SoS, the Department of Defense (DoD) defines SoS as “a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities [73].” Within this definition the system is treated as a group of regularly interacting elements forming a unified whole which are functionally, physically, or behaviorally related [73]. In the context of commercial aviation a system can be viewed at a number of levels. For instance, the aircraft itself is a system of physically and functionally related components making up a vehicle. In the same vein, the congregation and utilization of these vehicles at the level of air carriers can also be considered a separate system, where the interactions of the aircraft are behaviorally

related. This type of interplay among the systems ultimately continues through higher levels of the global air transportation system.

### **2.3.1 System-of-Systems Types**

Given this generalized definition underpinning SoS, it should be recognized that a number of different types of SoS exist. There are four basic types of systems-of-systems identified by the DoD that are often cited throughout SoS literature, which include virtual, collaborative, acknowledged, and directed [73-75]. Each of these forms of SoS will be briefly introduced here, with specific attention paid to how the air transportation system fits into the provided definitions.

#### **2.3.1.1 Virtual System-of-Systems**

Virtual SoS are characterized by a lack of central management authority or control, as well as an unspecified agreed upon purpose for the system-of-system [73]. Ultimately the behaviors that emerge may be desirable, but the SoS relies on unknown mechanisms to maintain it. In a sense, the interaction of a community without a central housing authority could be considered a Virtual SoS. In this example, individuals in the community would act as independent entities lacking any centralized control or goal. While their interactions may produce emergence that benefits the community as a whole or not, the connections throughout the community remain relatively invisible.

### **2.3.1.2 Collaborative System-of-Systems**

Building from the Virtual SoS, Collaborative SoS also lack centralized authority; however, the component systems tend to interact voluntarily to accomplish agreed upon purposes [73]. As such, the component systems retain independence and individual control while working toward a more collaborative goal. The most widely discussed and established Collaborative SoS throughout literature is the Internet [73, 76]. In this SoS, the entities comprising the interconnected web services collectively decide methods for providing or denying service. So, while the Internet Engineering Task Force exists to work out standards (agreed upon central purposes) it has no actual authority on which to enforce them. Despite this lack of centralized control, the Internet tends to produce behaviors which enforce and maintain the standards established by the Internet Engineering Task Force.

### **2.3.1.3 Acknowledged System-of-Systems**

Taking this buildup one step further, Acknowledged SoS are characterized as having recognized central objectives, a designated manager or authority, and resources for the SoS. However, the component systems in an Acknowledged SoS retain independent ownership, objectives, funding, and development and sustainment approaches [73]. In this sense, the commercial air transportation system can be viewed as an Acknowledged SoS. The ATS operates at a high level in order to transport people and goods throughout the world, and is ultimately managed by a number of control authorities and regulatory bodies, sharing common resources such as airports, air space, and the like.

Additionally, the component systems represented by air carriers and aircraft manufacturers operate independently, retaining ownership and funding of their individual activities. Ultimately, what is important to note from this recognition is that commercial air transportation can have agreed upon central goals (ie. the mitigation of CO<sub>2</sub>), has a designated managing authority (such as ICAO, the FAA, etc.), but the systems that comprise the ATS retain independent functionality.

#### **2.3.1.4 Directed System-of-Systems**

Finally, Directed SoS take the concept of integration within a SoS to its logical extreme where the system-of-systems is developed and managed to fulfill specific purposes [73]. These Directed SoS are centrally managed throughout the life of operations to fulfill any purposes the managers of the SoS may wish to address. While the component systems maintain the ability to operate independently, typical modus operandi subordinates control to the centrally managed purpose. An example of such a SoS would typically come from a national defense perspective, where a number of component systems operate to fulfill a specified mission under the control of a central command [77].

#### **2.3.2 Proposed Definition of System-of-Systems**

Moving beyond this generalized understanding, the underlying concepts of SoS tend to share a number of key tenets, and as such, SoS generally entail physically distributed systems with overall functionality dependent on linkages between heterogeneous, distributed systems [78]. Within some systems, such as the air



transportation system, many of these component systems are sentient, and involve the complex interactions of thinking and evolving resources. In order to capture this nuance of the particular SoS being studied here, a more complete definition adopted as provided by DeLaurentis:

*“[SoS are] a collection of trans-domain networks of heterogeneous systems likely to exhibit operational and managerial independence, geographical distribution, and emergent behaviors that would not be apparent if the systems and their interactions are modeled separately [79].”*

This definition provides a rather comprehensive summary of SoS, and incorporates the five principles of true SoS outlined by Maier [74]. These principles are operational independence, managerial independence, evolutionary development, emergent behavior, and geographic distribution. A summary of these properties is reproduced in Table 2.1, and is adapted from [74]. They will ultimately be used to define public policy as an integral part of SoS, and adapted to formally define systems-of-policy-systems (SoPS).

**Table 2.1: Properties of Systems-of-Systems (SoS)**

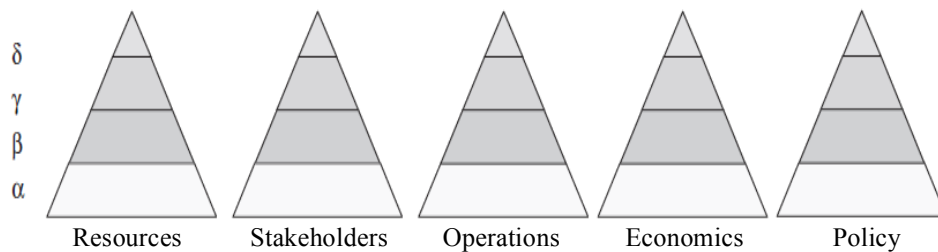
<b>Principle</b>	<b>Description</b>
Operational Independence of Elements	The systems comprising the SoS can operate independently and are useful in their own right.
Managerial Independence of Elements	The systems comprising the SoS not only can but do operate independently in a useful way.
Evolutionary Development	The SoS is never fully formed. Functions are often added, removed, and modified.
Emergent Behavior	The principle behaviors of a SoS cannot be localized to any component system. They are emergent properties of the system as a whole.
Geographic Distribution	The geographic extent of the systems in a SoS is large enough such that information can be shared but not mass or energy.

### **2.3.3 SoS Lexicon**

These definitions and principles provided by the DoD and academic researchers provide a foundational basis for understanding SoS; however, defining a SoS is only the first step in identification of true SoS problems. Moving past identification, to classify and discuss the SoS, a lexicon is required. This lexicon must serve as the common language among SoSE that allows ideas and solutions to be discussed throughout the community at large. Unfortunately, this formal lexicon has been largely absent or underdeveloped by many SoSE in the field, although in recent years the idea of promoting a lexicon and ultimately taxonomy specific to SoS has taken hold. Leading this effort has been academics such as DeLaurentis and Callaway, who in 2004 proposed one of the first explicit lexicons describing the categories and hierarchy of transportation SoS problems [80]. This lexicon has been adapted somewhat since first being proposed in

2004, and the lexicon provided here is an interpretation of DeLaurentis' work since that time.

The lexicon consists of two primary structures, system categories and hierarchical levels of organization. The system categories provide a decomposition of the distinguishing traits of SoS problems, each of which is composed of multiple hierarchical levels, where each level represents a collection of systems organized in a network. The levels are given Greek symbols in order to avoid confusion with naming conventions (i.e. subsystem, system, system-of-system, architecture) [80]. DeLaurentis presents this overarching structure as an “unfolded pyramid”, and a reproduction of this pyramid is provided below in Figure 2.1 [80, 81]. Additionally, a more complete description of the system categories is provided in Table 2.2 below [80-82].



**Figure 2.1: System-of-Systems (SoS) Structure [80]**

**Table 2.2: System-of-Systems (SoS) Category Descriptions [80]**

<b>Category Name</b>	<b>Description</b>
Resources	Entities that give physical manifestation to the SoS
Stakeholders	Non-physical entities that give intent to the SoS operation through established values
Operations	The application of intent to direct the activity of physical and non-physical entities
Economics	The non-physical, sentient systems that give a “living system” character to the operation of physical entities in a market economy
Policy	External forcing functions that impact the operation of physical and non-physical entities

#### **2.3.4 Civil Aviation as a Transportation SoS**

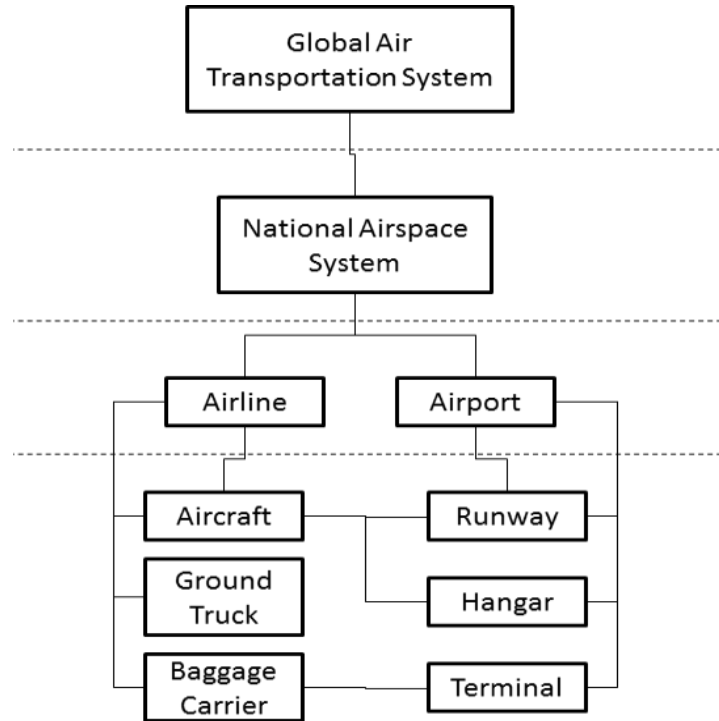
Civil aviation as a transportation SoS has been widely discussed throughout literature [78-80, 83-92]. As such, a discussion of the application of the principles of SoS will be directed to existing literature, while the discussion of civil aviation as a SoS here will illustrate the hierarchical structure of the air transportation system. In order to begin to discuss civil aviation as a SoS, the lexicon previously developed will be utilized. As a starting point, the application of this lexicon for general transportation SoS is introduced in Table 2.3 [80]. This table provides a general description of the resources, operations, economics, and policies at each level of the SoS.

**Table 2.3: Lexicon for Understanding Transportation System-of-Systems [80]**

	Resources	Operations	Economics	Policy
$\alpha$	Vehicles & infrastructure (e.g., aircraft, truck, runway)	Operating a resource (aircraft, truck, etc.)	Economics of building/operating/ buying/selling/leasing a single resource	Policies relating to single-resource use (i.e., no. of attendants per passenger for vehicle type)
$\beta$	Collection of resources for a common function (an airport, etc.)	Operating resource networks for common function (e.g., airline)	Economics of operating/buying/ selling/leasing resource networks	Policies relating to multiple vehicle use (i.e., local airport noise policies)
$\gamma$	Resources in a transport sector (e.g., air transportation)	Operating collection of resource networks (e.g., commercial air Ops)	Economics of a business sector (e.g., airline industry)	Policies relating to sectors using multiple vehicles (FAA certification, safety, etc.)
$\delta$	Multiple, interwoven sectors (resources for a national transportation system)	Operations of Multiple Business Sectors (i.e., operators of total national transportation system)	Economics of total national transportation system (All Transportation Companies)	Policies relating national transportation policy
$\epsilon$	Global transportation system	Global operations in the world transportation system	Global economics of the world transportation system	Global policies relating to the world transportation system

In order to translate this table to the hierarchical structure of the unfolded pyramid previously developed, specific entities in each category and level can be mapped through their given interactions. To provide a brief look at how such a mapping could occur for the global air transportation system, Figure 2.2 provides a resource example of a notional SoS structure for civil aviation. This figure has been adapted from the previous work of DeLaurentis and Callaway [80]. As can be seen here, at the lowest level of the SoS hierarchy are individual system resources, such as aircraft, runways, and terminals. These resources serve as component systems of higher level systems, such as the airlines and airports, which in turn are grouped in the national airspace systems, and ultimately the global air transportation system. While the greek symbols representing the hierarchical

levels do provide a general structure for mapping, future discussions regarding SoS will utilize more descriptive names of levels.



**Figure 2.2: Resource Example of the Global Civil Aviation System-of-Systems Hierarchy**

It should be noted here that while policy is given a category in the SoS structure, there is no differentiation between the internal policies of an organization and policies coming from regulatory bodies. As such, there is still a great deal of confusion regarding the treatment of regulatory policy in these transportation systems. While select academics such as DeLaurentis and Augusdinata have discussed the implementation of regulatory policy analysis and design in a SoS, these ideas have yet to be implemented in such a context [78, 80]. Ultimately, one purpose of this dissertation is to provide a sound

foundational framework to include policy analysis in the context of such transportation SoS. This idea will continue to be explored throughout this document.

## **2.4 Policymaking in Civil Aviation**

Given this understanding of the physical structure of the civil aviation industry, it's next important to provide an overview of regulatory policy in the context of this SoS. The following discussion will provide an historical perspective on regulatory policy in commercial aviation, as well the environmental policies currently gaining traction throughout the industry.

### **2.4.1 An Historical Perspective**

Since the late 1960s, regulatory policy has been a part of the civil aviation industry. As mentioned in the Chapter 1 of this document, regulation in the civil aviation industry has typically only come about as a result of immediate concern or annoyance, which will be highlighted in this discussion. Additionally, a number of unintended consequences have occurred and will be mentioned.

While the Wright brothers' first flight occurred in 1903, regulatory policy was absent from the civil aviation community until the late 1960s, when the noise resulting from the rapid growth in civil aviation began to become a nuisance. In 1969, less than a decade after the introduction of the Comet 4 and Boeing 707, widespread complaints of noise around airports led the U.S. Federal Aviation Administration (FAA) to introduce its first aircraft noise regulations, Federal Aviation Regulation (FAR) Part 36 [28, 93].

Almost immediately after this ruling, ICAO followed suit in 1971 by adopting similar standards in ICAO Annex 16, Chapters 1 and 2, which outlined acceptable noise levels for both early jet engines, as well as the relatively new aircraft powered by the quieter low bypass ratio turbofans [28]. These rules were updated in 1977 when ICAO adopted Chapter 3 Noise Standards, setting much more demanding requirements for new aircraft entrants that could only be met by medium and high bypass ratio turbofan engines, and in 1990 further regulations began to require all Chapter 2 aircraft to be withdrawn from service within 12 years [28]. In 2001, ICAO adopted Chapter 4 noise requirements, which now impact all new aircraft types certified after January of 2006 [28]. This progression of stricter noise requirements has occurred as a result of ever increasing demand and utilization of airports, which has created a great deal of noise pollution around many of the world's largest airports.

The main instrument through which newer aircraft have been able to meet noise requirements has been the progressive increase in engine bypass ratio, which was driven by the demand from airlines for better fuel economy and lower noise; however, there have been adverse consequences as a result of these decisions. While high bypass turbofan engines do reduce fuel burn and noise, they require higher engine pressure ratios, which in turn increase engine temperatures and thus NO<sub>x</sub> production [1]. Ultimately, the combination of increasing demand and increasing bypass ratio created an environment where local NO<sub>x</sub> pollution became a public health concern, and in the 1980s regulatory bodies began to consider air quality standards for civil aircraft. The first standard to address such concerns were the ICAO standards on soot, which came into

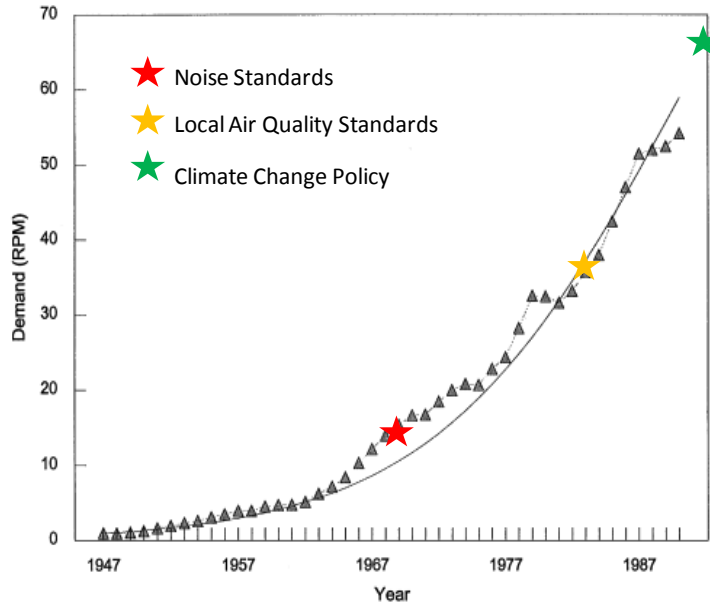


effect in 1983 [28]. The soot standards were followed in 1986 by additional standards on unburned hydrocarbons, carbon monoxide, and NO<sub>x</sub> [28]. This year represented a major milestone in international civil aviation regulatory history, as the Committee on Aviation Environmental Protection (CAEP) under ICAO established its first cycle for emissions monitoring.

Despite the rapidly growing importance of regulatory policy in civil aviation through the 1980s, it was not until the late 1990s that the impact of aviation GHG emissions on global climate change became part of the regulatory discourse. The beginnings of this recognition occurred in 1996, following a request from ICAO, which directed the IPCC to produce a special report assessing the consequences of GHG emissions from aircraft engines [28]. This directive ultimately led to the 1999 IPCC report titled “Aviation and the Global Atmosphere”, which was the first report to consider the effects of aviation in global climate change [5]. While this report was being written, the Kyoto Protocol was agreed upon, which committed signatories to cutting GHG emissions by 12.5% of 1990 levels by 2012; however, this agreement explicitly excluded international civil aviation [28, 94]. This type of exemption of international aviation from regulation is not uncommon, and in 2003 Council Directive 2003/96/EC, restructured the framework for the taxation of energy products while specifically exempting aviation fuel from taxes [40]. As a result, while the recognition of aviation’s impact on global climate change gained popularity in the late 1990s, little was done to actually address GHG emissions until the late 2000’s. Ultimately, the first binding resolution passed to address CO<sub>2</sub> mitigation from civil aviation came from the adoption of EU Directive

2008/101/EC, which included aviation in the European Union's Emission Trading Scheme (EU ETS) starting in 2012 [95-97]. Despite this step forward in mitigating CO<sub>2</sub> emissions from commercial aviation, there has been substantial pushback throughout the world regarding inclusion of aviation into the EU ETS, especially in the United States [98, 99]. With that said, more substantial international collaboration on CO<sub>2</sub> mitigation has occurred since 2009 in civil aviation, with the continued development of an aircraft certification standard under the direction of CAEP [100]. While it's not clear when this standard will ultimately take effect, it is expected to be finalized within the coming years. Due to the fact that they are the basis of the case study explored later in this research, both the EU ETS and the concept of an aircraft CO<sub>2</sub> standard will be discussed in much greater detail later in this chapter.

Given this discussion, what should be apparent from this historical perspective is that regulation within commercial aviation has only come about as a result of immediate concern or annoyance. These concerns over noise, air quality, and the climate have developed as the demand for aviation has grown exponentially since the 1950s, with passage of regulation first addressing immediate annoyance (noise), then localized concerns (air quality), and only recently a global crisis (climate change). This fact is highlighted in Figure 2.3 [101], where the introduction of different types of regulation are identified on a plot of demand growth in aviation.



**Figure 2.3: Policy Introduction as a Result of Demand**

In order to provide a more illustrative representation of the history of regulatory policy in civil aviation, the reader is referred to Appendix E. Here, the timeline outlining the major regulatory policies discussed in this section is provided in a single figure.

In the end, what is most evident regarding the history of regulatory policy in civil aviation is the order of attention given to the concerns of noise, local air quality, and climate change. What is meant by this is that the issues addressed first in commercial aviation were those that can be solved immediately, while the issues currently being addressed may take many generations to produce realizable results. It is unfortunate that climate change concerns are only recently being discussed, since ultimately they will require the greatest time and effort to produce sustainable behaviors.

## **2.4.2 Regulatory Policies Relevant to CO<sub>2</sub> Mitigation in Civil Aviation**

Despite this inaction, in the last four years policymakers have been able to agree on a number of regulations specifically targeting CO<sub>2</sub> emissions in civil aviation. In large part, these policies have come about as a result of growing interest in market based measures to regulate energy and transportation sectors, and have been focused on aircraft operators. However, more recently, there has been a push by ICAO to establish an aircraft CO<sub>2</sub> certification standard for aircraft manufacturers. The following section will address the result of these recent pushes in international policymaking in civil aviation throughout the last few years. The purpose of this discussion is to provide a basis of knowledge for the regulatory policies in questions. Due to the fact that they are expected to have great importance in the coming years, this research is attempting to first answer *“What are the impacts of an aircraft CO<sub>2</sub> standard or ETS in isolation?”* It is hoped that addressing this question will help answer, *“How will the combined effect of these policies differ from their implementation in isolation?”*

### **2.4.2.1 Market-Based Measures**

Due to the fact that market based regulatory measures have gained popularity in recent years, a number of emerging national and regional trading schemes have begun to address CO<sub>2</sub> emissions in civil aviation. The result has been the creation of a number of regionally specific CO<sub>2</sub> policies throughout the world. Likely the most important of these trading schemes is the European Union Emissions Trading Scheme (EU ETS), which was established in 2005, and modified in 2008 to include aircraft operators in the EU starting

in 2012 [1, 2, 95, 102]. Other countries, such as New Zealand, Canada, and Japan have introduced their own emissions trading schemes (ETS) [2, 40]; however, in New Zealand and Japan participation in the ETS has been voluntary, and in Canada it is still unclear whether aviation will be included. In other parts of the world, such as the United States and Australia, cap and trade systems have been considered, but there has yet to be formal rules for the inclusion of aviation into such schemes [2].

In addition to these trading schemes, other regionally specific policies are taking hold. For instance, Norway has implemented a CO<sub>2</sub> tax on aviation fuel for the domestic civil aviation industry, and Switzerland has voluntarily agreed to an 8% reduction in domestic CO<sub>2</sub> emissions from all transportation fuels, including aviation compared to 1990 levels by 2012 [40]. The introduction of a fuel tax in Norway is actually a very progressive measure regarding civil aviation CO<sub>2</sub> policy, and is a rather unique environmental levy in the civil aviation industry. There is the potential this type of environmental levy could become more common though, as it's one of the measures proposed by a number of environmental groups to mitigate CO<sub>2</sub> emissions in civil aviation [28].

#### **2.4.2.2 European Union Emission Trading Scheme (EU ETS)**

As aforementioned, previous experience with cap and trade policy mechanisms in the United States have been somewhat limited, however, these policies have been in effect since the Clean Air Act of the 1970s [103]. Ultimately, the SO<sub>2</sub> emission trading program created under the Clean Air Act of 1990 produced significant abatement of

emissions primarily from the power sector at a lower cost than expected [103, 104]. In this way emission trading tends to offer the ability to meet environmental goals in the most cost-effective way by creating a market price for carbon that is “equal to the lowest marginal abatement cost amongst all controlled sources” [103].

Further, it should be noted that cap and trade systems are also advantageous due to the fact that they provide environmental certainty on overall emissions levels from covered sources. This is accomplished through the establishment and enforcement of an overall cap on emissions. Given these facts, emission trading has been observed to be an effective way of meeting environmental goals while minimizing the distortions to competition in covered markets [103]. As such, in recent years it was deemed advantageous to integrate international aviation into existing emission trading schemes, namely the EU ETS, instead of designing a new trading model exclusively for aviation [105]. In order to become better acquainted with such schemes, Appendix C provides an overview of the EU ETS, performance throughout the trial period, known issues with the implemented policy, and insights from other studies on the EU ETS. The key features of emission trading schemes will be highlighted here for future work in this document.

#### ***2.4.2.2.1 Aviation’s Inclusion in the EU ETS***

A number of aviation specific EU ETS studies have been conducted throughout literature. More frequently, these studies are becoming objective and quantifiable in nature, relying on established models of the EU economy and business practices of the regulated entities. Dr. Annella Anger provides a good overview of some of the most

widely cited studies in a recent review of the impacts of the EU ETS on aviation, which is reproduced in Table 2.4 from [106].

**Table 2.4: Parameters and Assumptions of EU ETS Reviewed Studies**

<b>Study</b>	<b>Year</b>	<b>Trading Period Considered</b>	<b>Allowance Price (€)</b>	<b>Growth Rate of CO<sub>2</sub> Emissions</b>	<b>Cost pass-through Rate</b>	<b>Fuel Efficiency Improvements</b>
<b>Boon et al.</b>	2007	2012-2020	15-45	4%	47.3%-100%	1%
<b>Ernst and Young</b>	2007	2011-2022	6-60	4%	29%-35%	1%
<b>Frontier Economics</b>	2006	2030	27-40	3.5%-5%	Unclear	1%
<b>ICF</b>	2006	2008-2012	5-21	4%	Unclear	1%
<b>Mendes and Santos</b>	2008	2013-2017	7-30	4%	100%	Unclear
<b>Morrell</b>	2007	2005-2006	28	4%-30%	100%	Unclear
<b>Scheelhaase and Grimme</b>	2007	2008-2012	15-30	0.5%-4%	100%	1%-1.5%
<b>SEC</b>	2006	2010-2030	6-30	2%-4%	100%	1%
<b>Wit et al.</b>	2005	2012	10-30	4%	100%	1%

While many of these studies differ in design and theoretical background, a number of them have modeling similarities that can be addressed. For instance, Wit et al., Boon et. al., and SEC all use the “Aviation Emissions and Evaluation of Reduction Options Modeling System” (AERO-MS) to forecast impacts of different policy constraints on the aviation industry for both the environment and economy [106-109]. The AERO-MS model is a disaggregated, sector-specific model requiring inputs of many different exogenous assumptions, namely economic growth rates, changes in fare levels, and changes in technology efficiency [106].

In the EC’s Impact Assessment Report [109] the macroeconomic impacts, changes in transport demand, and changes in kerosene demand were all accomplished

using separate models [106]. This type of mixed modeling paradigm has been quite common throughout the literature on aviation's inclusion in the EU ETS, and often the design and theoretical background of the models are different enough to make them not comparable. As such, it's proposed by Anger that a singular model or modeling paradigm be implemented to estimate these impacts, such as the Energy-Environment-Economy Model for Europe (E3ME) [102, 106, 110, 111]. The E3ME model is described as a hybrid post-Keynesian macroeconomic dynamic simulation model designed to assess short and medium term GHG mitigation policies [112-114].

While it's agreed that consistency among modeling paradigms and assumptions is necessary for traceable policy analysis among different scientists, further discussion of such a specific modeling platform is not deemed useful for understanding the impact of aviation's inclusion in the EU ETS from current studies. It is proposed here however, that consistency in the modeling framework and traceable assumptions ought to be made in order to compare results across studies in the future.

Despite these differences, there are a number of resulting trends that are consistent among the various studies on the impact of aviation's inclusion in the EU ETS. One of the most consistent results from these studies, which has been described subjectively in previous discussion, is the fact that the air transport sector will be a buyer of allowances at any price for EUAs [102, 106-111]. This observed phenomenon from various models agrees with the subjective reasoning that the abatement costs for the aviation sector are likely to be significantly higher than for those of other sectors covered under the EU ETS. Further, a number of studies also show that the impact to airlines is



dependent on the cost of EUAs, and will range from slight (~0.5%) to moderate (~5%) changes in demand over a business as usual scenario [102, 106, 115]. Despite the expected impacts to air travel demand, the overall effect on the EU Economy is expected to be insignificant in most studies [102, 106-111]. Subsequently, it can be argued that the results from a partial equilibrium model of the aviation sector will perform similarly to those anticipated through a general equilibrium framework.

While there are many similarities among the resulting trends from these studies, there are still some differing opinions among many of the authors. One of the most evident is the determination of whether lost opportunity cost of freely allocated allowances will be passed onto consumers in the aviation market. Some authors argue that due to the level of competition and thin profitability margins, these costs will not be passed on in order to ensure competitiveness [115]. Others however, argue that like energy generators, airlines will treat all EUAs as having a market value that must be passed on to consumers, leading to potential problems with windfall profits [106]. At the moment it's unclear how airlines will treat freely allocated EUAs, however, as long as the pass through of lost opportunity costs is treated as an input variable, any modeling framework can be useful in assessing the range of possible outcomes for the inclusion of aviation in the EU ETS.

#### ***2.4.2.2.2 Key Features of Emissions Trading Schemes***

While the preceding discussion detailed the impacts of the EU ETS during its initial phases of implementation and its expected impact on the inclusion of aviation,

there are a number of key features of any emission trading scheme that can be generalized for future study. It is proposed that these features can be discussed in terms of scope of applicability, cap setting, and the allowance allocation process for emission trading schemes.

The scope of applicability is taken here to include both the entities covered under such a policy, as well as the effective date of applicability. For the EU ETS, trading initially began in 2005 (date of applicability) covering primarily power generators throughout the EU. Ultimately, this was expanded to include aviation activities starting in 2012. In general, one of the main features of any emission trading scheme is a good definition of who is covered under the scheme, and the time frame for which it is applicable.

Next, the cap setting process is necessary for any emission trading scheme. Ultimately, the absolute rule set by which the scheme will operate is intended to meet an emission target. This target is often based on scientific projections of necessary GHG emissions reductions in order to avoid catastrophic climate impacts, such as those set forth in the Kyoto Protocol and IPCC assessment reports aforementioned. The cap that is set must be reported, monitored, and verified by regulatory authorities, thus a key tenet of the cap setting process is that it must be easily measureable and the process ought to be traceable. For instance, in aviation's inclusion in the EU ETS, the cap is based on fuel sales (which can be equated to CO<sub>2</sub> production) based on a reference year output (2004 to 2006 average) that diminishes to meet emissions reductions goals from the Kyoto Protocol.

Finally, the allocation process provides the means by which allowances are allocated to trading entities covered in the scope of applicability. As has been shown in literature, this can be done through benchmarking, whereby covered entities receive allowances according to a benchmark of emission rates and a level of economic activity [105]. In aviation, this is accomplished through a benchmark period based on fuel sales, and a measure of market share through revenue-ton-kilometers [95]. In addition to this benchmarking, some harmonization may be necessary to mitigate unintended consequences in allocation to similar entities located in different member states covered under the same emission trading scheme [105]. This would be necessary for instance, if the U.S. were to adopt a cap and trade system for aviation with specific linkage to the EU ETS.

Ultimately, the initial challenge with the establishment of any emission trading scheme is to demonstrate the potential to signal appropriate short and long-term GHG mitigation by providing a real price for emissions. By internalizing the cost of emissions in this way, a system can be created to demonstrate the societal decision that the abuse of our atmosphere is not free.

#### **2.4.2.3 Aircraft CO<sub>2</sub> Emissions Standard**

At the other end of the regulatory policy spectrum are command and control policies. These policies provide a strict rule set by which covered entities must comply, such as the CAFE standards discussed previously. While not currently in effect, in 2009 States representing 93% of global commercial air traffic reached an agreement to further

reduce aviation's impact on climate change through the development of a global CO<sub>2</sub> standard for aircraft [10, 116]. The urgency of such a standard is quite apparent, since many airlines have indicated a desire for large fuel reduction goals in the next decade, driven largely through investments in fleet renewal [25]. The implicit expectation from such claims is that an aircraft CO<sub>2</sub> standard will push manufacturers to produce fleet replacements getting airlines closer to their stated environmental goals. This represents an area where the interdependency of multiple policies is quite direct. Despite this, the interaction of this standard with emissions trading schemes, namely the EU ETS, has yet to be considered in depth.

However, there has been a great deal of work on the establishment of the metric system [117], and on July 11, 2012 CAEP reached unanimous agreement on a CO<sub>2</sub> metric system for the standard [118]. This has been touted as great progress throughout international civil aviation community. The next stage in this process will include the definition of certification procedures for parameters in the metric system, and the determination of the scope of applicability for the standard [118]. Following this, official approval of the CO<sub>2</sub> metric system, and the final aircraft CO<sub>2</sub> standard, is expected from ICAO in coming years [118]. The following discussion will highlight the information available publically regarding the possible metric system chosen by ICAO, as well as the potential form of a resulting Aircraft CO<sub>2</sub> Standard.

#### ***2.4.2.3.1 Aircraft CO<sub>2</sub> Standard Metric System***

While ICAO CAEP has yet to publically identify the specific form of the metric system that will be employed in the final standard, there has been some indication as to what it may be through literature. Despite this fact, literature is relatively limited, including just a few news releases from ICAO [116, 118], as well as a report from the U.S. FAA's PARTNER Project 30 and a conference paper from researchers at the Georgia Institute of Technology [117, 119]. What is clear from this literature is that the metrics considered are simple and will directly reflect the physical properties of interest for the given standard.

From the work of Lim et. al. a number of potential metric systems were investigated and ultimately analyzed through the use of evaluation criteria. These evaluation criteria (EC) were based on historical lessons throughout the metric setting process and include [117]:

1. Differentiation of technology generation.
2. Independence of purpose and utilization.
3. Reflects fundamental design elements and capabilities.
4. Fairness and equitability across stakeholders.

Given the fact that CO<sub>2</sub> emissions are directly proportional to the amount of fuel burned for a given fuel type, all candidate metrics considered for the notional standard were based on fuel burn performance and related to fuel efficiency concepts [117]. The metric systems considered generally fall into two basic types, being full mission metrics

and instantaneous performance metrics. Full mission metrics typically normalize fuel consumption with respect to a quantifiable measure of usefulness or capability as a measure of fuel efficiency. From literature, it is clear that a number of full mission metrics were considered throughout the metric setting process, including those shown below in Figure 2.4 [117]. In these metrics, FB represents block fuel burn, which is normalized by a number of proxy measures of useful capability, including R (range), P (payload), UL (useful load), and MTOW (maximum takeoff weight).

$$\begin{array}{ccc}
 \frac{FB}{R} & \frac{FB}{P * R} & \frac{FB}{UL * R} \\
 \frac{FB}{MTOW * R} & \frac{FB}{FL * R} & \frac{FB}{Seats * Range}
 \end{array}$$

**Figure 2.4: Full Mission Metrics [117]**

Alternatively, instantaneous point performance measures of fuel efficiency were also investigated. The metric considered is known as specific air range (SAR), or nautical air mileage (NAMS), and is the air distance flown per unit fuel in steady-state flight [117]. In many ways this is analogous to miles per gallon (MPG) reported for automobiles. The advantage of such a measure is that it has been used historically in the aviation industry among operators and government agencies to classify aircraft fuel efficiency. SAR is often reported to airlines by manufacturers as a guarantee of product effectiveness. This measure is typically calculated as shown below in Equation 1 and Equation 2 [117].

### Equation 1: Generic Form of Specific Air Range

$$SAR = \frac{Speed}{Fuel\ Flow} = \frac{Speed}{TSFC \times Thrust}$$

Here TSFC represents the thrust specific fuel consumption. Additionally, if we consider the case of steady flight where Thrust = Drag and Lift = Weight, Equation 1 can also be written:

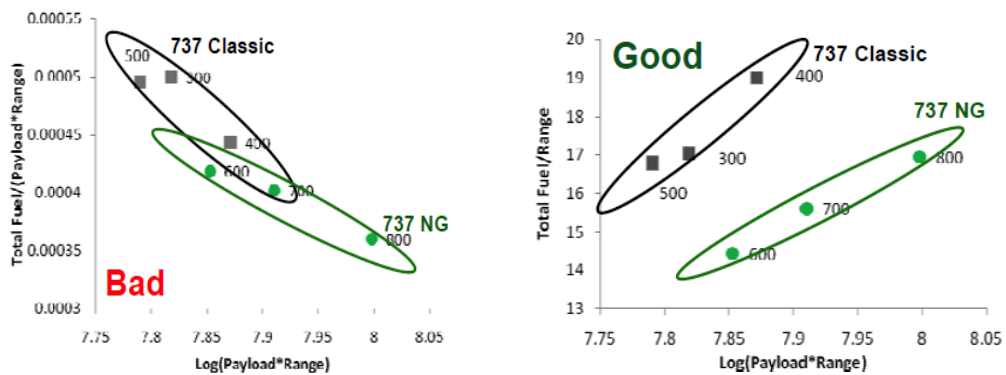
### Equation 2: Alternative Form of Specific Air Range

$$SAR = \left( \frac{Speed}{TSFC} \times \frac{Lift}{Drag} \right) \times \frac{1}{Weight}$$

As can be observed in the above equations, SAR includes measures of efficiency, namely TSFC and L/D, as well as a measure of aircraft size through weight. Due to the fact that it's currently also reported from manufacturers, it would likely have a lower certification burden in the future. While the results of Lim et. al. investigate both forms of metric systems, a recent news release from ICAO in 2012 indicates that the selected metric system was based on cruise point fuel burn performance, aircraft size, and aircraft weight [118]. While not explicitly stating this is the case, it seems quite apparent that the metric system chosen is based on a measure of 1/SAR, which would be consistent with the findings of Lim et. al. It should also be noted that the general observations of both types of metric systems indicated very similar characteristics between 1/SAR metrics and FB/R [117].

In addition to a metric, it has been shown that metric systems should also adopt a correlating parameter in order to normalize the differences in size or capability, allowing

for uniform application across the fleet [117]. These metric systems, including a metric and correlating parameter, were tested against the EC aforementioned. As just one example of the tests considered, take EC1: separation of technology generation, for instance. In this EC, the goal is to see distinct separation among similar aircraft with different levels of technology. Taking information for the Boeing 737 family based on the proposed metric systems earlier, it can be quite obvious that some metric systems show distinct separation while others do not, as seen in Figure 2.5 below [117].

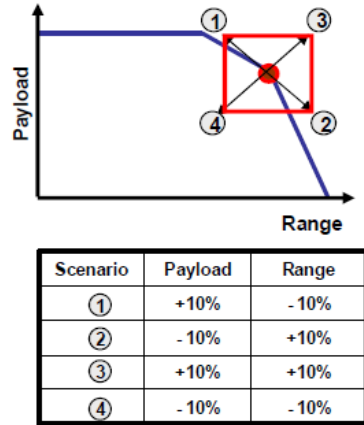


**Figure 2.5: Evaluation of Separation of Technology Generation [117]**

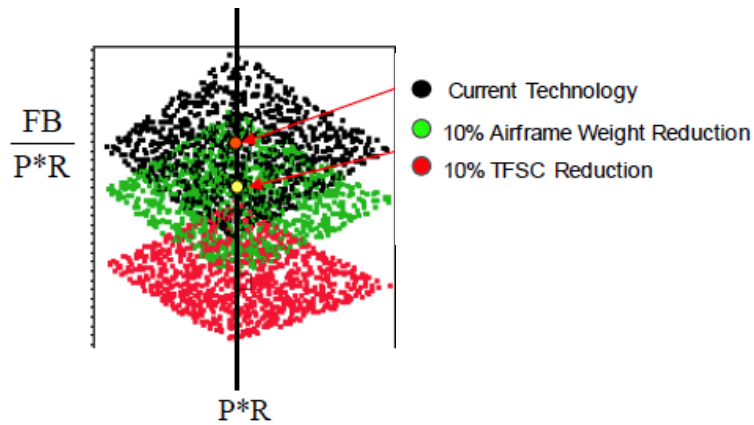
Tests have also been conducted for a number of other specific vehicles for each of the ECs listed previously. In order to conduct these tests, the Environmental Design Space (EDS) was leveraged for analysis [117, 120]. For the study conducted by Lim et. al., five vehicle classes were considered using generic vehicles in EDS [117]. In order to test two of the ECs, EC1: differentiate technology generation and EC2: be independent of purpose or utilization, physical characteristics of the vehicle were varied. The main parameters varied were the design payload and range capabilities, in order to test independence of purpose, as well as increased fuel efficiency (red dots) and weight



reduction (green dots), in order to test differentiation of technology generations [117]. Figure 2.6 shows the extent of the design payload and range changes implemented, and Figure 2.7 demonstrates the result of infusing those design change vehicles with technology integration [117].



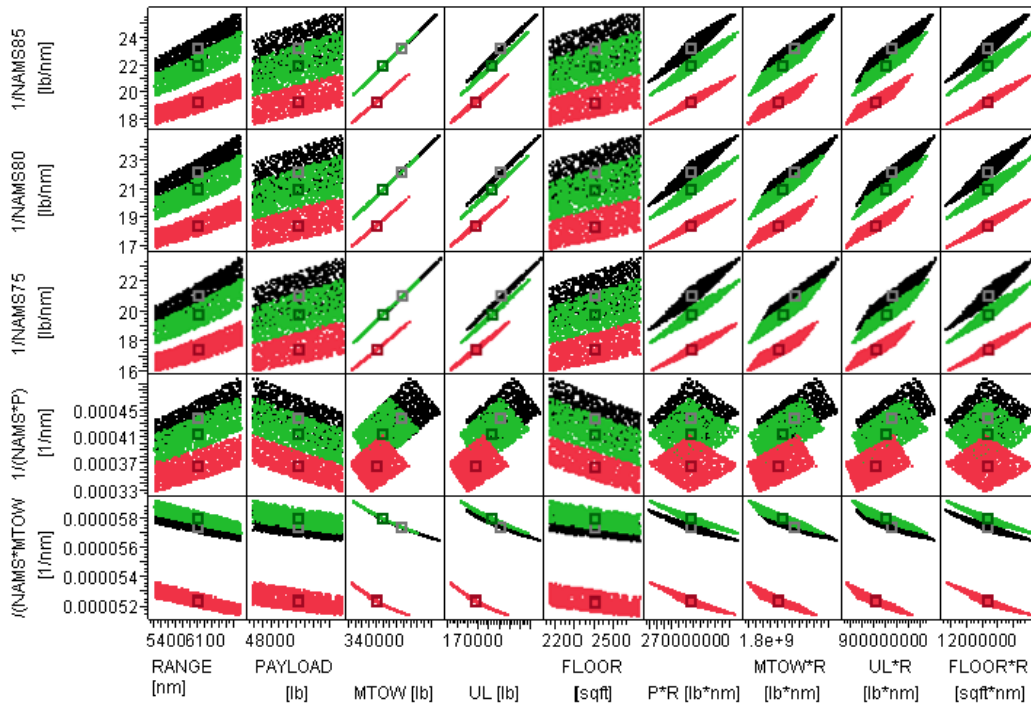
**Figure 2.6: Generic Vehicle Design Changes**



**Figure 2.7: Generic Vehicle Technology Integration**

By performing these changes simultaneously it's possible to observe the potential overlapping of design changes and technology integration. In order to provide some understanding of how the tests for EC1 and EC2 were evaluated, it should be noted that

separation of technology generation would result in a clear distinction between the colors black, green, and red. Further, independence of purpose or utilization would be favorable in a metric system if each of the colors collapsed onto a single line or curve, indicating no spread in metric value [117]. Ultimately, this analysis was conducted for all five vehicles, and all metrics and correlating parameters were evaluated. For brevity here, the results for the SAR based metric systems for the small twin aisle aircraft will be discussed, and are shown below in Figure 2.8. Here, each box represents a potential form of the metric system.



**Figure 2.8: SAR Aircraft CO2 Standard Metric System Evaluation [117]**

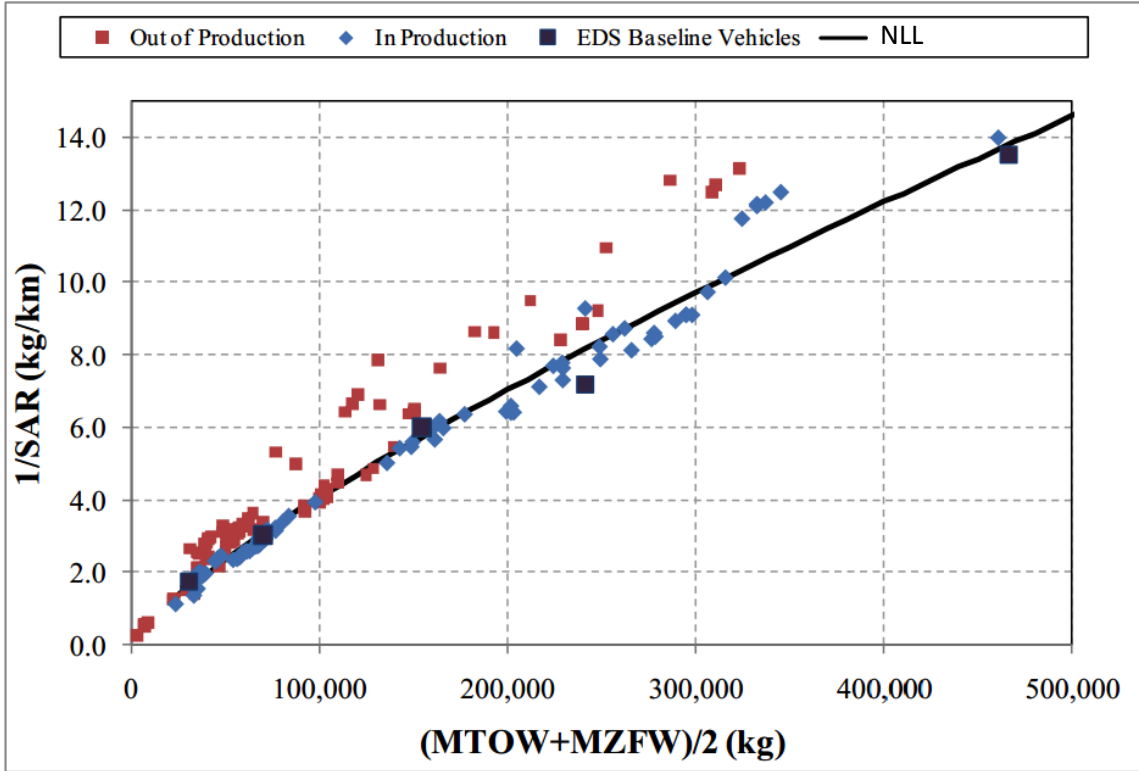
As can be seen in the above figure,  $1/NAMS$  correlated against MTOW shows the best collapse of aircraft in the same technology group, thus satisfying EC2 completely. Further, there is a relatively clear separation of technology generation within these metric

systems, and as Lim et. al. point out, this metric-CP combination has the advantage of being much simpler than any other metric system considered [117]. In the end, it's likely the metric system decided on by ICAO CAEP is some form of 1/SAR correlated against MTOW, as ICAO has stated that the overall design of the aircraft is represented in the CO<sub>2</sub> metric system by the certified maximum takeoff weight [118]. So, while it's clear that no metric system fully satisfies all evaluation criteria across the fleet, the most promising candidates identified in literature are the metric-CP combinations which include 1/SAR and MTOW.

#### ***2.4.2.3.2 Aircraft Stringency Options***

In addition to a metric system on which to evaluate fuel efficiency, some level of stringency must be placed on manufacturers in order to push technology development and integration. These stringency options are in many ways analogous to the caps set in emission trading schemes, as they provide stringency to CO<sub>2</sub> generators covered by that standard. For the notional standard, insight into these stringency options is provided by the work of the FAA's PARTNER Project 30, where in a publically available findings report a number of notional limit lines (NLL) serve as the basis for analysis of a potential CO<sub>2</sub> certification framework [119]. In order to establish the NLL, a database of 192 vehicles is utilized. The aircraft included in the database are classified based on production status, and all applicable parameters to various metric systems under consideration are collected. Additionally, a number of fitting procedures for the notional stringency lines is considered, and due to the fact that the 1/SAR based metric systems showed very simple trends, these fits tended to include linear and second order

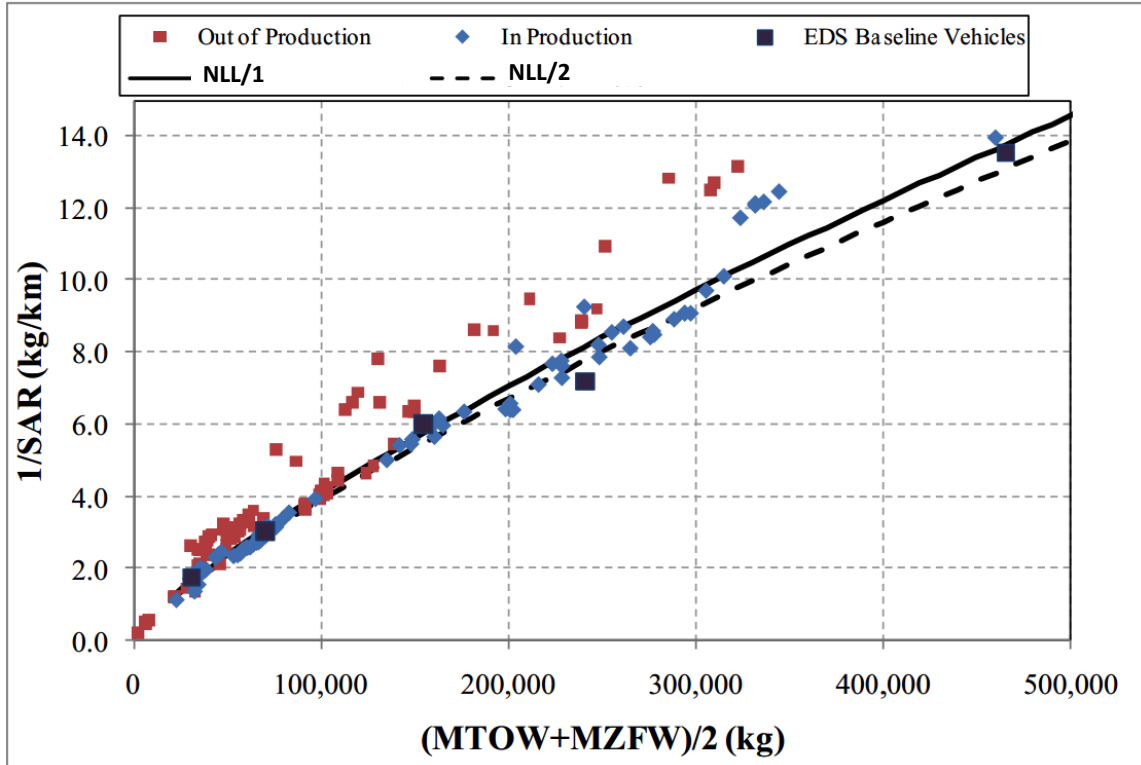
approximations of in-production vehicles [119]. The establishment of such an initial NLL can be seen in Figure 2.9.



**Figure 2.9: Initial NLL Fit for CO<sub>2</sub> Metric System [119]**

While this provides a starting point for the study of different stringency options, a general rule for reducing the baseline trend needed to be established to study more stringent standards. Generally this was done through a fixed percentage reduction from the initial limit line, with preference given to levels which affected older certification dates first [119]. From the results of the PARTNER Project 30 findings report, insights from the EDS technology roadmaps were ultimately used to anticipate near-term technologies, and it was determined that that a reduction of 5% from the initial limit line

shown above was reasonable for the updated limit under study [119]. This updated NLL can be seen in Figure 2.10.



**Figure 2.10: NLL Update for Aircraft CO<sub>2</sub> Standard [119]**

#### 2.4.2.3.3 *Scope of Applicability*

The last major component of a new standard is the scope of applicability. As with the emission trading schemes discussed previously, this tends to include covered entities, as well as a basic timeline for implementation.

As with any policy, timing can be very difficult to predict. However, it has been assumed that the initial CO<sub>2</sub> NLL studied assumed an adoption of the standard in 2017

with introduction in 2018 [119] and an alternative s assumed to correspond to an adoption date of 2023 with introduction in the following year [119].

Further analysis of such a standard must keep this in mind regarding both timing and definitions of entities covered. However, this dissertation is focused on the concepts of policy decision tradeoffs, and the examples herein are notional.

### **2.4.3 Policy Analysis Process**

Given this knowledge regarding emission trading schemes and a new certification standard, it's important to address the policy analysis process pursued by regulatory agencies throughout the world. It has been noted in literature that economic policy analysis approaches commonly used for policy assessment include cost-benefit analysis (CBA) and cost-effectiveness analysis (CEA) [121]. The use of these analyses varies depending on the study under consideration and regulatory body conducting the study. The benefits and drawbacks to each approach will be briefly introduced here. It should be noted however, that for each of these analysis approaches a well-defined baseline scenario must first be established.

#### **2.4.3.1 Cost-Benefit Analysis**

Cost-benefit analysis (CBA) requires the effect of policy relative to the baseline scenario be calculated in consistent units, such as USD, in order to make the costs and benefits directly comparable, and is aimed at the assessment of social benefits [121]. This approach is often promoted as the recommended basis for assessing policy alternatives;

however, it requires the transference of benefits measured in any number of units to those used for cost [122, 123]. A number of regulatory bodies throughout the world have employed such approaches, most notably for noise and NO<sub>x</sub> standards in aviation [124]. Such an approach can be quite difficult given the complexities of calculating the monetary effects of releasing GHG into our atmosphere, since isolating the impacts of the release of any emission species to a climate change event is highly uncertain, as aforementioned.

#### **2.4.3.2 Cost-Effectiveness Analysis (CEA)**

Cost-Effectiveness Analysis on the other hand is used to evaluate policies with similar expected benefits, such that all benefits and all costs associated with the policy can be grouped independently and directly compared [121]. The idea behind CEA is that the policy that achieves an expected benefit at the lowest cost can be shown to be ideal compared to all other policies considered [123]. Most government agencies throughout the world require the assessment of both the costs and benefits of any given policy. In the U.S., the Office of Budget and Management produces the executive orders and circulars that outline the regulatory framework on which to assess these costs and benefits [125-127]. These documents outline a generic framework on which to assess costs and benefits, however, they do not specify whether CBA or CEA be used explicitly for policy analysis. Despite this, it's quite apparent that CEA is the typical approach employed [128, 129]. The likely reason for such an approach is that for each of these policies the benefits can be quantified using a singular measure, such as tons of NO<sub>x</sub> or number of people removed from a given noise contour. In the context of this study, where the primary

benefit being studied is the mitigation of CO<sub>2</sub> from the atmosphere, this indicates that CEA is the appropriate technique for policy analysis since the physical amount of CO<sub>2</sub> removed from the atmosphere due to policy can be quantified from both emission trading schemes and a new standard directly. As such, CEA will serve as the policy approach taken to satisfy the policy analysis requirements.

## **2.5 Uncertainty in Policy Analysis**

Ultimately, one of the greatest challenges in approaching policy problems in such a holistic manner comes about due to the uncertainty associated with complex systems or SoS. Due to the desire for policymakers to pursue “robust” policies, the uncertainty of the physical system, as well as uncertainty introduced via exogenous policy, must be addressed. Here robustness is taken to mean policy that addresses a specified public issue. The following discussion will introduce the concerns regarding regulatory policy uncertainties, and follow with a foundation for understanding the framework of quantifying different forms of uncertainty analytically.

### **2.5.1 Regulatory Policy Uncertainty**

The civil aviation industry constitutes a complex SoS with a number of organizations implementing individual strategies based on risk assessments to make strategic investment decisions. As such, they need to understand the regulatory uncertainties in order to fully assess those decisions, and policymakers must also understand these uncertainties in order to improve the effectiveness of regulatory policy actions [130]. From literature, regulatory uncertainty typically addresses the unknown



aspects of regulatory pressure originating from the unpredictability of an entity's future policy environment [130].

This perceived uncertainty can be broken down more generally as state, effect, and response uncertainty [130, 131], where state uncertainty is the inability to predict the future state of the economic or industry environment, effect uncertainty is the inability to determine the effect of such a future state, and response uncertainty is the inability to understand the ultimate consequences of those effects [131]. As an example of how these basic forms of regulatory uncertainty manifest throughout the world, consider the EU ETS. As of 2005, the regulatory policy environment provided no clear view of the regulatory schemes that would occur past the second phase of trading after 2012, which represents a case of regulatory policy state uncertainty [132]. A result of this regulatory state uncertainty is that the covered entities faced high ambiguity regarding future investment decisions with a payback beyond 2012, such as coal power plants with an amortization on the order of 20 to 30 years, leading many to purchase EAUs rather than invest, representing a form of effect uncertainty [133]. With this environment of effect uncertainty in place, many entities including the regulatory bodies had a high level of response uncertainty, which led to many of the issues associated with initial trading periods for the EU ETS, as aforementioned.

It should be clear from this level of discussion that addressing regulatory uncertainty is most effective if the regulatory state uncertainty can be reduced. As such, the question that must be addressed is, *“How can regulatory state uncertainty be reduced in the context of concurrent policy implementation?”*

Analyzing regulatory uncertainty in the initial planning phases of policymaking can help alleviate some of the known issues with state, effect, and response uncertainty. Doing so requires a good understanding of the nature of uncertainty itself.

## **2.5.2 Epistemic and Aleatory Uncertainty**

To begin to discuss uncertainty quantifiably in a policy context, the nature of uncertainty should first be addressed. Typically uncertainty can be divided into two basic forms, epistemic and aleatory uncertainty [78]. Epistemic uncertainty is the result of imperfect knowledge, and is characterized by the ability to be reduced through careful analysis and planning [78, 134]. Aleatory uncertainty, also often referred to as variability uncertainty, derives due to the inherent variation within a system, and cannot be reduced through further knowledge [78, 134].

In the context of the environmental policies facing civil aviation being discussed here, epistemic uncertainty relates primarily to the regulatory uncertainty previously discussed. It should be evident through the example provided by the EU ETS that state uncertainty can be reduced through more long term policy studies, and that reduction would ultimately flow through effect and response uncertainty. As such, when considering policy, precaution can be taken to deal with the epistemic uncertainty involved in policy analysis. This can be accomplished by paying specific attention to the impact of policy forecasted well into the future, considering different time frames for the scope of applicability, as well as various stringency options for either policy.

Aleatory uncertainty on the other hand, can be considered exogenous to the policy systems under consideration. While it cannot be reduced by definition, it can be quantified. Sources of aleatory uncertainty in the context of the policies under consideration may include, but are not limited to, factors such as fuel price and allowance price volatility, disruptive technology integration, or unexpected events that alter demand significantly, such as the financial collapse that occurred in 2007. Quantifying this uncertainty can be accomplished through both probabilistic and stochastic modeling paradigms. Doing so typically requires the determination of expected values and probability distributions for uncertain parameters. Moving forward in this study, many of the results of current literature may serve quite well in helping define the ranges for the parametric variables deemed important to quantify aleatory uncertainty for this policy study [106, 117, 119]. Attempting to address these aleatory variables is meant to answer the question, “*How can specific forms of aleatory uncertainty be quantified in the presence of regulatory policy for commercial aviation?*”

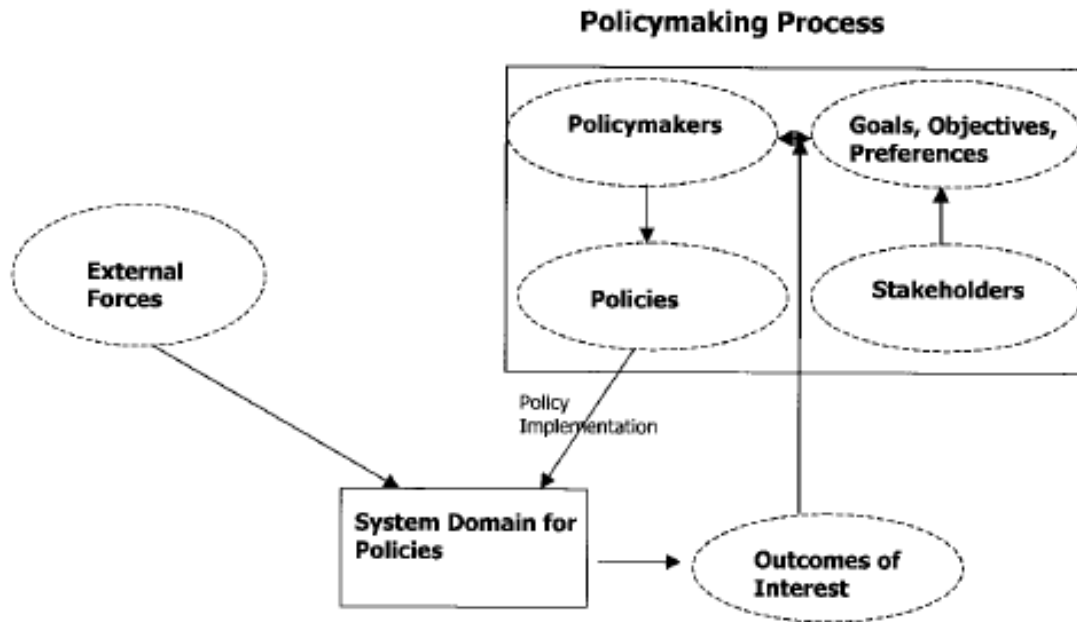
## **2.6 Exploratory Modeling for Policy Analysis**

In order to provide information for all possible alternatives of these regulatory policies, the argument was made that an exploratory rationale ought to be employed. Appendix D provides a more formal overview of exploratory modeling, from its inception at RAND among researchers such as Steven Bankes, to its use for environmental policy analysis by academics such as Augustin. This discussion also overviews specific applications in the transportation sector, as well as toward policy design.

## 2.7 Existing Policy Analysis Frameworks

In order to assess these policies in the context of civil aviation from an exploratory rationale, a suitable policy analysis framework ought to be employed. Borrowing from literature, Walker provides a useful generic framework for policymaking that has been shown to work well with a number of different methodologies [135]. This approach is constructed around a general description of the policy field, and is reproduced in Figure 2.11 below [135].

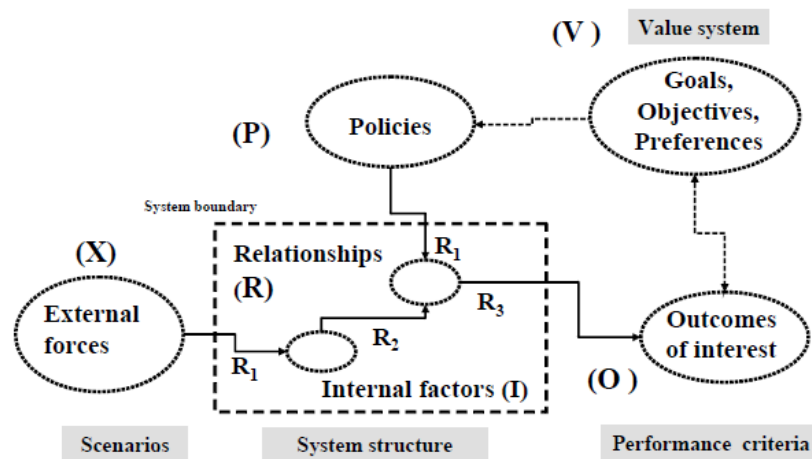
As can be seen, at the center of the process is a representation of the system domain. It has been noted that this does not necessarily have to represent a computer model of the system, but it does define the boundaries of the system and its structure [135]. Affecting the system domain are two distinct sets of external factors. The first are forces outside the control of actors in the policy or system domain, and can include a number of factors such as the economic environment, technology development, or behavior preferences of actors involved [135]. Next, are policy changes stemming from the policy domains that directly affect system behaviors. These policy changes are controlled by policymakers who construct policies based on stated goals. The process of attaining goals is measured through outcomes of interest, which act as a feedback loop in the generic framework.



**Figure 2.11: Walker's Generic Policymaking Framework [135]**

In a similar vein to Walker's generic framework, Lempert, Popper, and Bankes also propose a classification for external factors and the system domain [136]. This has been termed the "XLRM framework", where X represents exogenous uncertainties, L are policy levers, R the system relationships, and M are the measures. Policy levers (L) are the actions that make up the strategies employed by policy makers, while the exogenous uncertainties (X) are factors outside the control of decision makers that may determine the success of those strategies. The measures (M) are equivalent to the outcomes of interest proposed by Walker, and simply help to rank the outcome of various scenarios. Finally, the relationships (R) describe how these various factors relate to one another, and ultimately help describe overall system behavior under different scenarios [136].

More recent work by Augusdinata has combined the structure of Walker’s policymaking process with the ideas supporting the “XLRM framework” to provide a more structured policy analysis framework to act as the conceptual basis for studying policy in the context of highly complex systems. This adapted policy analysis framework has been termed the “XPIROV” framework, borrowing notation from both Walker and Lempert et. al., and is recreated in Figure 2.12 [78].



**Figure 2.12: XPIROV Policy Analysis Framework [78]**

As with Walker’s framework, the XPIROV framework is built around a representation of the system domain. Here, however, the system structure represented within the system boundary is more completely expressed than in either the XLRM framework or Walker’s generic policymaking framework. Each of the elements of the XPIROV framework are defined below [78]:

- Policies (P) represent all instruments controlled by decision makers that can have an effect on the system.

- External forces (X) are analogous to the definition provided by Walker, and represent factors that cannot be controlled by the decision maker yet still influence the system (exogenous factors).
- The system boundary, as seen in Figure 2.12, defines all relevant elements of the system model. This includes the set of internal factors (I) together with relationships (R).
- The outputs from the system boundary are the outcomes of interest (O), which refer to the characteristics of the system that are deemed relevant to evaluate the performance of policy measures. These outcomes of interest result from changes in X and P which in turn change the states of I, and such changes are ultimately governed by the relationships, R. Thus, the outcomes of interest can be represented as:

$$O = R(X, I, P)$$

It should be noted here that these outcomes (O) are generally based on broad categories, but in practice are represented through proxy measures. As an example consider the health of the planet as an O, while this can't be measured directly, other proxies such as global average temperature and atmospheric emissions can be measured that directly influence the health of the planet.

- The relationships, R, are divided into three distinct classes:
  - Relationships between the system of interest and external forces (R<sub>1</sub>).
  - Relationships among the internal factors within the system boundary (R<sub>2</sub>).

- Relationships between the internal factors and outcomes of interest ( $R_3$ ).
- Value systems (V) represent the goals of decision makers and stakeholders. The value system is used to evaluate policy outcomes measured through proxy indicators, and is typically one of the main responsibilities for policy makers.

## **2.8 The State of Policy Making for Civil Aviation**

The preceding discussion has highlighted the growing importance of regulatory policy to mitigate anthropogenic CO<sub>2</sub> emissions from civil aviation. In order to achieve system wide goals, a number of mitigation measures will certainly need to be employed throughout the world, nested at many levels of commercial aviation's hierarchal structure. Two of the most widely considered policies are emission trading schemes, which will impact aircraft owners and operators, and a new certification standard, which will directly affect aircraft manufacturers. Understanding the tradeoffs and uncertainties associated with these policies will require a framework on which to make informed decisions based on testable quantitative data. Unfortunately, this framework does not currently exist. Despite this fact, there are established policy analysis frameworks that have been shown to work well for highly complex systems that can serve as a key enabler for an overall process of informed decision making for regulatory CO<sub>2</sub> policy in civil aviation. Establishing this process will still require the expansion of a lexicon to discuss regulatory policy in the context of SoS, as well as modifications of existing policy analysis frameworks for inclusion in a SoS structure.



## CHAPTER 3

### APPROACHING POLICYMAKING QUANTITATIVELY IN A SOS

#### 3.1 Quantitative Analysis of a Concurrent Policy Approach

As indicated in recent civil aviation regulatory literature, an aircraft standard and emission trading schemes are two of the primary measures member states throughout the world are considering in order to address the mitigation of anthropogenic CO<sub>2</sub> into our atmosphere. It is expected that significant reductions in CO<sub>2</sub> emissions can be accomplished through these policies, yet the interaction and tradeoffs among them have not been fully addressed. Further, the policy analysis process for member states and regulatory bodies has been lacking a standardized framework on which to quantitatively assess the impacts of these “baskets of measures”.

Subsequently, the aim of this study is to provide a suitable framework on which to assess quantitative concurrent policy analysis. Further, a methodology standardizing the policy analysis process will be defined to provide systematic and traceable quantitative policy analysis. The policy tradeoffs that will be assessed are the effects of a certification standard on aircraft manufacturers and emission trading schemes affecting air carriers. Due to the fact that ICAO’s GIACC is tasking all member states with identification and evaluation of policy mixes, these policies will be assessed to demonstrate the potential for assessment at this level. As such, the U.S. national airspace system (NAS) will serve as the applicable region of study. It is believed that providing this framework, and demonstrating the potential for exploratory policy studies will also aid in the reduction of

regulatory uncertainties previously discussed. Finally, the ability to assess forms of aleatory uncertainty, such as fuel price, will also be demonstrated under the defined framework.

### **3.2 Quantitative Policy Tradeoff Research Objectives**

With the problem scoped to the study of a notional new CO<sub>2</sub> standard and emission trading schemes in the U.S. NAS, the research objectives must be established. This will be introduced through research questions and hypotheses, which will serve as the metrics of success for the study of these policies. There are four main objectives of this research, which include:

1. Quantitatively assessing regulatory policy in the context of an acknowledged system-of-systems (SoS).
2. Demonstrating the ability to assess the concurrent implementation of multiple policies throughout a SoS.
3. Objective identification of effective policy space.
4. Reducing the regulatory uncertainty, and quantifying other forms of aleatory uncertainty in the presence of multiple regulatory policies.

The following discussion will introduce the research questions associated with these objectives, and provide hypotheses of expected results.

#### **3.2.1 Quantitative Assessment of Policy in the Context of a SoS**

While the ultimate goal of this research is to identify a standardized process for the analysis and design of multiple policies throughout a SoS, the ability to quantitatively assess individual policies in a SoS must first be addressed. As such, the ability to

implement a single policy and quantitatively assess the impacts throughout a SoS must be established as a starting point.

### **3.2.1.1 Research Question 1**

*RQ1: What are the impacts to the U.S. NAS of a CO<sub>2</sub> certification standard or a trading scheme in isolation?*

#### **3.2.1.1.1 Hypothesis 1**

Due to the fact that a CO<sub>2</sub> certification standard and emission trading schemes will impact different actors in the U.S. NAS, it's expected that their impacts to the system will differ, although the overall effect, reduction in CO<sub>2</sub>, will be shared. As discussed, a new standard will impact aircraft manufactures to drive technology insertion on future aircraft. As such, the primary impact of this policy will be increasing the efficiency of the aircraft available to operators. This increase in efficiency will ultimately reduce fuel burn over a fixed technology fleet, and lead to mitigation of CO<sub>2</sub>. Despite this, there are physical limitations and issues with technology readiness that will limit the overall potential of such policy. Further, the costs associated with such policy will be placed primarily on aircraft manufacturers, and as such, economic limitations may also be imposed that may prevent setting a standard that would overburden manufacturers. Subsequently, it's expected that the implementation of a standard in isolation will reduce CO<sub>2</sub> emissions over a fixed technology fleet, although it's unlikely to stabilize emissions. Further, it's expected this standard will not impact expected demand growth, and thus will only work to increase efficiency of aircraft in service. The impacts of this policy will

be measured using the non-recurring cost to manufacturers to meet potential stringency options, and the overall reduction in CO<sub>2</sub> over a fixed technology fleet.

While an ETS will also reduce CO<sub>2</sub> emissions over a “no action” scenario, the mechanism by which this is achieved will be quite different. The expected effect of this type of policy is to reduce demand through the pass through of costs imposed to aircraft operators by providing a real price for CO<sub>2</sub>. This is accomplished by using an established rule set outlining an emissions cap and allocation process. Since it’s expected that demand growth in civil aviation will outpace efficiency improvements, it’s likely the civil aviation industry will have a performance gap from the cap, and will be a net purchaser of emissions allowances. The cost of these purchased allowances will ultimately be passed through to consumers, reducing demand based on price elasticity of demand assumptions from literature. The actual mechanism by which this works will be detailed later in 4.10.2. Ultimately, the impact of an ETS on the U.S. NAS will be measured through cost-effectiveness analysis. This will include determining the recurring costs associated with aircraft owners and operators, as well as the policy induced costs due to the implementation of an ETS. Further, the overall reduction in demand will be compared against a reference demand forecast of a fixed technology fleet used to initialize the simulation environment, and the overall reduction in CO<sub>2</sub> will also be presented.

### **3.2.1.2 Research Question 1.1**

Due to the fact that an ETS is anticipated to impact demand in the U.S. NAS, understanding the mechanisms and extent through which this occurs will be vitally

important to the overall success of quantitative policy assessment. Subsequently, two further sub-research questions are posed for the study of the ETS.

*RQ1.1: What are the impacts of an ETS on demand for passenger transport?*

#### **3.2.1.2.1 Hypothesis 1.1**

The main effect of market based policy mechanisms creating a real price for CO<sub>2</sub> emissions for air carriers is to increase ticket prices, and thus reduce demand for air travel. Due to the expectation of a performance gap under an ETS, this will occur through the requirement for air carriers to purchase allowances. Ultimately, the cost of purchased allowances will be passed through to consumers, creating a change in price. Literature has been surveyed to equate this change in price to a change in demand for air travel through the use of established air travel demand elasticities based on carrier type [137]. All price elasticity of demand values found for air carriers are negative, which indicates that an increase in price will ultimately lead to a decrease in demand. Ultimately, an equilibrium demand will be reached. This reduction in demand will be quantified by comparing future demand increases or decreases to a “no action” scenario. Further, through analysis of recent literature it is expected that demand reductions will be on the order of 1% to 2% per year for moderate allowance prices and caps, such as those seen under the EU ETS [106, 115]. As such, there are two expected outcomes from this research question: 1) demand will reach an equilibrium value lower than the input forecast, and 2) that reduction can be quantified and will be shown to be comparable to existing literature.

### **3.2.1.3 Research Question 1.2**

Due to the fact that different types of air carriers operate within the U.S. NAS, namely legacy carriers and low cost carriers, it's expected there may be disproportionate effects of an ETS based on carrier type.

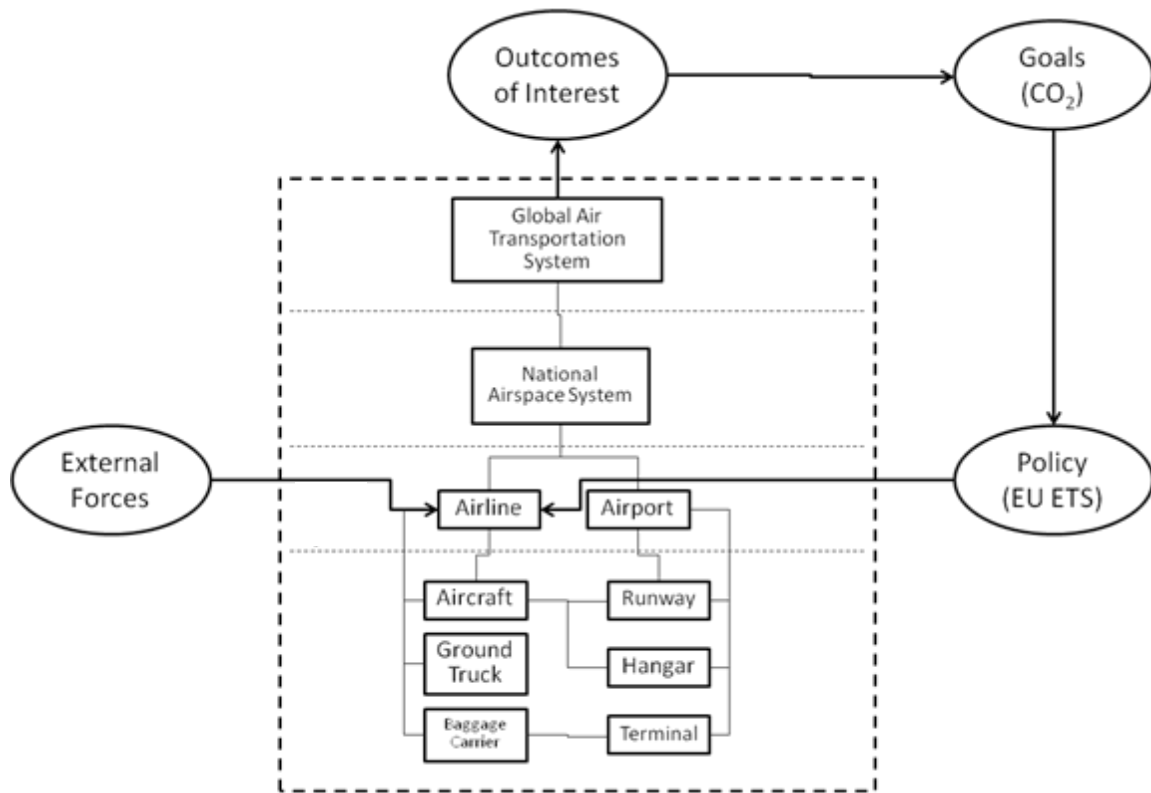
*RQ1.2: What are the relative impacts of an ETS to different air carriers?*

#### **3.2.1.3.1 Hypothesis 1.2**

As revealed in literature, price elasticity of demand for air travel varies depending on air carrier type. For instance, PriceWaterhouseCoopers estimates a demand elasticity of -1.23 for full service carriers and -1.38 for low cost carriers [137, 138]. Due to the fact that price elasticity of demand is equivalent to the change in demand over the change in price, it's expected that a similar change in price for low cost carriers would produce a greater change in demand over full service carriers. Further, due to the typically lower ticket prices of low cost carriers over full service carriers, it's expected that meeting the cap under an ETS will result in a higher change in price for low cost carriers over full service carriers. Subsequently, it's expected that the relative change in demand will be greater for low cost carriers over full service carriers. This will be measured by comparing the change in demand for individual air carriers over a notional demand forecast used to initialize the modeling environment, with the expectation that low cost carriers will reach lower equilibrium demand than full service or legacy carriers.

#### **3.2.1.4 Addressing Quantitative Assessment of Policy**

In order to address the quantitative assessment of these policies in the context of the U.S. NAS, the XPIROV policy analysis framework established by Augustineta and adapted from the work of Walker, can be applied directly to the system of interest. To provide an illustrative example of how this framework can be applied to a SoS, such as the civil aviation SoS aforementioned, Figure 3.1 is provided. As can be seen, this figure provides a notional example of how current policy, such as the EU ETS, can be analyzed in the context of the global air transportation SoS. Here, the entire SoS represents the system boundary, and policy, goals, and outcomes of interest are tracked treating the SoS as a single system. From previous work in literature [78], there is strong evidence that the application of such a framework will be adequate for the study of the interaction of a single policy in the context of a SoS.



**Figure 3.1: Notional Application of XPIROV Framework to Civil Aviation**

### **3.2.2 Concurrent Quantitative Assessment of Policy throughout a SoS**

Given the ability to quantitatively model individual policies in the context of a SoS, the next step to concurrent policy design and analysis for the purpose of informed quantitative decision making must be to account for the existence of multiple policies impacting individual systems within the SoS. While the XPIROV framework is able to account for multiple policies, those policies are only directly tied to a single system of interest. As such, the implementation of such a framework may prove too general for the U.S. NAS where policies such as emission trading schemes and a CO<sub>2</sub> aircraft standard



apply to different systems and at different levels within the air transportation SoS. This recognition leads to the next question driving this research.

### **3.2.2.1 Research Question 2**

*RQ2: How will the combined effect of these policies differ from their implementation in isolation?*

#### **3.2.2.1.1 Hypothesis 2**

Due to the fact that a CO<sub>2</sub> standard affects aircraft efficiency, and an ETS will impact demand, there is an obvious tradeoff between the two policies. Subsequently, it's expected that when both policies are implemented concurrently there will be a reduction in overall cost for an expected effective reduction of CO<sub>2</sub>. This is due to the fact that as manufacturers are required to produce more efficient products for aircraft owners and operators, their fuel burn will be reduced helping them meet the cap for an ETS, and ultimately reducing the number of allowances needed to be purchased. As such, there will be a relative reduction in cost for aircraft owners and operators to meet an emissions cap, effectively sharing the costs of CO<sub>2</sub> reduction between the manufacturers and airlines. However, due to the fact that increases in efficiency will reduce the overall cost associated with emission trading schemes, there will also likely be a reduced impact on demand reduction. This effect may offset the overall impact of an ETS in the presence of a new standard, which will be quantified through cost-effectiveness analysis. Particular attention will be paid to the costs imposed on manufacturers and air carriers, in addition to the overall cost on the system. This research question is expected to show two primary

outcomes, 1) the impact to demand in the presence of an ETS and an aircraft standard will be lessened (ie. higher demand) over a comparable ETS in isolation, and 2) meeting a predetermined reduction in CO<sub>2</sub> can be accomplished through a combination of policies and at a reduced cost over either policy in isolation.

### **3.2.2.2 Policy Analysis Benchmarking Question 2.1**

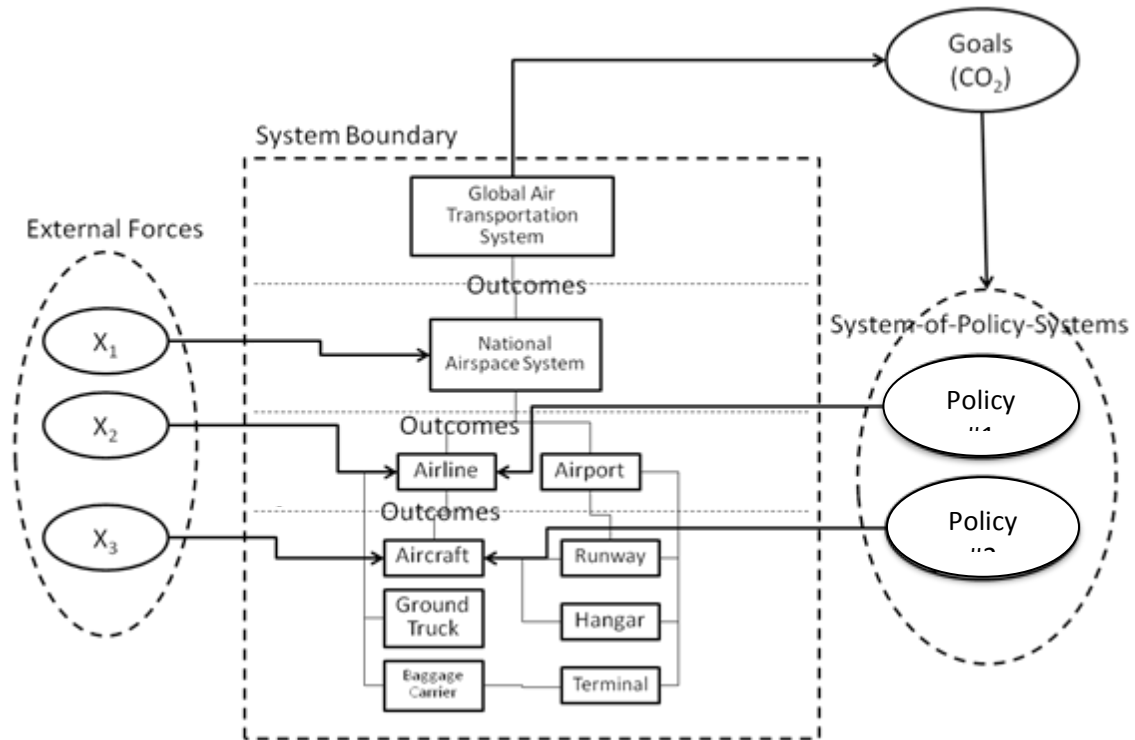
Providing a policy analysis framework that will allow such a combination of policies at different hierarchical levels of a SoS to be tested, requires a structure more specific to real world SoS than is provided by the standard XPIROV framework. As such, to operationalize this second research question the following sub-question must first be answered.

*RQ2.1: Can existing policy analysis frameworks, such as Augusdinata's XPIROV framework, be used in the design and analysis of systems of policies?*

### **3.2.2.3 Hypothesis 2.1**

Existing policy analysis frameworks can and should be implemented in the design of systems of policies, however, these frameworks must be modified to account for their implementation in a SoS with multiple policies. This can be achieved by modifying the XPIROV framework to allow external forces, outcomes of interest, and policies to be applied directly to their respective systems, while policy goals at high levels of the SoS are tracked for policy decisions. In order to illustrate this concept, Figure 3.2 provides a notional example of how two policies can be concurrently analyzed throughout the global

air transportation system. Due to the fact that this type of expansion of XPIROV can occur for any number of systems, policies, or external factors, this policy analysis framework will be labeled the Generalized Policy Assessment Framework (GenPAF).



**Figure 3.2: Notional Application of GenPAF to Civil Aviation**

### 3.2.3 Objective Identification of Effective Policy Space

With the demonstration of policy interactions for point designs of multiple policies, and the GenPAF policy analysis framework in place to quantitatively assess the concurrent implementation of multiple policies throughout the U.S. NAS, the identification and analysis of effective policy mixes can now be addressed. As has been recognized by international regulatory bodies, there are number of policy measures that can provide effective mitigation of CO<sub>2</sub> in civil aviation, and each State should be

allowed to decide on the most efficient means of meeting international CO<sub>2</sub> emissions reductions targets [2, 53]. Despite this recognition, it is clear that this will require the exploration of a number of policies in the context of the U.S. NAS. Establishing the realm of policy measures that may be implemented can be accomplished by exploring all possible mixes of policies, levels of stringency, and types of compliance mechanisms. Doing so will require a method for identification and evaluation of these systems of policies.

### **3.2.3.1 Research Question 3**

*RQ3: How can this knowledge of a policy tradeoff be used to help meet goals, such as those established under the Kyoto Protocol?*

#### **3.2.3.1.1 Hypothesis 3**

Areas of effective policy space can be identified through the population of policy alternative space and downselection using inverse design principles, in which a heuristic (or many heuristics) provide the basis for data filtering. It is extremely likely that the region of effective policy space is dependent on both the heuristic used to measure effectiveness and the absolute measure used for downselection. As such, there may be great jumps in effective policy space based on small perturbations of heuristic value especially where a number of categorical parameters exist. Further, this filtered alternative policy space approach can provide insight into the value systems driving policymaking. This is due to the fact that such an approach will likely reveal Pareto

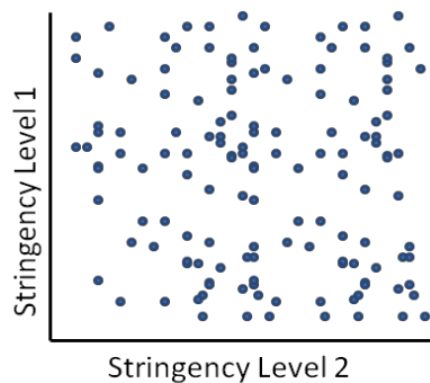
frontiers in effective policy space, highlighting the tradeoff between different policy approaches throughout the SoS.

In the context of studying the cost-effectiveness of two policy options in the U.S. NAS, the heuristics used to measure effective policy space will be the overall mitigation potential of the policy mixes given through CO<sub>2</sub> reductions, and the costs associated with both aircraft manufacturers and air carriers. The U.S. State Action Plan submitted to ICAO indicates that the primary goal of all efficiency measures is to produce carbon neutral growth relative to 2005 emissions levels by 2020 [63]. While this stated goal can be used to identify effective policy, a number of alternative measures are also being pursued. As such, the implementation of goals throughout this research are purely notional, and not necessarily tied to specific SAP goals. The purpose here is to demonstrate the usefulness of policy tradeoff assessment for any potential goal. It is expected that using these heuristics will reveal reductions in overall effective policy space as either greater reductions in CO<sub>2</sub> are attempted to be achieved, or reduced costs to market actors throughout the U.S. NAS. This will ultimately be shown through the variation of these heuristics during filtering of the policy alternative space.

### **3.2.3.2 Addressing Research Question 3**

To accomplish this, a design of experiments (DoE) [139] on the physical attributes of the SoS and policies comprising the policy mixes can be experimentally run through the virtual cost-effectiveness environment of the U.S. NAS to populate the policy design space. This will require varying the exogenous factors in addition to the metric

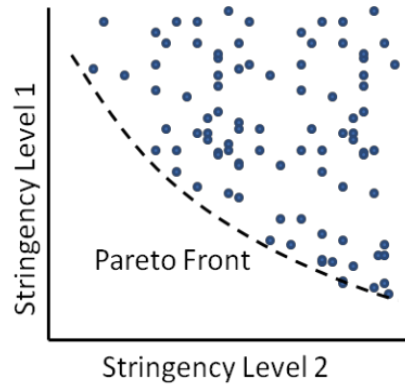
systems, stringency levels, and compliance mechanisms. The result will be a populated policy design space, which can be visualized in any dimension of the problem of interest. As a notional example, consider Figure 3.3 below which shows the policy design space represented by varying stringency limits for two separate policies in a SoS. Here, the stringency level of two notional policies are varied independent of one another while all metrics of interest are tracked throughout the SoS.



**Figure 3.3: Notional Policy Space from DoE**

Due to the fact that metrics of interest are tracked throughout the SoS, data filters can be applied to this Monte Carlo Simulation in order to identify effective policy space. Continuing with this example, consider these two policies to be various CO<sub>2</sub> mitigation measures throughout civil aviation. If international bodies were to agree on a limit for CO<sub>2</sub> emissions from global aviation, the effect can be tracked on these potential policy measure stringency limits. The effect may be similar to Figure 3.4. Here, the emergence of a Pareto frontier is obvious. It's apparent that in meeting this notional CO<sub>2</sub> limit there will be a tradeoff in the stringency of these two policies. While it is not the goal of the

scientist to select the mix of policies, in this manner the scientist can describe the inherent tradeoff in policy space.



**Figure 3.4: Filtered Notional Policy Space from DoE**

In addition to being able to visualize the tradeoff between different policy measures, such an approach would also allow the visualization of other factors relevant to the problem. For instance exogenous factors, internal parameters of the system, and other high level goals, such as economic measures of the civil aviation system, can be assessed. As such, this method of analysis is suitable even for problems of high dimension.

It is expected that implementing this method for exploratory policy studies will reveal effective policy space in an objective manner. For the two policies under consideration, high level goals such as those established under the Kyoto Protocol can be used for effectiveness filtering, while anticipated levels of economically viable costs can be used for cost filtering. The result should be the ability to objectively visualize effective policy space to help inform policy decisions.

### **3.2.4 Reducing and Quantifying Uncertainty in the U.S. NAS**

As aforementioned, there are two basic forms of uncertainty to consider in the context of policymaking for acknowledged SoS. These are the regulatory uncertainties associated with the policies themselves, and the uncertainty in the physical system. Due to the fact that these types of uncertainty are philosophically different, reducing and quantifying uncertainty in the U.S. NAS under policy implementation will be explored through two distinct avenues.

#### **3.2.4.1 Reducing Regulatory Uncertainty: Research Question 4.1**

Regulatory uncertainty includes state, effect, and response uncertainty due to policy implementation. As aforementioned, the response uncertainty is compounded by effect uncertainty, and effect uncertainty is in turn compounded through state uncertainty, thus reducing regulatory uncertainty inherently necessitates control over regulatory state uncertainty.

*RQ4.1: How can regulatory state uncertainty be reduced in the context of concurrent policy implementation?*

##### **3.2.4.1.1 Hypothesis 4.1**

Due to the fact that regulatory state uncertainty concerns uncertainty in the specific policies, stringencies, and dates of applicability, it is anticipated that regulatory uncertainty can be reduced through the identification of effective policy space. This identification of effective policy space will be the outcome of RQ3, and will provide



greater certainty regarding the range of potential policy measures that may be implemented earlier in the policy analysis process. Further, it is anticipated that as greater emissions reductions targets and reduced costs to market actors are sought, the effective policy space will shrink. This reduction of effective policy space will inherently lead to a reduction in regulatory state uncertainty. As such, it's expected that reducing regulatory state uncertainty will be dependent on the desires of policymakers to mitigate CO<sub>2</sub> emissions and impact the aviation industry.

#### **3.2.4.2 Addressing Research Question 4.1**

In order to address the relative regulatory state uncertainty associated with effective policy space identification, the results from the objective identification of effective policy space will be used. It is posed that the relative regulatory state uncertainty of the policy system can be assessed through the range of potential policy measures occupying the effective policy space, thus the size of effective policy space can be used as a measure of regulatory state uncertainty. Subsequently, it's expected that as desired CO<sub>2</sub> mitigation potential increases and allowable costs decrease, effective policy space and thus regulatory state uncertainty will be reduced. Conclusions will be drawn from these observations regarding the relationship between regulatory state uncertainty, and the policymaker's willingness to impact aviation through regulatory policy.

#### **3.2.4.3 Quantifying Uncertainty in the SoS: Research Question 4.2**

Uncertainty in the system is typically discussed in terms of epistemic and aleatory uncertainties. Epistemic uncertainties are those that can be reduced through greater

knowledge, and in the context of this study are largely represented by the regulatory uncertainties aforementioned. Aleatory uncertainty however, is the result of natural variability that cannot be reduced, but can be quantified. For commercial aviation, some common forms of aleatory uncertainty that may be considered are atmospheric conditions, such as wind and other weather, as well as economic considerations outside the control of the aviation industry, such as fuel price volatility. Quantifying these impacts is ultimately necessary to understand the relative cost-effectiveness of the policy measures in question, since a drastic change in a factor such as fuel price can have a substantial impact on the overall cost to the system.

*RQ4.2: How can specific forms of aleatory uncertainty be quantified in the presence of regulatory policy for commercial aviation?*

#### **3.2.4.3.1 Hypothesis 4.2**

It is anticipated that the GenPAF policy analysis framework established for the study of the policy measures in question will also be suitable for the quantification of aleatory uncertainty through the mapping of exogenous factors to specific systems of interest within the system boundary. As such, specific exogenous factors impacting the U.S. NAS can be identified and varied while tracking changes to the relative cost-effectiveness of policy measures. It's anticipated that a change in the associated costs for a given effect under a predefined policy mix will be shown as uncertain parameters, such as fuel price, are varied.

#### **3.2.4.4 Addressing Research Question 4.2**

In order to demonstrate the ability to quantify aleatory uncertainty of the physical system, fuel price will be varied under policy considerations for a notional aircraft CO<sub>2</sub> standard. It will be shown later in this document that two of the biggest cost drivers for air carriers are capital costs and fuel costs. As the fuel price varies, the relative impact of fuel costs and capital costs will change based on policy implementation, especially in the presence of a new standard, as it will impact the price and fuel burn of new aircraft. Subsequently, it's anticipated that the marginal abatement costs will be reduced for a lower fuel price. What is meant, is that as a standard is made more stringent there will likely be a point at which increases in capital expenditures from technology adoption may outweigh reductions in fuel cost. As a result, there tends to be a natural limit to the stringency of such a standard that is deemed economically viable, called the marginal abatement cost. As fuel price is reduced, its relative impact will be lower, thus the increases in capital expenditures, as a result of increasing stringency, will outweigh the fuel cost reductions more rapidly. This type of uncertainty quantification can be tested under the given framework, and will be limited to fuel price uncertainty to demonstrate the capability.

### **3.3 Considering Regulatory Policy in Civil Aviation as a SoS**

With these research objectives in mind, it's quite clear that understanding regulatory policy's role in a SoS context is necessary to complete this research. Many government bodies are now pursuing policies as "baskets of measures" [10]. As has been discussed, these baskets of measures include a number of individual policies which are

operationally and managerially independent, yet are meant to address the mitigation of greenhouse gases (GHG) from a holistic perspective. They are often considered and passed on an individual basis, and the geographic extent of their applicability can be widely distributed. Despite this, they are meant as a whole (basket of measures) that is greater than the sum of its parts (single policy). In this way, a new approach to regulatory policy making can include treating public policies as SoS themselves, or as will be outlined here and described by academics such as Agusdinata, as a system-of-policy-systems (SoPS). In order to solidify the assertion that public policy should be approached as an integral part of SoS, a number of existing European legislation relating to the global aviation system [140] will be discussed in the context of the aforementioned SoS principles and definitions.

	Certification	Operation								
		Mitigation at source	Noise				Emissions			
			Assessment and action plans	Land use planning	Operation restrictions	Low-noise procedures	Immission limits	Landing charges	Emission Trading	Fuel Tax
International	ICAO Annex 16 Vol.I (noise); Vol.II (pollutants)									
Regional		Environmental Noise Directive END (2002/49/EC)		Chapter 2 A/C Phase-Out (1992/14/EEC) Chapter 3 A/C Phase-Out (2002/30/EC) with marginal difference to limits (cum. 5EPNdB)		NAAQS (1999/30/EC 2000/69/EC)	ERLIG Recommendation (ECAC 27-4)	Emissions Trading Scheme ETS (closed, open, half-open)	Fuel Taxation System	
National	National adaption of ICAO certification (FAA/LBA)		German Aircraft Noise Protection Act (relevant for major airports)		NAAQS (22./33. BImSchV - outside airport area)	Emission Related Landing Charges (national system and local price definition)				
Airport/Airline			Local Noise Action Plan	sound insulation, restriction of new buildings, compensation	e.g. LHR quota, count, curfews, budget	RNAV, CDA at night (LHR, AMS)	e.g. Sweden, UK, Switzerland, Germany			

**Figure 3.5: Subset of Environmental Policies throughout Europe**

It has been well documented throughout literature that transportation systems, and specifically the air transportation system (ATS), fit well into the accepted definition and

principles of SoS [78-81]. In fact, much of the aforementioned work relates specifically to the ATS. Here the purpose is not to redefine the ATS as a SoS, as such the following discussion will serve to formally define public policy within the ATS as a SoPS. While the public policies mentioned here relate primarily to environmental regulations on airlines and aircraft manufacturers throughout Europe, other public policies regarding the ATS, such as safety and air traffic management, can also be included. However, for the purpose of this discussion only environmental policy throughout the European ATS will be discussed. Given this example of a basket of measures, the defining principles and definition for SoS can be applied to check for consistency in the statement that public policy in the European ATS is a SoS. In order to accomplish this, each of Maier's principles of a true SoS will be discussed in relation to Figure 3.5.

### **3.3.1 Operational Independence of the Elements**

In order to prove the operational independence of the system elements, if the system of environmental policies provided in Figure 3.5 were to be broken, leaving only the constituent parts, each piece of legislation must be able to continue to operate. This is absolutely the case, as the independent nature of each of the mentioned policies is an inherent characteristic. For instance, the ICAO Annex 16 Vol. 1 noise standards at an international level can operate independent of local noise action plans. Despite the fact that there is an obvious connection between aircraft noise certification requirements (ICAO Annex 16 Vol. 1) and operator noise emission limits (Local Noise Action Plan), neither policy is explicitly dependent on the other. While the usefulness and ultimately

true lack of connection between these constituent parts is dubious, the ability to operate these elements independently is quite clear.

### **3.3.2 Managerial Independence of the Elements**

The managerial independence of these policies is quite clear as we consider many of the policies regarding aircraft and operator noise and emissions standards throughout Europe. While it has been shown that these elements can operate independently, they currently do operate independently. All of the policies mentioned are currently implemented and each is operating in an independently useful way. In order to minimize noise and emissions at the aircraft level, ICAO has certification procedures outlined in Annex 16, and to mitigate noise and other emissions at airports other policies such as Local Noise Action Plans and the European Union Emission Trading Scheme (EU ETS) are in effect [140]. The simple fact that these policies are currently managerially independent serves as proof of both the operational and managerial independence of the system of policies.

### **3.3.3 Evolutionary Development**

The evolutionary development of policy in any system is one of the defining characteristics of regulatory policy. As has been mentioned throughout this document, policies are typically passed one at a time, although there can be concurrent work on a number of policies, and the number, scope, and goal of policy systems, such as that pictured above in Figure 3.5 is updated over time. In fact, the Committee on Aviation

Environmental Protection (CAEP) under ICAO operates on three year cycles during which current policies are updated and new policies are discussed. In this respect, evolutionary development is one of the most readily apparent traits of policy systems.

### **3.3.4 Emergent Behavior**

The topic of emergence can be contentious due to a multitude of definitions surrounding what constitutes an emergent behavior. However, borrowing directly from Maier's principle, emergence will be taken to mean that the system performs a function that does not reside in any component system. For the example in Figure 3.5 above, an emergent behavior may be a reduction in demand for air travel throughout Europe. While it's obvious that no single policy system accomplishes this, as it's not a stated goal of any of the policies mentioned, the interaction of these constituent systems within the SoS has the potential to affect consumer demand.

Synergies between policies could also lead to other forms of emergence within the ATS, such as unexpected changes in fleet mix, infrastructure growth, technology investment, aircraft utilization, and so on. While it's important to understand and track emergent behaviors of the system to avoid unintended consequences, it should be quite clear that the policy system considered has the potential to produce an emergent behavior that does not reside in any single policy.

### **3.3.5 Geographic Distribution**

Finally, this discussion defining public policy systems, in terms of accepted SoS principles would not be complete before mentioning the geographic distribution of the constituent parts. Typically for physical SoS, geographic distribution is taken to mean that the geographic extent of the many interacting systems is so great that only information can be shared, and not mass or energy. Obviously public policies are merely pieces of paper that are enacted through the rules and regulations they spell out. They cannot physically share mass, energy, or even information without the government bodies acting on their behalf. Additionally, they can all potentially be stored in the same location. It will be argued here however, that despite these issues with the conventional treatment of geographic distribution in SoS, policy systems can be defined as geographically distributed.

It should be noted that geographic distribution of typical SoS regards spatial relations of the constituent systems. Public policy as well can be spatially distributed in terms of region of applicability. While all of the policies mentioned are European specific, they are geographically distributed in the sense that some, such as Noise Action Plans, are spatially local, while others, such as Annex 16 Vol. 1, are international. Further, as has been outlined in this approach, ICAO's GIACC is calling on world member states to determine policy mixes best suited for their own region, inherently creating a geographically distributed system of policies. Ultimately, this distribution of the region of applicability is similar to geographic distribution in physical SoS.



In order to avoid future confusion, the following discussion defining SoPS will include an adaptation of the principles, as well as the definition of SoS. However, it should be quite clear in the preceding discussion that public policies fit quite well into SoS definitions and principles.

### **3.4 Defining Systems-of-Policy-Systems (SoPS)**

Due to the unique nature of public policy and its interaction with the physical SoS, the notional policy system considered will be defined separately as a SoPS. In order to formalize this idea, the following definition is provided for SoPS as an adaptation of the SoS definition aforementioned.

*SoPS are a collection of multi-domain heterogeneous public policies that exhibit operational and managerial independence, geographical distribution, and emergent behaviors that would not be apparent if the policies, physical systems affected, and their interactions are modeled separately.*

Additionally, the principles of SoPS, operational independence, managerial independence, evolutionary development, emergent behavior, and geographic (region of applicability) distribution, are more formally defined. A summary of these properties is produced in Table 3.1.

**Table 3.1: Principles of Systems-of-Policy-Systems (SoPS)**

<b>Principle</b>	<b>Description</b>
Operational Independence of Policies	The policies comprising the SoPS can operate independently and are useful in their own right.
Managerial Independence of Policies	The policies comprising the SoPS not only can but do operate independently in a useful way.
Evolutionary Development	The SoPS is never fully formed, and is typically approached a single policy at a time. Functions are often added, removed, and modified.
Emergent Behavior	The many behaviors of SoPS cannot necessarily be localized to any component system. They are emergent properties of the SoPS and corresponding physical system as a whole.
Geographic (Region of Applicability) Distribution	The region of applicability of the policies in a SoPS is diverse enough such that general information can be shared but is not directly related.

### **3.5 A Look at the SoS Lexicon for SoPS**

The uniqueness of SoPS also warrants a look into the usefulness of the established SoS lexicon for regulatory policy. As can be seen in Figure 2.1, the SoS categories include “Policies” [81]; however, this system category does not distinguish between an organization’s internal business policies or regulatory policies enacted by external agents. The definition provided simply describes policies as external forcing functions that impact the operation of the SoS. While regulatory policy and organizations’ policies certainly can impact the operation of a SoS, and do in the ATS, the mechanisms through which this is accomplished may not be captured if policy is viewed as a simple forcing function. In large part, this is due to the fact that policies, like the many distributed systems seen in SoS, can be quite varied in their form, function, and implementation. In order to pursue robust regulatory policies in the context of SoPS, these nuances ought to be captured in the modeling of policies, and as a first step, in the lexicon used to discuss

SoPS. The following discussion will attempt to identify and classify the distinguishing traits of regulatory policies to create a formal lexicon for SoPS.

### **3.6 Expanding SoS Lexicon for SoPS**

It should be noted here that the policies considered for this new lexicon in SoPS are regulatory policies, specifically relating to transportation SoS. For this reason, the following expansion of DeLaurentis' SoS lexicon may be incomplete or lacking for other applications outside this domain. With that said, most regulatory policies currently in place or being considered in the ATS tend to have four distinguishing traits: a metric system, providing a traceable measurement; a stringency level that gives intent to the metric; some form of compliance mechanism to operationalize the standard; and of course a set of policy stakeholders enacting and overseeing compliance. These policy traits can be considered system categories for SoPS in the same way resources, stakeholders, operations, and economics are for SoS. Each of these SoPS categories will be expanded on, and the similarities to the existing SoS lexicon will be discussed.

#### **3.6.1 Metric Systems**

Metric systems are the quantifiable entities that give traceability to the SoPS. They provide the measurements by which vehicles, organizations, and other physical characteristics of the SoS can be assessed. In a sense, metrics in the SoPS act similarly to resources in the SoS, in that they give “physical manifestation” to the SoPS. For the ATS, a number of quantifiable measurements serve as metrics at multiple levels of the hierarchy. At the base level of the SoPS metrics include  $D_p/F_{00}$  for engine  $NO_x$

certification, and for the planned manufacturer CO<sub>2</sub> standard metrics will likely involve specific air range (SAR) [117]. At other levels of the hierarchy, the aggregates of these metrics, or some equivalent, can serve as metrics for higher level policies. For instance, SAR at a vehicle level may provide some indication for fleet-wide fuel burn at the operator level, and ultimately total CO<sub>2</sub> emissions at the global ATS level. While there is no direct relationship, and there are a number of other contributing factors between levels of the SoPS hierarchy, mapping the relationship between metrics throughout the SoPS can provide valuable insights for policymakers.

### **3.6.2 Stringency Level**

The stringency level is the application of agreed upon quantifiable entities (metric systems) that demonstrate intent in the SoPS. In effect, a stringency level applies a given value system by placing a limit for the metrics used for assessment. The value system applied through a standard is set by the policy stakeholders, but the stringency level is the measurement through which values are quantified. Stringency levels can take many forms, such as a single value stating a maximum or minimum limit, or could be more complex involving correlating parameters for metric systems as well as stringency lines or even surfaces. One of the primary areas of policy uncertainty is in the setting of stringency levels, because of the potential for many forms and levels of stringency. For this reason, the setting of policy stringency, especially in the context of SoPS ought to be of paramount concern for analysts and policy makers involved with this type of work.

### **3.6.3 Compliance Mechanism**

The compliance mechanism is the application of intent meant to direct the activity of the entities involved in the corresponding SoS. The purpose of the compliance mechanism is to enforce the standards set by policymakers, which, as with stringency setting, can be accomplished in a number of ways. As has been shown, typical compliance mechanisms for regulatory policy can be classified as either market based or command and control approaches, which were discussed in more detail in Chapter 1.4 of this document.

### **3.6.4 Policy Stakeholder**

Finally, the policy stakeholders are simply the organizations and other entities that provide the values systems and oversee compliance in the SoPS and corresponding SoS. This SoPS category is very similar to the stakeholders as described by DeLaurentis for SoS, however, due to their interaction with the SoS as external agents to its operation, they ought to be treated separately from SoS stakeholders. Policy stakeholders can appear at different levels of the SoPS hierarchy depending on the intended application of policy at a given level. For instance, a given policy stakeholder may be involved at the base level of a SoPS where  $D_p/F_{00}$  is being measured to assess compliance with the  $NO_x$  standard, as well as at higher levels assessing fleet-wide implications of different standard levels. The purpose of understanding these policy stakeholders and their interactions throughout the SoPS is to track values applied at various levels of the SoPS

through different policies, in order to assess consistency of value systems across the SoPS.

### 3.6.5 Summary of SoPS Lexicon

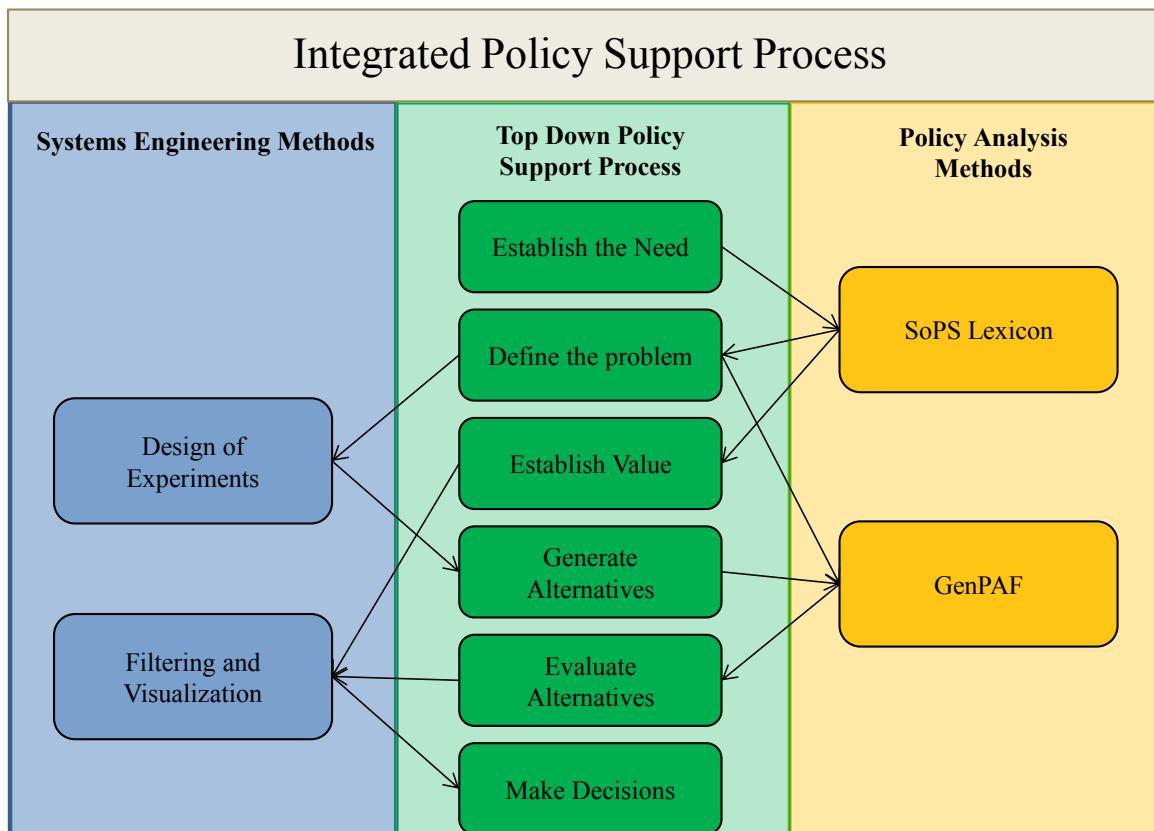
**Table 3.2: System-of-Policy-Systems (SoPS) Categories Description Summary**

<b>Category Name</b>	<b>Description</b>
Metric Systems	Quantifiable entities that give traceability to the SoPS
Stringency Levels	The application of quantifiable entities that demonstrate intent in the SoPS
Compliance Mechanism	The application of intent to direct the activity of physical and non-physical entities in the corresponding SoS
Policy Stakeholder	Organizations and other entities that provide value systems and oversee compliance in the SoPS

### 3.7 Operationalizing the Policy Analysis Process

Utilizing the GenPAF through a DoE approach and discussing these policy systems in the context of a SoPS will provide the individual methods supporting informed quantitative decision making for regulatory policy in the U.S. NAS. However, before attempting a full scale implementation of such an approach, an underlying process must be established in order to operationalize the method. This process will serve as the methodology on which informed policy decisions can be made. With the recognition that this approach to policy design and analysis is top down (ie. starting with high level objectives and propogating to lower level decisions), the proposed process for the identification and analysis of a SoPS is based on an adaptation of the Integrated Product and Process Design (IPPD) process [141]. Typically this process is employed for product design, however here the product is a system of policies addressing environmental mitigation in civil aviation. This process is generally considered to have six primary

steps, which include 1) establish the need, 2) define the problem, 3) establish value, 4) generate feasible alternatives, 5) evaluate alternatives, and 6) make decisions. Each of these steps will be expanded in the following sections with specific application to CO<sub>2</sub> mitigation in civil aviation, noting that the process is extendable for other policy scenarios. In order to provide an overview of this methodology, Figure 3.6 is provided illustrating the links between the top down policy support process, applicable systems engineering methods, and policy analysis methods developed in this research.



**Figure 3.6: Integrated Policy Support Process**

### **3.7.1 Establish the need**

As with most design problems, the first step is to establish the need. Obviously, this process will be different for each type of problem, but what should be identified here is a problem that must be addressed through regulatory policy. For the civil aviation industry, the need comes from a recognition that anthropogenic sources of CO<sub>2</sub> emissions are leading to global climate change effects that can have a catastrophic impact on the planet. As such, the mitigation of these anthropogenic CO<sub>2</sub> emissions must be addressed.

### **3.7.2 Define the problem**

Given this recognition of the problem, the type of problem and specific aspects must be defined. Here, the goal is to identify the structure of the systems being studied, including all exogenous and endogenous variables, as well as all metrics of interest to track throughout the system or system-of-systems. It should be noted here that the metrics of interest identified at this stage will be measures of performance for the system. These measures of performance should relate to the overall need established in the first step of this process, as well as factors passed from one system to another throughout the SoS that are aggregated to higher level measures of performance in the SoS. Due to their implementation in policy design, these measures should be made comensurable with measures of performance in the real world system. For a new aircraft CO<sub>2</sub> standard and emissions trading schemes in the U.S. NAS, these measures of performance will likely be measures of fuel burn, CO<sub>2</sub> mitigation potential, and economic considerations for both aircraft manufacturers and aircraft owners and operators.



### **3.7.3 Establish value**

In this step, the overall objectives of the problem are established. While the final setting of objective values does not need to occur here, at least the identification of parameters to be tracked for eventual down selection of alternatives should be the goal. This step will have a direct impact on the “Goals” used in the GenPAF policy analysis framework, and in fact the V represents the values established here. While there may be some confusion surrounding this step and the identification of measures of performance in the previous step, the values identified here are more closely associated with measures of effectiveness. These parameters will serve as the basis on which effective policy space can be identified in the systems of policies studied throughout the process. For the primary problem being discussed here, the measures of effectiveness used for eventual downselection of effective policy mixes will be total CO<sub>2</sub> emissions and the costs incurred on aircraft manufacturers and air carriers. The idea is that these measures establish value in both the mitigation of harmful anthropogenic GHG, as well as the economic sustainability of the industry.

### **3.7.4 Generate feasible alternatives**

In the typical product design process, generating feasible alternatives can be accomplished through the use of morphological analysis [141], and the parameterization of baseline architectures. Using these methods, all feasible alternative products can be identified. While a similar approach can be taken for policy design, there are some unique features of policy that ought to be addressed more thoroughly. For these policy systems,

the decisions that must be made are in the form of possible metrics, the range of stringency levels for the standard, and the type of compliance mechanism.

The combination of these categories establishes the possible alternatives for policy implementation. However, due to the fact that almost any measurable parameter on a system of interest can be used to establish a metric system, using morphological analysis as a basis for policy alternatives selection can be prohibitive. This is easily understood as a curse of dimensionality. As the number of possible parameters increases, and are combined to form metric systems, the number of metric systems will increase exponentially. Subsequently, this approach can lead to an unmanageable number of metric system alternatives to be evaluated.

Due to the large amount of research conducted by the U.S. Federal Aviation Administration investigating metric systems for a new aircraft CO<sub>2</sub> standard, a possible metric system consisting of 1/SAR and MTOW can be utilized as the foundation of the methodology demonstration conducted herein [119]. Further, due to the wide availability of research on the EU ETS, the metric of fuel burn, translated into CO<sub>2</sub> emissions, will be used for cap setting purposes [95]. A more complete description of these metric systems is provided later in this document on policy modeling in the U.S. NAS and implementation of this approach.

Once potential metric systems are established, the identification of stringency levels must be completed. For many metric systems this will simply require the setting of a range of possible metric levels, as with emission trading schemes; however, as is the

case for the notional aircraft CO<sub>2</sub> standard, the setting of stringency levels will require the establishment of notional limit lines [117]. This is due to the existence of both a metric and correlating parameter as part of the metric system, which requires the identification of a functional relationship between the metric and correlating parameter for the establishment of a stringency level. For the policies studied in this research, this will be assessed on a case by case basis, and is also more thoroughly explored later in 4.10.

The final aspect of generating feasible alternatives for policy design and analysis is the selection of a compliance mechanism. As aforementioned, these compliance mechanisms can either be command and control or market based mechanisms. Command and control policy is easily implemented, as the stringency level is considered a hard standard that must be met, and this is assumed to be the case for aCO<sub>2</sub> standard, as with the NO<sub>x</sub> and the noise standards. The market based mechanisms will typically either fall into the category of trading and offsetting or environmental levies. In order to implement these market based mechanisms, a generalized rule set will need to be established for the trading and offsetting schemes in order to effectively study implementation of an ETS.

### **3.7.5 Evaluate alternatives**

Once the possible metrics, stringency levels, and compliance mechanisms are established, they can be evaluated in a virtual environment. As previously mentioned, the population of policy alternative space will be accomplished here through design of experiments (DoEs). A number of sophisticated DoEs exist in literature that can be applied in this step. A combination of Central Composite Designs (CCD), Latin

Hypercube runs, and randomized designs are employed on all continuous variables of the problem, and a full factorial is run for all categorical parameters, such as the implementation date. The specific designs implemented to generate the alternative space, and corresponding ranges on all parameters, is provided in 5.5.

The selection of a suitable virtual environment can be highly dependent on the specific problem being addressed. The effects and interdependencies of an aircraft CO<sub>2</sub> standard and emission trading schemes in the U.S. NAS is the primary thrust of this research. As such, a suitable environment will be able to adequately capture the impacts of these policies in the region of interest. At the time of this study, two potential candidate environments have been identified: the Global and Regional Environmental Aviation Tradeoff tool (GREAT) [119] and the U.S. FAA's Aviation environmental Portfolio Management Tool for Economics (APMT-E) [142]. While APMT-E has been used to study policy such as emission trading schemes and NO<sub>x</sub> standards, the substantial run time on the order of many hours makes this tool ill suited for exhaustive exploratory studies, such as the research proposed here. GREAT has also been used to study policies, such as the aircraft CO<sub>2</sub> standard as noted previously, however, the ability to isolate air carriers for consideration of emissions trading schemes does not currently exist. Despite these limitations, the framework of the virtual environment provided by GREAT does offer the computational speed needed for exploratory studies. As such, the development of a virtual environment has been pursued here using this framework as a starting point. This virtual environment is representative of the U.S. NAS, and provides the ability to study the interdependencies of the policies in question. As such, it has been termed the

U.S. Policy Interdependency Tradeoff tool (U.S. PoInT). A more complete discussion of the development and usefulness of this virtual environment is provided in Chapter 4.

### **3.7.6 Make decision**

Once all experiments have been run through the virtual test bed, the measures of effectiveness and measures of performance can be gathered and analyzed. Here the goal is to identify the region of effective policy space. This is accomplished through visualization of the results using any dimensions of interest for the problem and data filters on the measures of effectiveness. The idea is that a policy maker can see all dimensions of the problem concurrently while high level goals for CO<sub>2</sub> emissions targets and economic sustainability are applied to remove any ineffective policies as defined by the given stakeholder. The final selection of the set of policies or SoPS is left to the policy maker, and as such the scientist is able to objectively provide the ability for quantitative downselection.

### **3.7.7 Goal of the Integrated Policy Support Process**

In the end, the purpose of applying this adapted top down policy support process to the identification and quantification of systems of policies is to provide a systematic methodology for policy analysis. By formalizing this methodology and the policy analysis framework, a traceable process is established that can be used to select the best policy mixes to meet high level environmental goals. One of the benefits of this methodology is that it's inherently exploratory in nature, providing the ability to fully

analyze the potential policy alternative space before applying constraints for down selection. These methods have shown great success in product and process design, yet have never been fully implemented for policy analysis and design. Ultimately, formalizing this process for policy analysis and design is expected to be one of the primary contributions of this research.

### **3.8 The Role of the Scientist and Policymaker in Public Policy**

As an integral part of this process, the role of the scientist and policy maker ought to be discussed. Literature has pointed out that many of the world's greatest problems, such as global climate change, can lead policy makers to require technical solutions from the scientific community and scientists to require public policy responses from policy makers [143]. However, it's quite apparent that there is a link between science and public policy, and the solutions to our planet's problems will require an integration of the disciplines. It is the author's belief that in pursuing this path, the goal of the scientist is to remain objective, predicting all possible outcomes to policy implementation. The subjectivity of applied value systems are left to the policy maker, which can be made transparent through the visualization of the policy tradeoff selections. The process outlined here provides specific steps where a clear delineation of these roles can be applied. As such, the objectivity of the scientist can be maintained while including the subjectivity of policy makers.

## **CHAPTER 4**

### **COST-EFFECTIVENESS SIMULATION ENVIRONMENT FOR THE U.S. NAS**

In order to accomplish the research objectives through the methodology established, there is a need for a suitable cost-effectiveness modeling environment for the study of both a notional aircraft CO<sub>2</sub> standard and emission trading schemes. The following section will detail the creation of such an environment for the U.S. national airspace system (NAS), which is named the U.S. Policy Interdependency Tradeoff tool (U.S. PoInT). This environment will employ the basic framework and assumptions of other applicable models, and account for the specific needs of the policy studies in question. As such, great effort has been put forth to capture the impacts at both the vehicle level, and on notional air carriers at the fleet level of the U.S. NAS. While more complete detail will be provided throughout this section, the following is an overview of the methodology employed in the creation of this model.

The model is initialized through the use of a baseline database of movements developed from the Bureau of Transportation Statistics for all U.S. air carriers [144]. This database provides not only information on the specific routes and air carriers operating in the U.S. NAS, but also provides specific aircraft types utilized throughout each fleet. With the known aircraft types in operation, fuel burn estimates are created at the vehicle level from BTS and augmented by utilizing state of the art aircraft performance analysis tool, EDS [120]. Ultimately, the database of aircraft movements and fuel burn estimates of specific aircraft are integrated to develop fleet level fuel burn performance estimates

for the base year of operation. In order to finalize initialization of the tool, it's also necessary to determine the initial fleet mix and age of aircraft for each air carrier. This air carrier inventory is utilized for determination of retirements and capital costs in other modules of the simulation environment, and is determined through reported inventories to the Bureau of Transportation Statistics [146].

In addition to providing estimates of the benefits throughout the U.S. NAS, the simulation environment also captures the costs associated with the operations of aircraft, development of new technologies, and the policies under study. The costs captured in this environment have been determined through analysis of both the CAEP and U.S. FAA cost-effectiveness studies available in the public domain for prior noise and NO<sub>x</sub> standards [52, 124, 129, 142, 147-149]. These costs can most generally be discussed in terms of the non-recurring costs (NRC) to aircraft manufacturers, and recurring costs (RC) to aircraft owners and operators. It should be noted here that the policy induced costs will be those associated with the implementation of a notional aircraft CO<sub>2</sub> standard and emission trading schemes. Ultimately, the technology investments occurring through the CO<sub>2</sub> standard will be captured in the NRC to aircraft manufacturers, and the costs associated with emission trading schemes will be captured in the RC to aircraft owners and operators. While these are the cost elements considered herein, additional parameters may be included depending upon the specific policies under investigation.

While these basic modules initialize the tool developed and provide performance and cost estimates, studying future policies also requires forecasting through future years. This is accomplished through employment of a notional operations demand forecast,



loosely based on the 2011 Terminal Area Forecast published by the FAA. . Applying forecasts of revenue-tonne-kilometers (RTK) allows the operations database to be extended to future years for the assessment of fuel burn, CO<sub>2</sub> emissions, and associated costs. One of the major efforts included in this forecasting is in determining the retirements, replacements, and additions of aircraft into air carrier fleets. This is accomplished based on retirement curves, and assessment of a gap between operations covered by aircraft in service and total operations forecasted. An assumption for average aircraft utilization of 9.4 hours per day is employed, as well as an assumption of a fixed passenger load factor of 75%.

Next, as aforementioned, the study of the policies under question requires implementation within the modeling framework developed. As such, modules for each of these policies are developed. For the notional aircraft CO<sub>2</sub> standard, the metric system is based on MTOW and 1/SAR for particular aircraft included in the operations and inventory databases based on previous literature research [117, 119]. Additionally, the implementation date for stringency options is provided as an input to the module in order to account for the uncertainty of the actual implementation. The notional stringency options themselves are predefined based on a study by Boling et.al. [119]. This implementation will provide all necessary information in order to calculate relative technology insertion levels used to estimate NRC to manufacturers, as well as fuel burn characteristics of new vehicles for fleet fuel burn performance estimation.

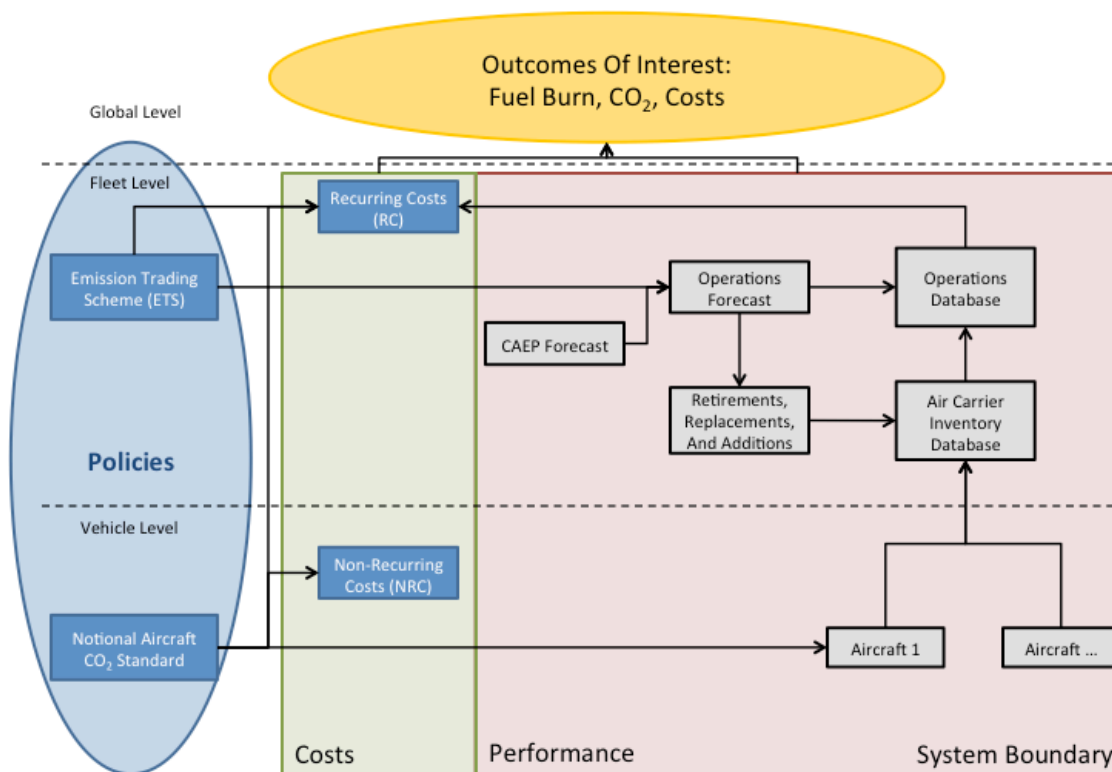
The module determining the impact of emissions trading schemes is based on the structure of the EU ETS discussed previously. This structure is largely taken from EU

Directive 2008/101/EC in terms of setting a cap and providing allocation of allowances to specific air carriers [95]. The cap setting process will be based on average emissions from an input reference year, which the modeler is free to set. The allocation of allowances will be based on relative market share of each notional air carrier included in the study based on the two previous years of operations, as is done in the EU ETS [95]. In addition, the potential to include the lost opportunity costs associated with freely allocated allowances is provided in the modeling framework to study the potential implications of windfall profits, as identified previously in literature. Allowance prices are assumed based on previous literature review, and can be varied parametrically. Since the aviation sector will likely be a net purchaser of allowances, it has been determined that linkage with an established ETS would provide a market suitable for realistic inclusion. Finally, it should be noted that as with the prior policy, the implementation date of the ETS can also be varied directly in this module.

The main effect of the ETS will be a reduction in demand over the provided forecasts, as noted throughout literature [96, 102, 106]. This is accomplished through the creation of a partial equilibrium model of demand, in which the opportunity costs associated with allowances increase ticket prices in future years, reducing demand based on known demand elasticities [137]. Accomplishing this task requires the determination of average ticket prices for all air carriers, which is assessed from information contained in the BTS [150]. Further, it is assumed that there is a one year lag in price increases due to opportunity cost pass through, however, consumer demand responds instantaneously.

This method of ETS employment proved to show similar trends to other studies regarding aviation’s inclusion in the EU ETS.

Each of these pieces of the modeling environment developed will be explored more completely in the following sections, and all applicable benchmarking will also be discussed. In order to provide a more illustrative view of this environment in the context of SoS structures included in this study, Figure 4.1 is provided.



**Figure 4.1: U.S. Policy Interdependency Tradeoff Tool (U.S. PoInT)**

#### **4.1 Operations Database Creation for U.S. NAS Fleet Analysis**

The first major effort in the creation of this virtual environment is the establishment of a database of operations for the U.S. NAS. This is accomplished through

the collection of BTS Form 41 T100 Segment data for U.S. carriers for years 2004 through 2012 [144]. The reason for extending the database back to year 2004 is to account for possible study of the EU ETS, in which average emissions from years 2004 through 2006 are used for cap setting purposes. Additionally, data is collected through the year 2012 as this is the most recent year for which a complete set of operations data is available by the BTS at the time of this study.

This data provides information for operations on specific origin-destination (OD) pairs with identification of the unique aircraft type. Additionally, each air carrier is identified through a unique airline identifier. In order to save internal computational memory and speed up analysis, only a subset of the data is carrier through analysis, and all text data is converted using numerical mappings. The data analyzed for this study included the number of departures performed on each OD pair, the corresponding payload, number of seats available, passengers carried, freight and mail payload, distance traveled, operational block time, air time, airline identifier, origin and destination, aircraft type and configuration, year and month of operation, and the service class of the air carrier involved. While all of this information is not fully utilized in other modules of the environment, this metadata may be useful in other studies. Additional metadata is also needed for this database, namely the definition of seat classes for all operations, which is accomplished using the definitions given in Table 4.8 and the number of available seats by aircraft type.

In analyzing the resulting database for years 2004 through 2012 it has been determined that 193 unique air carriers are represented. While studying the effects of

policy such as the ETS necessitates analyzing the effects on distinct carriers, only a small percentage of the carriers identified dominate the U.S. NAS market. Further, it is expected that showing the impact on different carrier types, namely low cost carriers (LCC) and legacy carriers, will not require the analysis of each unique air carrier operating in the region. In order to capture the most influential carriers operating in this region, the relative market share of each carrier is determined through analysis of both the revenue-passenger-miles (RPM) and revenue-ton-miles (RTM). This market share analysis is conducted for the most recent year data is available, 2012. Analyzing only this year is deemed acceptable because when market share analysis is completed for all years data has been collected a number of carriers no longer in service are shown to hold significant market share, namely Northwest Air Lines and Continental Air Lines.

#### **4.1.1 Revenue-Passenger Mile (RPM) Market Share Analysis**

The revenue-passenger mile (RPM) is a measure of consumer throughput for each airline. It is calculated on a per flight basis using Equation 3. The RPM for each OD pair is then aggregated over the year 2012 for each airline represented in the dataset, and the results provide a rank order of air carriers dominating the market.

##### **Equation 3: Revenue-Passenger Mile (RPM)**

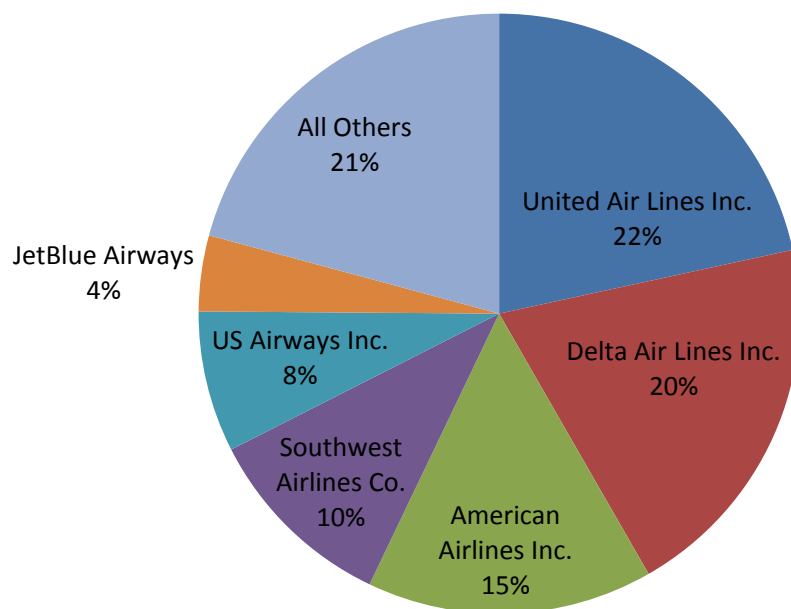
$$RPM = \text{Number of Passengers} \times \text{Miles Flown}$$

As aforementioned, only a small percentage of the 193 unique carriers dominate the U.S. NAS market. When analysis is performed for the top 80% of all RPM, it is found that only six air carriers are included, and when the top 90% of all RPM is analyzed, only

11 carriers are present. The relative market share of the top 80% of air carriers based on RPM is displayed below in Table 4.1 and Figure 4.2. As can be seen, the air carriers included are United Air Lines, Delta Air Lines, American Airlines, Southwest Airlines, US Airways, and JetBlue Airways. This set of air carriers includes both legacy carriers (United, Delta, and American) and low cost carriers (Southwest, US Airways, and JetBlue). As such, it represents a good minimum set of specific air carriers for the study of emission trading schemes, and will likely produce the high level trends of the U.S. NAS generally.

**Table 4.1: Relative Market Share of Top 80% of Air Carriers (RPM)**

<b>Carrier</b>	<b>%Share</b>
United Air Lines Inc.	21.59%
Delta Air Lines Inc.	20.13%
American Airlines Inc.	15.38%
Southwest Airlines Co.	10.42%
US Airways Inc.	7.60%
JetBlue Airways	4.09%
All Others	20.80%

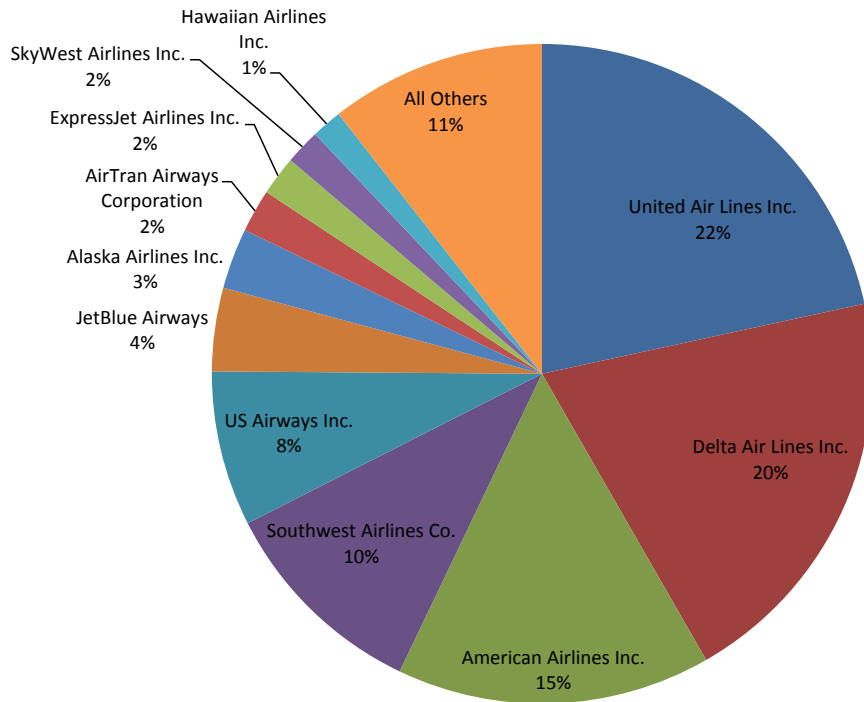


**Figure 4.2: Relative Market Share of Top 80% of Air Carriers (RPM)**

Despite the fact that the six air carriers already identified can adequately represent the different carrier types and dominant effects of the U.S. market, the top 90% of air carriers based on RPM is also analyzed for completeness. The relative market share of these air carriers is presented below in Table 4.2 and Figure 4.3. As can be seen, 11 distinct carriers are represented, meaning an additional five carriers account for 10% of the market not captured in the previous set. These five carriers are all different low cost and regional carriers operating throughout the U.S. As such, inclusion of this larger set would not be likely to produce additional information beyond the reduced set provided in Table 4.1.

**Table 4.2: Relative Market Share of Top 90% of Air Carriers (RPM)**

Carrier	%Share
United Air Lines Inc.	21.59%
Delta Air Lines Inc.	20.13%
American Airlines Inc.	15.38%
Southwest Airlines Co.	10.42%
US Airways Inc.	7.60%
JetBlue Airways	4.09%
Alaska Airlines Inc.	2.97%
AirTran Airways Corporation	2.11%
ExpressJet Airlines Inc.	1.93%
SkyWest Airlines Inc.	1.73%
Hawaiian Airlines Inc.	1.49%
All Others	10.57%



**Figure 4.3: Relative Market Share of Top 90% of Air Carriers (RPM)**



#### 4.1.2 Revenue-Ton Mile (RTM) Market Share Analysis

Revenue-ton miles (RTM) are also a measure of throughput for an airline, although instead of number of passengers carried, it is based on tons of payload. As such, this metric also provides a good measure of relative market share for air carriers. This RTM market share analysis is completed by calculating RTM on a per flight basis using Equation 4. As with RPM market share analysis, the results of these calculations are aggregated over the year 2012 for each airline, and provide a rank order of air carriers dominating the market.

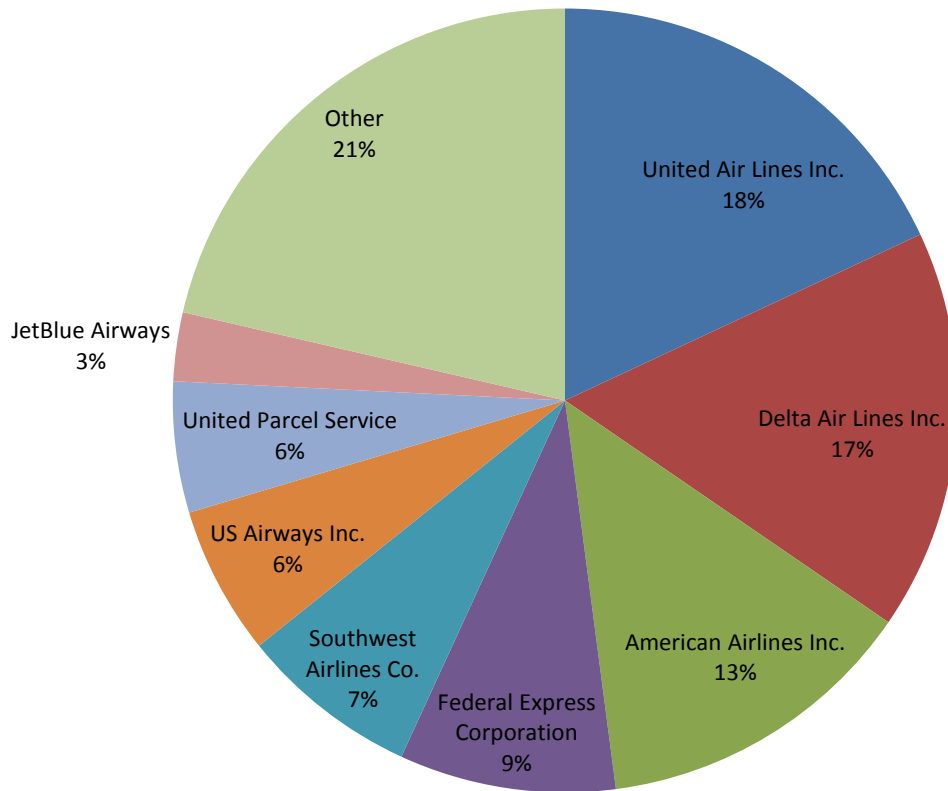
##### **Equation 4: Revenue-Ton Mile (RTM)**

$$RTM = Payload \times Miles Flown$$

The relative market share of each airline is calculated based on this measure, and the air carriers representing 80% of the market based on RTM are presented below in Table 4.3. While similar analysis could have been accomplished for the top 90% of the market, as was done with RPM market share analysis, the additional airlines included tended to be other low cost carriers, as was observed previously. As can be seen in this set, many of the same carriers are represented with the addition of two cargo air carrier servicers, Federal Express Corporation and United Parcel Service.

**Table 4.3: Relative Market Share of Top 80% of Air Carriers (RTM)**

Carrier	%Share
United Air Lines Inc.	18.04%
Delta Air Lines Inc.	16.53%
American Airlines Inc.	13.35%
Federal Express Corporation	8.92%
Southwest Airlines Co.	7.39%
US Airways Inc.	6.14%
United Parcel Service	5.40%
JetBlue Airways	2.83%
Other	21.38%



**Figure 4.4: Relative Market Share of Top 80% of Air Carriers (RTM)**

### 4.1.3 Comparison of RPM and RTM Market Share Analysis

While the absolute market share of the top air carriers varies depending on whether RPM or RTM is used as the metric, the variability is on the order of 3%. Further, in analyzing the air carriers with the greatest market share in the U.S. NAS it is noted that the passenger air carriers in the top 80% of the market for both RPM and RTM are ranked the same order regardless of which metric is used. As a result, the passenger airlines representing the top 80% of market share will be carried throughout this study. Their names and respective market share based on both RPM and RTM are provided in Table 4.4 below.

**Table 4.4: Relative Market Share of Passenger Air Carriers**

<b>Carrier</b>	<b>%Share (RPM)</b>	<b>%Share (RTM)</b>
United Air Lines Inc.	21.59%	18.04%
Delta Air Lines Inc.	20.13%	16.53%
American Airlines Inc.	15.38%	13.35%
Southwest Airlines Co.	10.42%	7.39%
US Airways Inc.	7.60%	6.14%
JetBlue Airways	4.09%	2.83%

Based on this analysis of relative market share, the BTS Form 41 T100 Segment data included in the database is down-selected, keeping only the six air carriers with the greatest market share. This list of carriers includes both legacy carriers, such as American Airlines, Delta Air Lines, and United Air Lines, as well as low cost carriers such as Southwest and JetBlue. For this reason, the resulting seed database for this study should be suitable for exploring the effects of policy such as emission trading schemes on the

U.S. NAS. In order to provide some level of anonymity to these air carriers, their names and respective placement will be replaced with generic labels, such as Legacy Carrier 1 and LCC 1 (Low Cost Carrier). All future analysis will present results for individual air carriers in this way.

## **4.2 Fuel burn estimation for baseline database movements**

Due to the fact that the BTS Form 41 T100 Segment data collected for the seed database did not include fuel burn estimates for specific flights, fuel burn calculations must be included. Further, the ability to fully study the impacts of a notional CO<sub>2</sub> standard also necessitate the inclusion of baseline fuel burn models for specific aircraft types represented in the database of operations. The calculations for the performance model will be dependent on the aircraft type, payload carried, and range flown. Estimates of block fuel are included based on simple regressions of specific aircraft types, as a function of both payload and range.

The data used for fitting these regressions can be generated using a number of existing tools, such as the Environmental Design Space (EDS), or the Advanced Emissions Model [120, 145]. There are number of advantages and disadvantages to each, which will be discussed. However, before evaluating the tools that can be used, it's important to understand the specific types of aircraft that are included in the database. In order to accomplish this, the database is queried for unique aircraft types, and the specific names are generated using the mapping provided by the BTS. This will be used to ensure that the final tool selected for block fuel estimates is suitable for all aircraft in the seed database.

### **4.2.1 Aircraft Emissions Prediction Tools Comparison**

Creating fuel burn performance estimating relationships for the aircraft included in the seed database requires data for each aircraft type over their respective payload-range envelope. There are a large number of existing, vetted environments suitable to produce these estimates; however, at the time of this study, two specific modeling environments were available for use. These include the Environmental Design Space (EDS) and Eurocontrol's Advanced Emission Model (AEM) [120, 145]. Each of these tools provides aircraft level performance estimates based on a large number of input parameters. In order to assess the relative usefulness for this endeavor, basic criteria are established, which include: the model has been proven useful for aircraft level emissions prediction, payload and range can be varied parametrically, results can be published, and all aircraft are represented.

Assessing these criteria requires a closer look at each of the identified tools. The first step is to establish that the tools can predict emissions through fuel burn estimation. Since that tends to be one of the primary measures of performance predictions, it has been determined that both tools are fully capable in this respect. Next, the ability to parametrically vary the payload and range of specific aircraft types is analyzed in order to fully understand performance throughout the payload-range envelope. EDS allows these parameters to be parametrically varied, however, the version of Eurocontrol's AEM available only allows for the range to be varied, as payload is fixed at a 65% load factor for all aircraft. Finally, one of the most crucial aspects of these tools is that all aircraft in the seed database need to be represented. In analyzing this criterion, it was found that

EDS provides generic representations of aircraft in different size classes; however, only a few calibrated models representing real aircraft exist. As such, only a small number of the aircraft in the seed database could be represented using this tool. However, Eurocontrol's AEM included most aircraft in this study. Subsequently, a mixed modeling approach for individual vehicle surrogates is completed through the use of Eurocontrol's AEM and supplemented with data provided by the Environmental Design Space.

#### 4.2.2 Aircraft Emissions Predictions

For each vehicle represented in the database, Eurocontrol's AEM is implemented to perform a mission sweep of range, and the corresponding fuel burn has been collected. Range is varied in 500 nautical mile (nmi) increments from 500 to 8,000 nmi. Estimates for the fuel burn impacts of payload are determined using vehicles in the Environmental Design Space and payload is varied as a percent of maximum allowable payload from 0% to 100%. The data generated from these tools is utilized to fit surrogate representations of the individual aircraft.

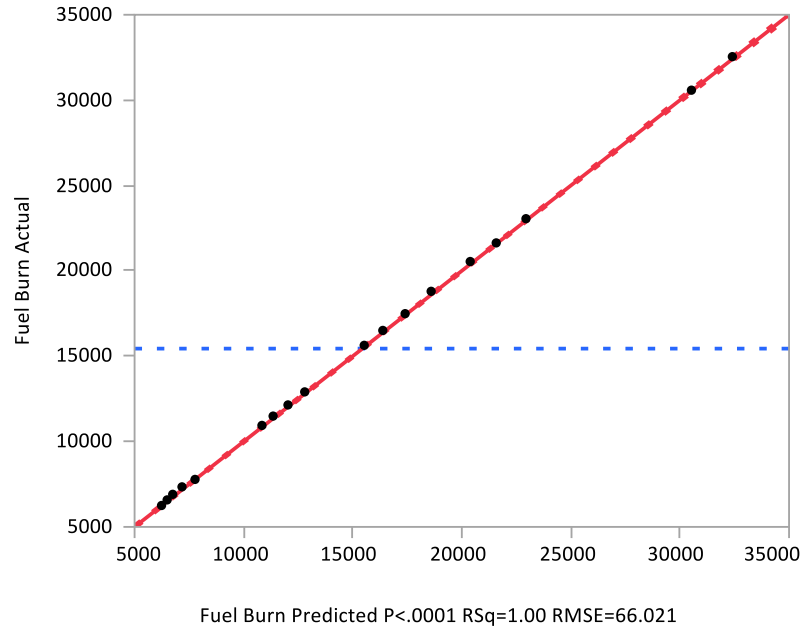
##### Equation 5: Aircraft Fuel Burn Surrogate

$$\begin{aligned} Fuel = & \beta_0 + \beta_1 \cdot Payload + \beta_2 \cdot Range + \beta_3 \cdot Payload \cdot Range + \beta_4 \cdot Payload^2 \\ & + \beta_5 \cdot Range^2 \end{aligned}$$

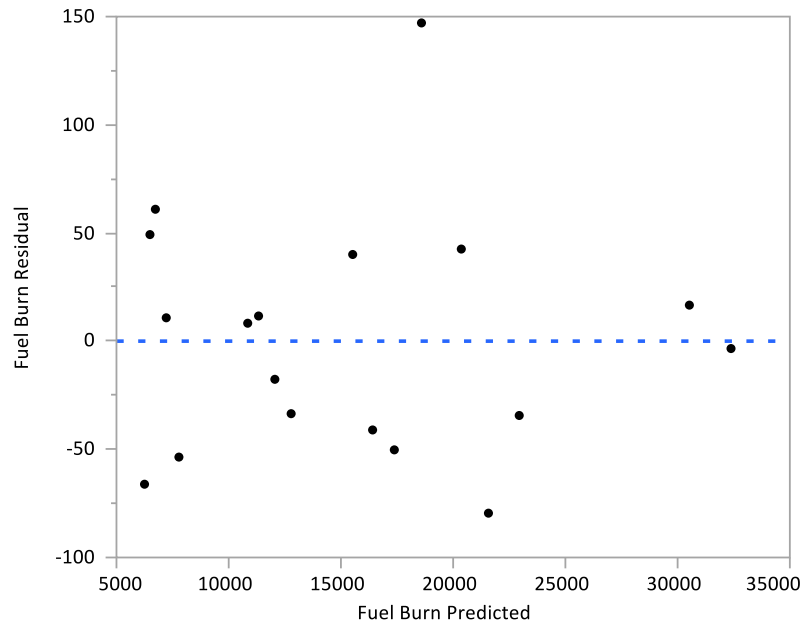
Fitting of the block fuel burn surrogates for each vehicle is accomplished using the nonlinear regression tool box in Matlab. All block fuel surrogates are of the form seen in Equation 5. In analyzing the goodness of fit for these regressions it has been noted that all coefficients of determination ( $R^2$ ) are above 0.99, and fall along a nearly one to one

mapping of actual against predicted data. Fit statistics for select regressions are provided in Figure 4.5 and Figure 4.6. It should be noted here that the figures provided are representative of all other surrogates, and in the interest of being succinct are not reported.

Due to its wide use, the EDS representation of the Boeing 737-8 is used as a test case for further statistical analysis. It has been determined that the results seen for this vehicle were similar across all other vehicles analyzed. Provided in Figure 4.5 are the actual by predicted results. As can be seen there's a nearly one to one mapping, indicating a very good fit. Further, the residual by predicted observations are also provided in Figure 4.6. As can be seen here, the spread in the residuals at the predicted values is on the order of 1%, also indicating very good predictive capabilities of the aircraft fuel burn surrogates.



**Figure 4.5: EDS Boeing 737-8 Representation Actual by Predicted Fuel Burn**



**Figure 4.6: EDS Boeing 737-8 Representation Residual by Predicted Fuel Burn**



### **4.3 Utilizing Aircraft Fuel Burn Surrogates for the Fleet**

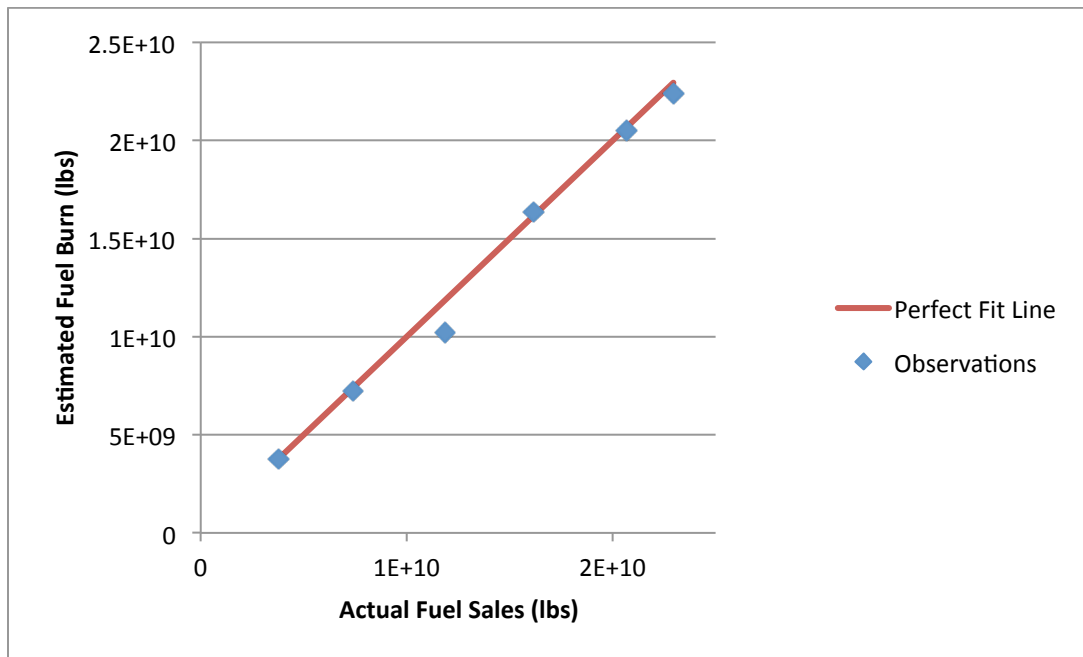
Given these block fuel burn surrogates, fuel burn for all flights in the operations database are calculated for the years 2004 through 2012 on a per flight basis. When fully implemented the block fuel estimates will be manipulated directly in forecasting out to future years, and altered for new technology vehicles due to the notional CO<sub>2</sub> standard, both of which will be discussed later. Further, it should be noted that estimating fuel burn also provides a direct estimate of overall CO<sub>2</sub> emissions, using a conversion factor of 3.15 lb CO<sub>2</sub> per lb of fuel [119].

In order to validate this method of fleet fuel burn estimation, the resulting fuel burn is compared directly to fuel sales for each air carrier included in this study. This is accomplished by comparing the fuel burn predictions for 2012 against data extracted from BTS Form 41 Schedule P12A for the air carriers included [151]. This data set provides actual fuel sales reported by all U.S. air carriers. Gross fuel sales for each air carrier are provided along with estimates resulting from this technique in Table 4.5. Additionally, the error is also reported. From this comparison the validation results reveal that the fuel burn estimation technique closely matches actual fuel sales, typically within 2% error, with the exception of LCC 1. It's unclear why LCC 1 estimates are significantly lower than expected, and with the available data it's not possible to determine. However, due to the fact that the bias in estimated fuel burn is below actual sales it seems probable that LCC 1 may have employed a fuel price hedging strategy by purchasing additional fuel not needed in the year used for validation. Despite this, it is generally clear that the method behaves appropriately for most air carriers included in

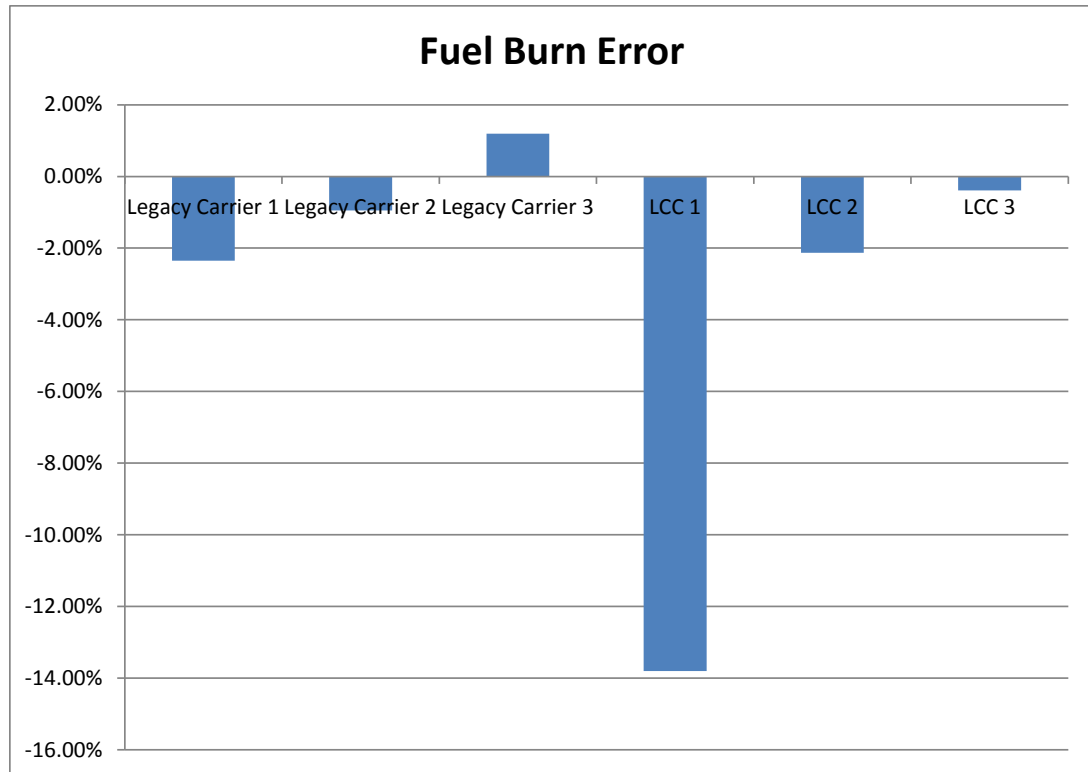
this study. Accuracy can obviously be improved with higher quality fuel burn estimates, if available. It will be assumed that the reported fuel sales to LCC 1 included fuel not specified by flights reported in the BTS T100 Segment data, but the predictions for LCC 1 are still reasonable for the purpose of this thesis. In addition, Figure 4.7 and Figure 4.8 are provided to provide a more visual representation of actual against predicted fuel sales and the associated error respectively.

**Table 4.5: Fleet Fuel Burn Validation**

Carriers	Fuel Sales (lbs)	Fuel Estimates (lb)	Error (%)
Legacy Carrier 1	22950442925	22410179495	-2.35%
Legacy Carrier 2	20685011182	20488292259	-0.95%
Legacy Carrier 3	16168207178	16360998184	1.19%
LCC 1	11879918800	10240069887	13.80%
LCC 2	7392023242	7234788679	-2.13%
LCC 3	3779636995	3764968257	-0.39%



**Figure 4.7: Actual by Predicted Fuel Sales for 2012**



**Figure 4.8: Percent Error in Predicted Fuel Sales for 2012**

#### **4.4 Air Carrier Inventories**

To finalize initialization of the tool, it's necessary to determine the number of aircraft and aircraft age for each air carrier. This will allow determination of retirements and capital costs in other modules of the simulation environment. Inventory data has been collected from the BTS Form 41 Schedule B-43 Inventory datasets for all applicable years [146]. The data collected for these air carrier inventories includes the year of first delivery for each aircraft, number of seats available, maximum payload capacity, acquisition date of the vehicle, operational status as of 2012, and aircraft type. In addition to collecting this data, the aircraft types present in the inventory for each air carrier are also cross referenced with aircraft used for operations reported in the dataset used for operations projections to ensure all vehicles are adequately accounted for. This data is

then stored for each air carrier as the existing inventory list for the year used for future projections, 2012. Table 4.6 is provided, giving the number of aircraft for each air carrier included in the study to demonstrate the fleet mix present in 2012. As can be seen, most legacy carriers operate a more diverse fleet than the low cost carriers, especially LCC 1 and LCC 3, which each only operate a few specific aircraft types.

**Table 4.6: Air Carrier Fleet Mix, 2012**

	<b>Legacy Carrier 1</b>	<b>Legacy Carrier 2</b>	<b>Legacy Carrier 3</b>	<b>LCC 1</b>	<b>LCC 2</b>	<b>LCC 3</b>
Boeing 737-700/700LR	72	45	0	1343	0	0
Boeing 737-800	260	366	543	34	0	0
Boeing 737-500	93	0	0	95	0	0
Boeing 737-400	0	0	0	0	131	0
Boeing 737-300	91	0	1	547	97	0
Boeing 757-200	485	777	607	0	165	0
Boeing 757-300	42	48	0	0	0	0
Boeing 767-400	32	105	0	0	0	0
Boeing 767-200	15	0	75	0	54	0
Boeing 767-300	148	399	243	0	0	0
Boeing 777-200ER/200LR	274	80	204	0	0	0
Boeing 737-900	109	0	0	0	0	0
McDonnell Douglas DC-9-50	0	82	0	0	0	0
McDonnell Douglas Super 80/MD81/82/83/88	0	596	594	0	0	0
McDonnell Douglas MD-90	0	164	0	0	0	0
Embraer 190	0	0	0	0	76	210
Airbus A330-300	0	96	0	0	63	0
Airbus Industries A320-100/200	393	197	0	0	255	511
Airbus Industries A330-200	0	15	0	0	23	0
Airbus Industries A319	228	169	0	0	312	0
Airbus Industries A321	0	0	0	0	208	0
Boeing 747-400	115	48	0	0	0	0
B787-800 Dreamliner	6	0	0	0	0	0

## **4.5 Cost Calculation Module**

As aforementioned, the costs captured in this environment are the recurring costs (RC) to aircraft owners and operators, as well as the non-recurring costs (NRC) to aircraft manufacturers. The costs included have been determined through analysis of prior cost-effectiveness studies for both the noise and NO<sub>x</sub> standards [52, 124, 129, 142, 147-149]. All costs are reported in 2012 U.S. dollars (USD), as this represents the base year of operations used for forecasting. The following section will detail the implementation of recurring costs and non-recurring costs included in this study. It should be noted however, that the recurring costs associated with emission trading schemes will be covered later in 4.10.2.

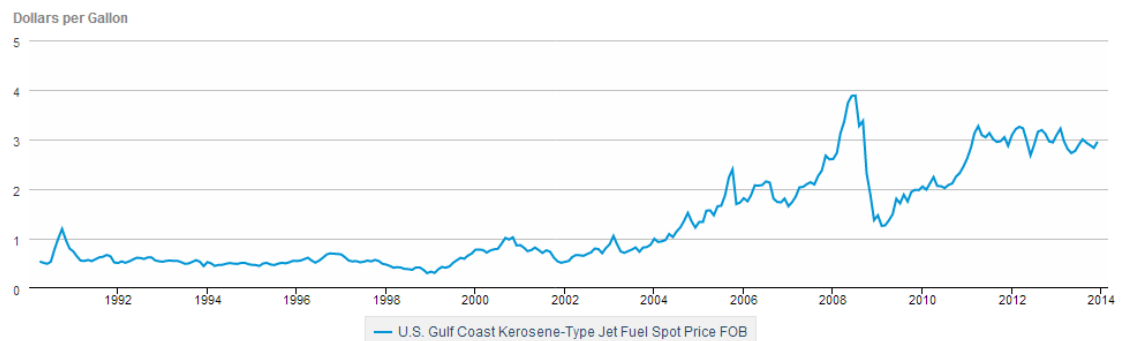
### **4.5.1 Recurring Costs**

The recurring costs (RC) captured in this simulation environment are the direct operating costs (DOC). The following section will detail the methodology used to calculate DOC, which include the fuel costs, capital costs, crew and maintenance costs, and route and landing fees.

#### **4.5.1.1 Fuel Costs**

Fuel costs are estimated directly utilizing results from the fuel burn performance module of this tool, as well as an assumed price of fuel of approximately \$3 per gallon based on the Energy Information Administration's spot price for kerosene type jet fuel [152]. The primary reason for considering this cost as a constant value is due to the

relative stability in recent years where kerosene type jet fuel has hovered around \$3 per gallon. This can be seen below in Figure 4.9, which displays the spot price in 2012 USD. Despite this, the cost assumption can be varied directly in the cost calculation module to account for uncertainty regarding future fuel prices. As such, scenarios can be assessed to quantitatively account for the aleatory variability of fuel price.



**Figure 4.9: Spot Price for Kerosene Type Jet Fuel**

#### 4.5.1.2 Capital Costs

Capital costs are those associated with ownership or leasing of specific aircraft, and include consideration of both financing and depreciation. These costs are ultimately annuitized over the useful life of the vehicle, and are calculated based on the aircraft price, finance rate, depreciation rate, number of years financed, and scrap price of the aircraft after its useful life. Subsequently, the primary assumptions for the calculation of capital costs are the finance and depreciation rates, which are assumed to be 5% and 3% respectively. While information regarding actual rates for airlines is not readily available, these values produce trends consistent with other tools.

Due to the fact that the capital required for aircraft investments are very high, vehicle costs are typically annuitized through loans or lease arrangements. The proposed method for determination of annuitization utilized in this study is based on an annuity due formulation, which would be consistent with lease payments made at the beginning of each period, where a period could be considered by year. This is accomplished by first calculating the present value of the scrapped item at the end of its useful life, determining the present value of the annuity due, and finally calculating an equivalent annual cost associated with vehicle purchase [153, 154]. Calculation of the present value of the scrapped item is accomplished using Equation 6.

**Equation 6: Net Present Value of Scrapped Item**

$$PV_{scrap} = SV \times \frac{1}{(1 + d)^n}$$

Here, SV is the scrap value, d is the depreciation rate, and n are the years of useful life. It has been assumed here that the scrap value of each aircraft is 10% of the initial price, and the number of years of useful life is equivalent to the years in service.

Following this, the present value of the annuity due is then calculated using Equation 7. In this equation, i represents the finance rate.

**Equation 7: Present Value of Annuity Due**

$$\ddot{a}_{ni} = \frac{1 - (1 + i)^{-n}}{d}$$

Given the present value of the scrapped item, the annuity due, and purchase cost (PC) of the vehicle, the equivalent annual cost (EAC) can be determined through Equation 8.

**Equation 8: Equivalent Annual Cost (EAC) of Capital Purchase**

$$EAC = \frac{(PC - PV_{scrap})}{\ddot{a}_{ni}}$$

This calculation is completed for all vehicles maintained in the air carrier inventories, and the EAC is applied throughout the useful life of the vehicles. Ultimately, the overall capital costs associated for each air carrier are determined by summing the EAC for each vehicle in operation in each year throughout the simulation.

***4.5.1.2.1 Determining Aircraft Price***

One of the key pieces of information needed for these capital cost calculations that has not been addressed yet is the purchase cost (PC) or aircraft price associated with the vehicles in operation. The aircraft price has been collected for a number of available vehicles based on existing literature, and the CPI-U is used to translate all costs to 2012 USD [155]. The list of vehicles included in the inventory list aforementioned and their associated costs in 2012 USD are provided below in Table 4.7. Additionally, the sources are also provided in this table. Due to the fact that the BTS inventory grouped a number of similar aircraft, determining the base price for the group proved challenging. In order



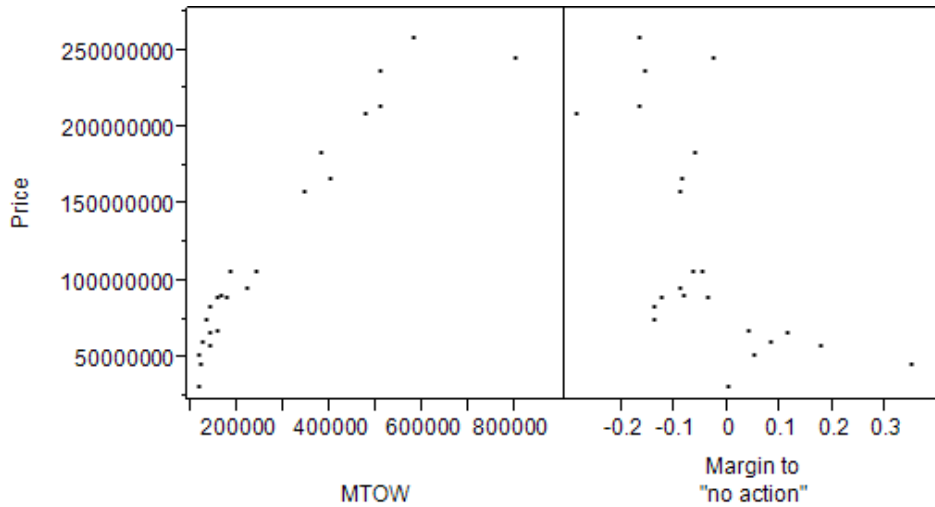
to overcome this obstacle, the price for each vehicle is determined, and the average price for the group is ultimately input for capital cost calculations.

**Table 4.7: Aircraft Purchase Price (2012 USD)**

<b>Aircraft</b>	<b>Price (2012 USD)</b>	<b>Source</b>
McDonnell Douglas MD-11	172,488,706.16	[156]
Airbus Industries A300-600	73,923,731.21	[157]
Embraer 170	26,119,718.36	[158]
McDonnell Douglas DC-9-30	45,000,000.00	[159]
McDonnell Douglas DC-9-40	45,000,000.00	[159]
Fokker 100	29,569,492.48	[160]
Boeing 737-100/200	59,264,770.41	[161]
Boeing 737-700	74,909,380.96	[162]
Boeing 737-800	89,201,302.33	[162]
Boeing 787-8	208,760,616.94	[162]
Boeing 777-200ER	257,747,409.49	[162]
Boeing 777-200LR	291,752,325.85	[162]
Boeing 777-300ER	315,605,049.78	[162]
Boeing 777 AVG	288,368,261.05	[162]
Boeing 767-300ER	183,133,723.45	[162]
Airbus A320	90,186,952.08	[163]
Airbus A321	105,760,218.12	[163]
Airbus A330-200	212,998,910.86	[163]
Airbus A330-300	235,964,550.03	[163]
Airbus A330-200F	215,955,860.11	[163]
Boeing 737-500	52,023,850.54	[164]
Boeing 737-400	65,805,003.00	[164]
Boeing 737-300	59,603,484.39	[164]
Boeing 757-200	95,434,480.79	[164]
Boeing 757-300	106,459,402.76	[164]
Boeing 767-400/ER	166,751,944.78	[164]
Boeing 767-200/ER	157,901,089.87	[165]
Boeing 737-900	89,600,000.00	[162]
DC-9-50	45,000,000.00	[159]
DC9 Super MD80	57,191,782.71	[166]
MD-90	66,838,589.44	[167]
Embraer 190	31,540,791.98	[168]
Boeing 747-400	244,270,927.37	[164]

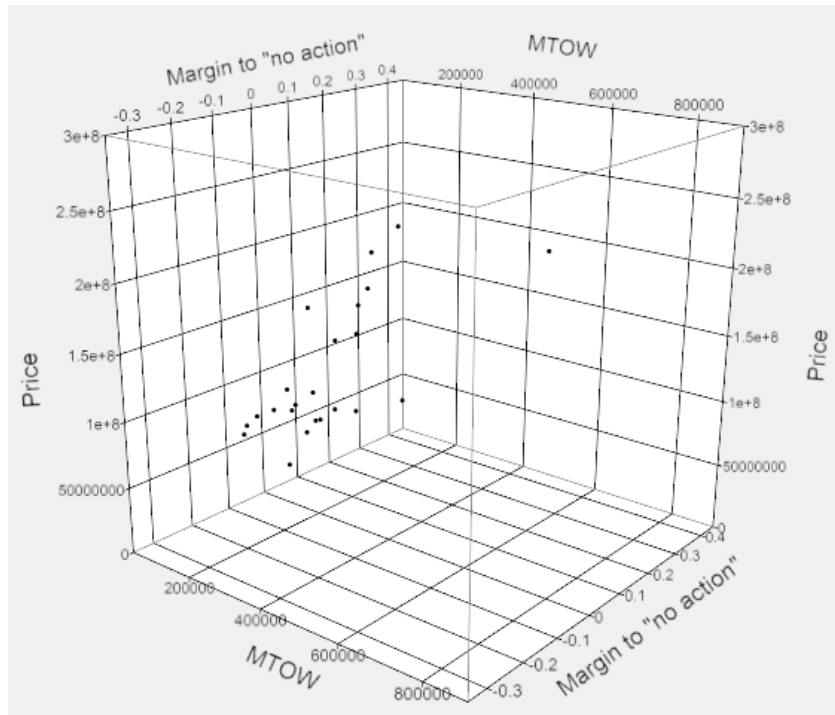
Due to the fact that the aircraft prices for new vehicles are unknown, a method for determining aircraft price based on available information must be identified. It is expected that the aircraft price is likely a function of the size of the vehicle, as well as the relative technology generation. Given this, it's proposed that a model of aircraft price can be developed based on these two parameters, provided a suitable quantitative mapping for each. Aircraft size is readily quantified through the maximum takeoff weight (MTOW), and given the wide availability of this data it is selected as the size parameter. Technology generation however is much more nuanced, and a simple, widely available parameter does not exist. While the year of production may be a suitable measure of technology generation, if the technology generation can relate specifically to the notional aircraft CO<sub>2</sub> standard it may be more appropriate in this context. As such, technology generation will be measured by the aircrafts' margins to a "no action" notional stringency scenario. A more thorough explanation of this "no action" stringency scenario and determination of the margin for particular aircraft are included in 4.10.1.

Subsequently, future aircraft prices are modeled as a function of the maximum take-off weight (MTOW) of the vehicle and the respective margin to a "no action" stringency scenario. To accomplish this, the existing vehicles in the inventory database are employed to map aircraft price against MTOW and the margin to a "no action" stringency option, which is explained in detail later. This mapping can be seen more visually through analysis of each dimension (MTOW and margin), which is provided in the scatterplot matrix in Figure 4.10.



**Figure 4.10: Impact of MTOW and Margin to Aircraft Price**

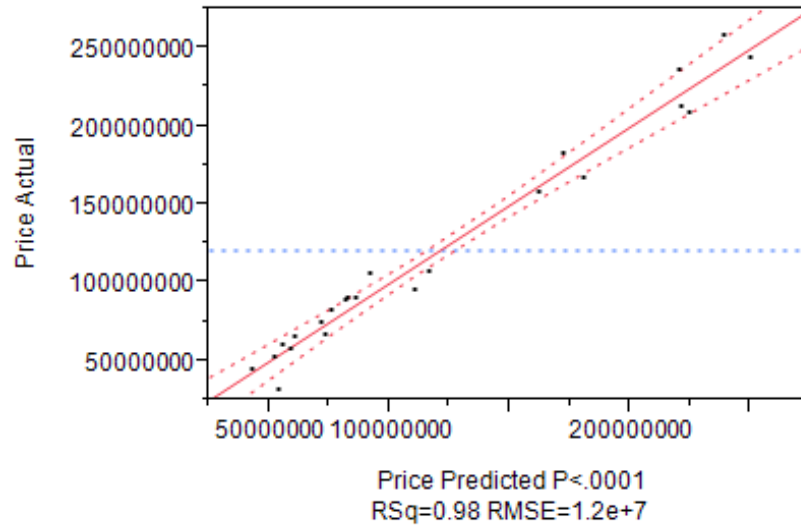
As can be seen in Figure 4.10, price tends to increase for larger vehicles, as well as for more technologically advanced vehicles (ie. those with a larger negative margin to the “no action” stringency). It’s also quite obvious these trends are not entirely linear. As such, the three dimensional space should be analyzed to determine a suitable functional form for modeling. Figure 4.11 is provided to visualize the functional space of the aircraft price in the database in three-dimensional space.



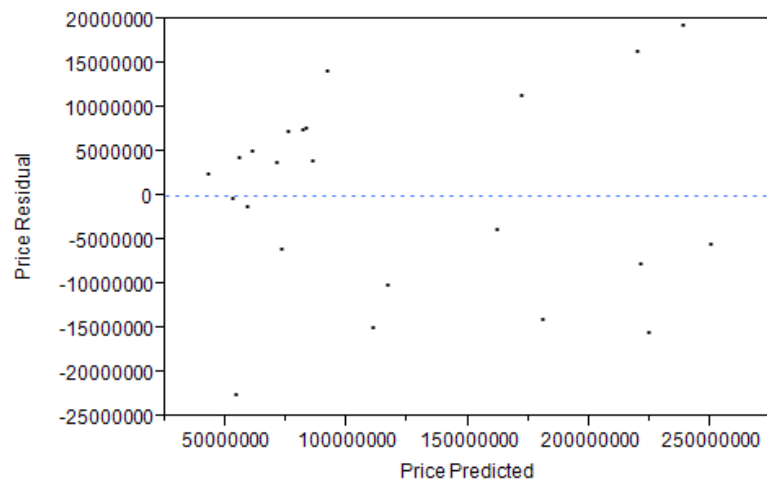
**Figure 4.11: Visualization of Aircraft Price to MTOW and Margin**

Due to the relatively tight formation of points, it has been determined that a response surface equation would likely adequately predict the data observed above. Further, it is noted that the nonlinearities observed in the data will likely require a nonlinear response surface equation. As such, a second order response surface equation, including terms for twist, is used to fit price as a function of MTOW and margin to the stringency. The resulting response surface is found to have a coefficient of determination ( $R^2$ ) of 0.98, indicating the predicted values closely matched those used to fit the curve. In order to more fully check the goodness of fit for the resulting response surface equation, the actual by predicted values and residuals are also analyzed. The actual by predicted price values can be seen in Figure 4.12. As is shown, the predicted values follow a very close 1:1 trend with actual prices. Additionally, the spread of the residuals,

as seen in Figure 4.13, are within approximately 10% of the predicted prices which is deemed acceptable. Subsequently, the resulting 2<sup>nd</sup> order response surface for price is determined to be acceptable.



**Figure 4.12: Aircraft Actual by Predicted Price**



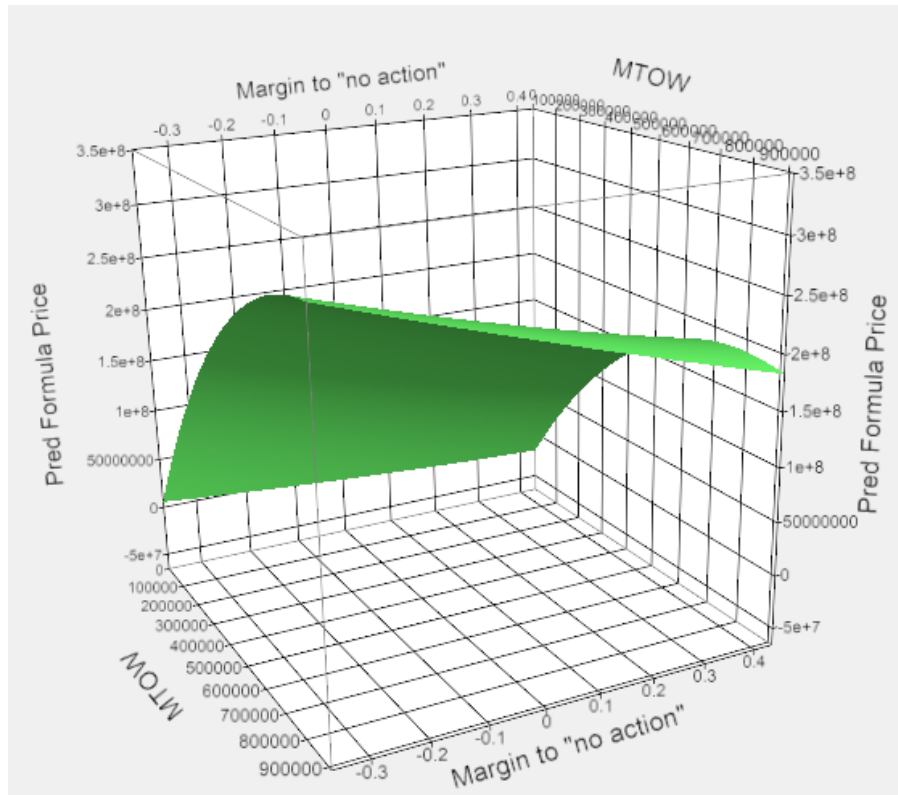
**Figure 4.13: Aircraft Residual by Predicted Price**

The response surface equation for price as a function of MTOW and the margin to a “no action” stringency scenario is provided in Equation 9. The surface is further

illustrated in Figure 4.14. As is expected, price is shown to increase for increases in both MTOW and margin.

**Equation 9: Aircraft Price Response Surface Equation**

$$Price = -9032297 + 591.77 \cdot MTOW - 33596460 \cdot Margin - 0.000341 \cdot MTOW^2 - 131.73 \cdot MTOW \cdot Margin + 18420359 \cdot Margin^2$$



**Figure 4.14: Aircraft Price Response Surface**

**4.5.1.3 Crew and Maintenance Costs**

Both the crew and maintenance costs are based on an assumed cost per operational block hour, which is consistent with other aviation cost-effectiveness analyses. These costs are reported based on a seat class categorization, which are

provided in Table 4.8. The assumptions associated with these costs are generated using the Aircraft Life Cycle Cost Analysis (ALCCA) tool in conjunction with five generic vehicle classes represented in the Environmental Design Space (EDS). For all seat classes not represented by the generic vehicles, linear interpolation is used to determine an estimate of crew and maintenance costs per block hour. This combination of tools is chosen for their availability, but it's anticipated the results will be similar to other studies. Here, the assumptions are provided as simply a cost per block hour for each seat class, with maintenance costs differentiated based on production status.

Due to the fact that both crew and maintenance costs require the determination of block hours for each seat class, this must also be assessed. The operations database used to seed forecasting includes operational block hours in the form of ramp to ramp time. This time is reported in minutes, and ultimately converted to total block hours. Given the mapping of specific aircraft types in the operations database to seat classes, the overall block hours for each seat class can be aggregated for all air carriers considered. This block time can further be used in forecasting, and is assumed to be constant per operation for all future years considered. Ultimately, this assumption negates any consideration of operational speed changes in future aircraft, but can be updated if such changes are expected in future revisions of the simulation environment.

**Table 4.8: Seat Class Definition**

<b>Seat Class</b>	<b>Number of Seats</b>
19	0-19
1	20-50
2	51-100
3	101-150
4	151-210
5	211-300
6	301-400
7	401-500
8	501-600
9	601-650

Crew costs are distinguished based on aircraft use. Due to the fact that the air carriers considered in this study all provide passenger service, only the passenger crew costs from the ALCCA estimates are provided here. These assumptions are given in Table 4.9.

**Table 4.9: Crew Cost Assumptions (2012 USD)**

<b>Seat Class</b>	<b>\$ Per Block Hour</b>
19	252.98
1	317.80
2	317.80
3	508.80
4	563.90
5	765.90
6	854.70
7	1120.53
8	1342.97
9	1565.42



Maintenance costs are distinguished based on operational status. This assumption stems from the fact that maintenance costs tend to be age dependent, increasing for older vehicles, which is a well-documented phenomenon in aviation literature [169]. Using both EDS generic vehicles and ALCCA, these costs can be determined as a function of block hours, which are provided for both out of production and in production vehicles. The production status for the vehicles included in the operations and inventory databases are based on information from BTS Form 41 Schedule B-43 [146]. Due to the fact that data is not available for future maintenance costs, the assumptions used for in production vehicles are also applied to all vehicles added to the fleet in forecasted years. Table 4.10 provides the assumed values for these maintenance costs.

**Table 4.10: Maintenance Cost Assumptions (2012 USD)**

<b>Out of Production (OP) Aircraft</b>		<b>In Production (IP) Aircraft</b>	
<b>Generic Type</b>	<b>\$ Per Block Hour</b>	<b>Generic Type</b>	<b>\$ Per Block Hour</b>
SC19 OP	252.30	SC19 IP	253.10
SC1 OP	252.40	SC1 IP	308.30
SC2 OP	252.40	SC2 IP	308.30
SC3 OP	391.57	SC3 IP	463.46
SC4 OP	490.30	SC4 IP	557.10
SC5 OP	514.70	SC5 IP	589.00
SC6 OP	563.20	SC6 IP	783.58
SC7 OP	724.61	SC7 IP	966.50
SC8 OP	845.71	SC8 IP	1149.42
SC9 OP	0	SC9 IP	1332.35

#### **4.5.1.4 Route and landing Fees**

The final component of the DOC calculations are the route and landing fees associated with operations. These charges are typically based on seat class, and also include consideration of the region of operation. In order to provide estimates for these costs a subset of data acquired through the Bureau of Transportation Statistics is utilized [170, 171].

Route charges are typically provided based on a cost per distance for each seat class and region of operation. Due to the structure of available data provided by the BTS, a singular route charge per nautical mile is determined for this analysis. While this approach does not directly model reality, these costs in the U.S. NAS are relatively small compared to all other cost elements, and the estimates provide useful values. Based on analysis of a subset of the BTS Form 41 Schedule P-5, the route charge is assumed to be approximately \$0.01 per nautical mile.

Landing fees are a result of airport charges to air carriers to maintain facilities. These fees are dependent on the airport, and the landing fees are also typically based on the size of the aircraft. As such, the assumptions for landing fees utilized here are given per operation. These estimates have been determined through analysis of a subset of the BTS Form 41 Schedule P-6 [171]. They are assessed using the mapping of the seat classes in the operations database, and aggregated for each air carrier. Table 4.11 provides the assumed fee per operation in 2012 USD.

**Table 4.11: Landing Fee Assumptions (2012 USD)**

<b>CAEP Seat Class</b>	<b>Landing Charge (\$/Operation)</b>
19	78.24
1	146.46
2	215.29
3	307.75
4	791.84
5	1022.47
6	1337.78
7	1342.08
8	1708.47
9	1427.97

#### **4.5.2 Non-Recurring Costs**

The other major cost element included in the cost calculation modules of this environment, are the non-recurring costs (NRC) to aircraft manufacturers. These costs are quite separate from the RC to aircraft owners and operators, as they impact manufacturers and not air carriers, thus they are accounted for independently. The NRC to manufacturers is the cost associated with technology investments for future aircraft development incurred as a result of the notional CO<sub>2</sub> standard. Estimating these costs in a bottom up approach can be accomplished through extensive analysis of future technology packages and impacts [172, 173], but such detailed analysis would require resources and time outside the scope of this study. As such, a normative forecasting approach is taken here utilizing an NRC estimating relationship based on the policy under consideration. This NRC estimating relationship includes consideration of both airframe and engine costs for an entire aircraft family.

While data associated with the new development of aircraft families is relatively limited, some expected improvements in aircraft from manufacturers in the 2018 to 2020 time frame provide a useable dataset to fit such an NRC curve. Typically, the reported investments must be taken from news sources, thus are gross estimates in the billion dollar range. Despite this fact, the method ought to be adequate for the purpose of analyzing the resulting trends in technology investments due to the notional standard. Further, it should be noted that since this cost is a result of the notional standard, the metrics used in the assessment will appear in the formulation of the NRC curve. As with future aircraft price mapping, the NRC method will employ MTOW as the size parameter and the percent improvement in metric value, measured through  $1/SAR$ , as the level of technology insertion.

Data for 14 different aircraft families were identified throughout literature with corresponding estimates for airframe and engine development costs. While these aircraft families do not necessarily directly correspond to the aircraft included in the air carrier inventories, it does provide a sufficient set of data to fit an NRC estimating relationship. The data used for this purpose is provided in Table 4.12 with all sources identified. It should be noted here that the improvement in margin provided below has been calculated based on a “No-Action” limit line for the Aircraft CO<sub>2</sub> Standard. The methodology by which this line has been constructed will be discussed in upcoming sections of this chapter. The improvement is simply the percent difference in these vehicles compared to the notional limit line discussed later.

**Table 4.12: Airframe and Engine Cost Assumptions for NRC**

<b>Aircraft Family</b>	<b>MTOW (lb)</b>	<b>% Improvement in Margin</b>	<b>Reported NRC (billion USD)</b>	<b>Source</b>
Airbus A320neo	170000	7.54	1.3	[174]
Airbus A330/A340	609406	11.13	5.1	[175]
Airbus A330-200	524552	19.64	0.67	[176]
Airbus A340-500/600	837520	15.04	3.7	[177]
Airbus A350	679000	32.26	15	[178]
Airbus A380	1267300	16.40	14	[179]
Boeing 747-8	986731	17.88	4.2	[180]
Boeing 777-200/300	774789	27.28	9.4	[181]
Boeing 787-8	502363	29.09	11	[182]
CRJ-1000	91774	2.36	0.32	[183]
CRJ-700	74979	7.03	0.88	[184]
Cseries	146000	13.70	3.5	[185]
E170/E190	115247	0.63	1.3	[186]
E2 Family	111973	-0.27	1.7	[187]

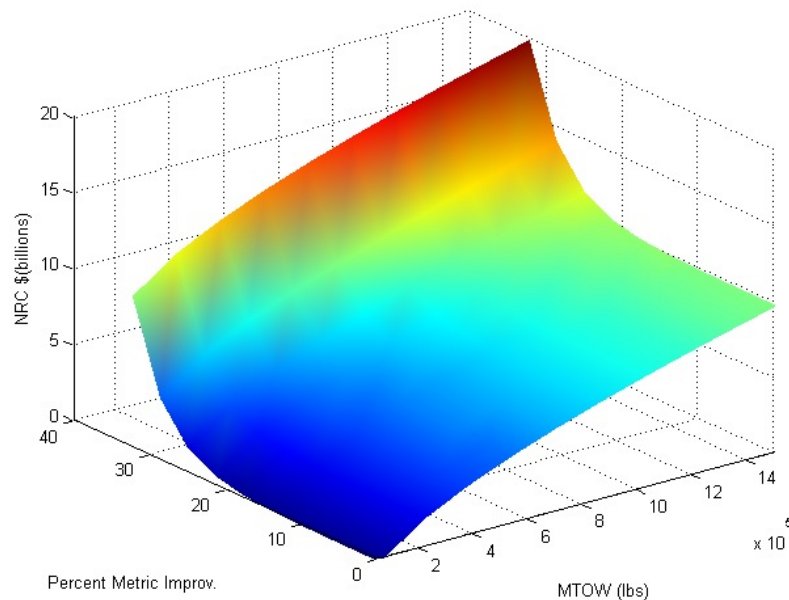
Due to the fact that technology costs can increase drastically beyond economically viable technology insertion, an exponential relationship for technology insertion is chosen as a function of the percent margin captured through the notional standard, and MTOW as the size parameter. The basic functional form of this equation is provided in Equation 10.

**Equation 10: NRC Estimating Relationship**

$$NRC(\text{billions}) = (\alpha_1 \cdot e^{\alpha_2 \cdot \text{Margin}} + \alpha_3) \cdot (\text{MTOW})^{\alpha_4}$$

The resulting NRC estimating relationship can be visualized in Figure 4.15, which provides a mesh showing the contours of the surface. As is expected, the NRC increases

with the size of the aircraft, and exponentially increases with increasing improvements in margin. This behavior is expected, as there is likely a technological limit to improvements in future aircraft, which can now be assessed through an associated cost to aircraft manufacturers or maximum reduction of the metric. One other aspect of this relationship to note is that there is a positive cost associated with 0% improvement to the margin. This is ultimately deemed acceptable, as there is likely a cost associated with even considering changes, whether they are made or not.



**Figure 4.15: NRC Estimating Relationship Surface**

## 4.6 Operations Forecasting

Given the ability to assess operations, inventory, and costs for the fleet, the next component necessary to determine policy implications is forecasting into future years. This is accomplished through the employment of a notional traffic and fleet forecasts out

to year 2036 [23]. The growth forecasts are provided for three different scenarios, and provide growth in revenue-tonne-kilometers (RTK) for route groups representing the global air transportation system. While this forecast is notional, any specific demand forecast can be used. The percent growth per year for this forecast is provided for the route group covering the domestic U.S. and global trends below in Table 4.13. Further, it should be noted that this forecast of RTK is used to seed performance and cost forecasting, but the overall growth per year for each air carrier is updated under emission trading scheme scenarios. This fact will be explored more completely in 4.10.2. Applying this forecast to the 2012 operations database ultimately provides estimates for fuel burn, CO<sub>2</sub> emissions, and cost.

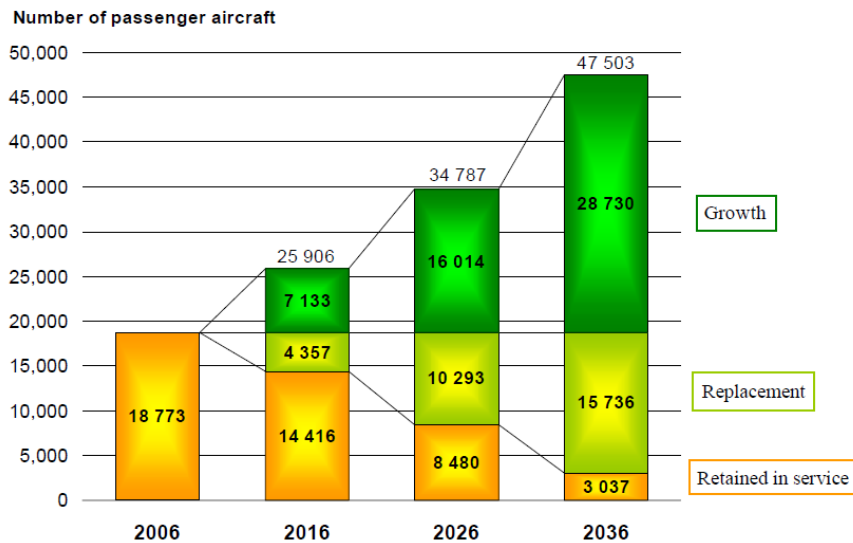
**Table 4.13: Notional Demand Forecast Projection**

<b>Sector</b>	<b>2006-2016</b>	<b>2016-2026</b>	<b>2026-2036</b>
North America	3.0	2.5	2.0
Total International	5.4	5.0	4.6

## **4.7 Fleet Evolution**

In addition to forecasting the growth in operations, the evolution of the air carrier fleets must also be assessed. This necessitates predictions for the retirements, replacements, and additions of aircraft to air carrier inventories throughout the simulation. In order to provide a more illustrative representation of what corresponds to retirements, replacements, and additions, Figure 4.16 is provided [23]. As can be seen, as aircraft age they are retired from the fleet, which necessitates the replacement of those vehicles to cover the operations no longer in service. Moreover, as the number of

operations grows, additional aircraft are needed to cover that growth. The following discussion will provide more detail on the specific method employed for retiring, replacing, and adding vehicles to the air carrier fleet. It should be noted here though, that these actions are ultimately stored in the aircraft inventories throughout the simulation by adding data on the date of retirement, new date of acquisition, replacement aircraft type, and whether the new aircraft is a technology derivative.



**Figure 4.16: Retirements, Replacements, and Additions [23]**

### 4.7.1 Retirements

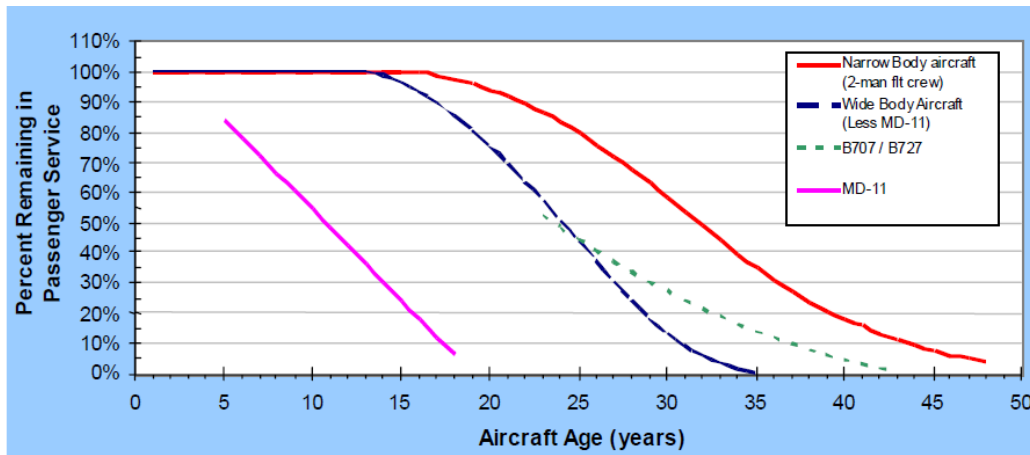
Assessing when aircraft will retire is based on probability of survival curves, which are shown in Figure 4.17 [23]. The inventory in 2012 for the air carriers considered has been cross referenced, and it is determined that only the curves for narrow body and wide body aircraft are applicable. Utilizing these curves however requires the distinction within the inventory dataset between narrow and wide body aircraft. Further,



the curves provided are strictly visual, thus must be mapped to an analytic measure that can be used to assess probability of survival. To address the first issue, the distinction between narrow body and wide body aircraft is based on the number of available seats. Typically, wide body aircraft tend to have more than 210 seats, thus this cutoff was used to establish aircraft type. Next, the curves are converted to a functional form that can be analytically assessed. The functional form is provided in Equation 11, where  $\beta$  represents the age at which a 50% probability of survival occurs,  $\gamma$  controls the slope of the curve, and  $n$  corresponds to the aircraft age. Based on visual inspection, it has been determined that for the narrow body probability of survival curve,  $\beta = 0.19$  and  $\gamma = 30.7$ , and for the wide body,  $\beta = 0.36$  and  $\gamma = 24$ , produce nearly identical results to those seen in the figure below.

**Equation 11: Aircraft Probability of Survival**

$$P(Survival) = 1 - \frac{1}{(1 + e^{-\gamma(n-\beta)})}$$



**Figure 4.17: Probability of Survival Retirement Curves [23]**

With this analytic representation of the probability for survival, the initial inventory database for each air carrier is assessed based on age of the aircraft present to produce a probability of survival into future years. Next, a random number generator is implemented to determine the future year at which each aircraft will retire. It should be noted here that due to the implementation of random number generation this process is inherently stochastic. In order to ensure repeatability of results the random number generator is seeded. It should be noted that a number of seeds have been tested, and produced negligible changes in terms of macro effects on fleet fuel burn and cost considerations. As such, this approach appears to be adequate.

#### **4.7.2 Replacements**

As vehicles are retired from the fleet they must be replaced in order to account for the existing operations. The replacement of aircraft is assessed throughout each year of the simulation as aircraft from the initial inventory list are retired. Due to the fact that an air carrier may decide to purchase another vehicle than the one retired, or potentially the vehicle retired may be out of production, a system for replacing retired aircraft must be established. This is accomplished by assessing the maximum payload and seating capacity of in production aircraft present in the inventory. An equal probability of selection for any aircraft with similar payload and seating capacity is given when aircraft are retired, and the replacement aircraft is randomly selected from the list. This process also requires the seeding of a random number in order to provide repeatable results. Additionally, as aircraft are replaced it is possible that the notional standard may be implemented. As such, if the standard is in place in the forecast year being assessed, the

selected vehicle is also identified as a technology infused vehicle. The meaning and assessment of these technology infused vehicles is explored more thoroughly in 4.10.1.

### **4.7.3 Additions**

Finally, the growth in operations must be assessed to determine the number of additional vehicles needed in future years. This is accomplished by forecasting the 2012 operations database using the growth forecast for each air carrier. The additional block hours necessary for each aircraft type is aggregated to determine the total additional operational hours each year. An assumption on utilization of 9.4 hours per day was then used to calculate the number of new vehicles necessary for the growth in operations [23]. In addition, since the block time is manipulated directly from the operations database there is an inherent assumption of constant load factor throughout the fleet. This can be updated in the future to account for growing load factors, but is not attempted here.

With an overall assessment of the number of new vehicles needed in each aircraft type, the process employed for replacements is implemented to select the specific additional vehicles. Similar vehicles are given an equal probability of selection, which amounts to an assumption of equal market share among aircraft manufacturers. Further, if a standard is implemented in the year of assessment, the vehicle selected is identified as a technology infused vehicle. Ultimately, the retirements, replacements, and additions are tracked by maintaining an inventory database for each air carrier throughout the simulation. This database provides vehicle specific information, year of acquisition, and retirement year for performance and cost assessment.

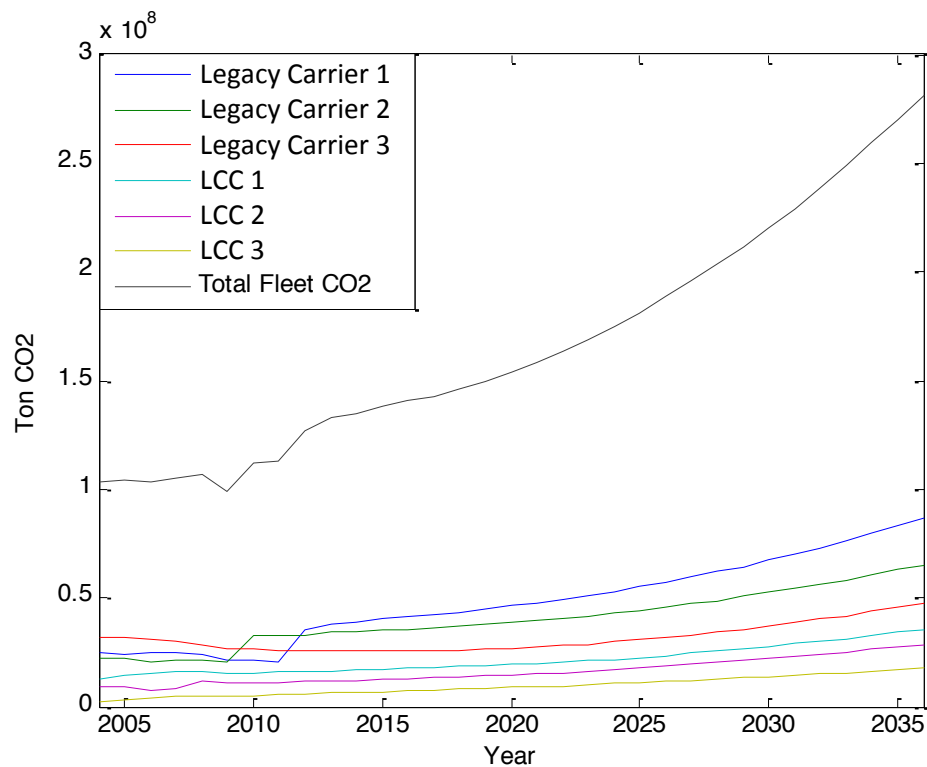
## **4.8 Fuel Burn Forecasting**

While the method for fuel burn estimation has already been discussed, the implementation of aircraft fuel burn surrogates in forecasted years can now be introduced. As aforementioned, all operations in the operations database used for forecasting have an associated aircraft type. As growth is forecasted vehicles may retire, and the replacements and additions are associated with the vehicle types in the operations database through an accounting strategy in the inventory databases. Subsequently, in forecasted years of the simulation an equal utilization assumption is employed for similar aircraft types owned by an air carrier. This means that in each forecast year the fleet mix is analyzed to assess the relative number of operations fulfilled by existing, replacement, and additional vehicles using the fuel burn surrogates associated with the vehicles in the inventory. Conducting fuel burn forecasting in this way provides a more accurate account of fleet evolution, and demonstrates the trends in improvement expected from previous literature.

## **4.9 Baseline Cost and Performance of the U.S. NAS**

At this point, the simulation environment for the U.S. NAS can be used to predict performance and costs in the absence of policy. This baseline scenario is often referred to as a “no action” scenario, and will be used later to assess the relative costs and benefits due to policy implementation. As a reminder, due to the fact there is an equivalency between fuel burn and CO<sub>2</sub> emissions, the performance aspects used for comparison are always in tons or pounds of CO<sub>2</sub>. Figure 4.18 provides the projection of CO<sub>2</sub> performance forecast out to 2036 for the air carriers included in this study, as well as aggregated fleet

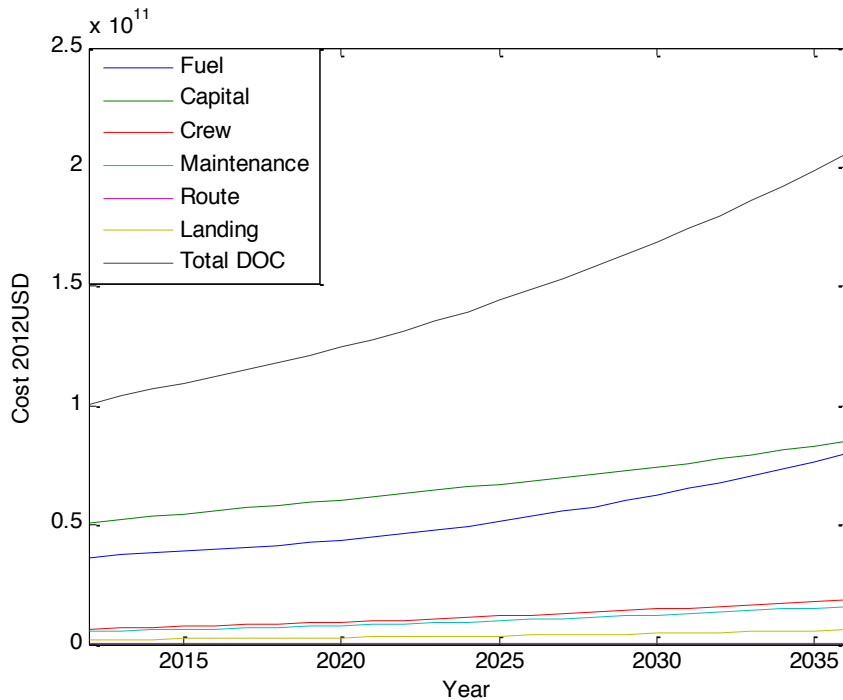
CO<sub>2</sub>. As can be seen in this figure, the projected fuel burn trends from 2012 (the year used for forecasting) through 2036 show growth trends exponentially increasing, which is expected since the projected growth is given as a percent per year that is compounded over the course of the simulation.



**Figure 4.18: Projected "No Action" CO<sub>2</sub> Emissions in the U.S. NAS**

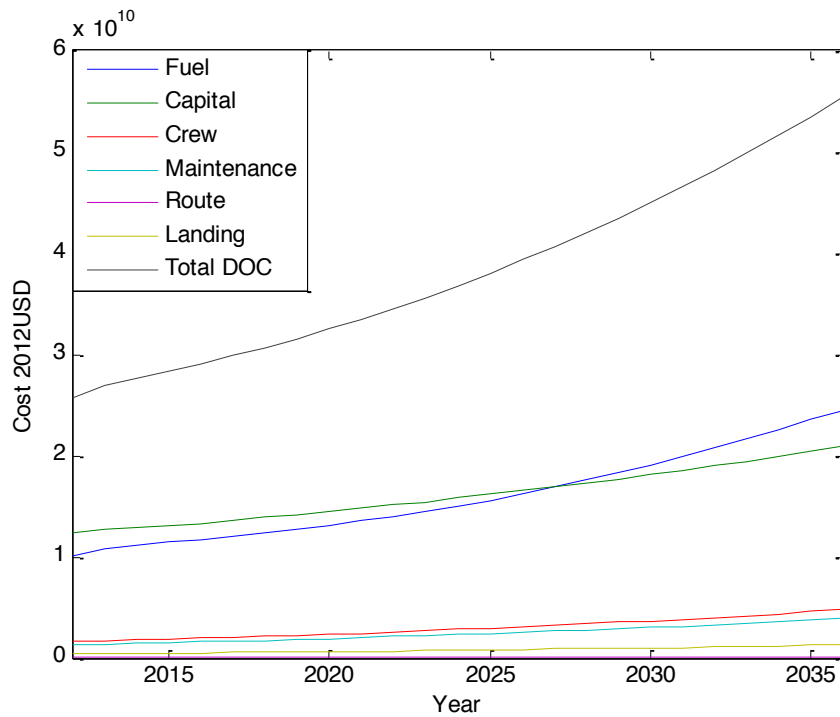
In addition to analyzing the performance of the fleet, the costs are also stored, and can be assessed. The total direct operating costs and the respective components are displayed for this "no action" scenario in Figure 4.19. As aforementioned, all reported costs are given in 2012 USD. As can be seen in this figure, the primary components of DOC are the fuel and capital costs. It may also be noted that the relative fuel cost tends to

increase more rapidly than the capital costs toward the end of the simulation timeframe. This behavior can be explained in more detailed analysis of the cost buildup. Due to the fact that fuel cost is proportional to fuel burn, this cost increases at the same basic rate as overall fuel burn described previously. Capital cost increases come about due to the need for additional vehicles to meet growing demand. The number of vehicles needed is ultimately dependent on an assumed utilization rate of 9.4 hours per day. In further analysis of the baseline operations dataset used to seed the forecast it is determined that this utilization is significantly higher than the typical aircraft utilization in the base year. This means that as the existing aircraft are retired, fewer vehicles are needed to replace and meet additional growth due to the increasing utilization rate. The combination of these facts is what accounts for this relative change in overall fuel and capital costs.



**Figure 4.19: DOC for “No Action” Scenario in the U.S. NAS**

In addition to analyzing the overall fleet DOC, each of the respective air carrier costs can also be analyzed in isolation. Doing so here for all air carriers included in the study is not necessary, but to demonstrate this capability Figure 4.20 is provided. Here the DOC for Legacy Carrier 1 is reported, with all corresponding cost components. As can be seen, the cost trends follow those of the fleet quite closely in terms of overall DOC. However, there are a few notable differences, with the most obvious being the tradeoff in fuel and capital costs over the course of the simulation. This follows the basic trend of the fleet fuel and capital costs in terms of relative cost changes however, and the reason for this behavior can be explained in the same way.



**Figure 4.20: DOC for Legacy Carrier 1 for “No Action” Scenario**

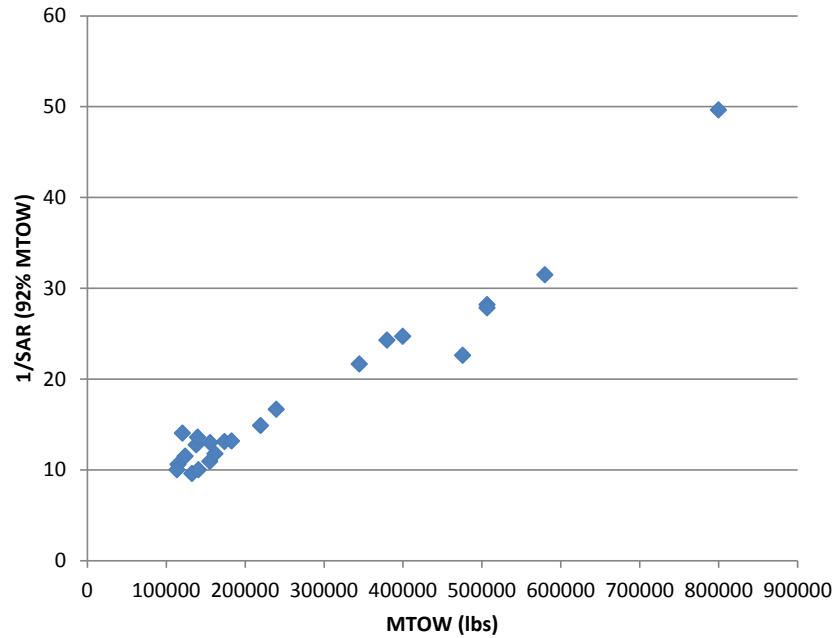
## **4.10 Defining CO<sub>2</sub> Mitigation Measures and Modeling**

With a functional performance and cost simulation environment for the U.S. NAS, the next step in this study is providing the functionality to study policy implications. As discussed in Chapter 3 of this document, the two policies under consideration in this study are a notional CO<sub>2</sub> standard and emission trading schemes. The implementation of modules and links between the existing simulation environment will be discussed for each of these policies in the following sections.

### **4.10.1 Notional Aircraft CO<sub>2</sub> Standard**

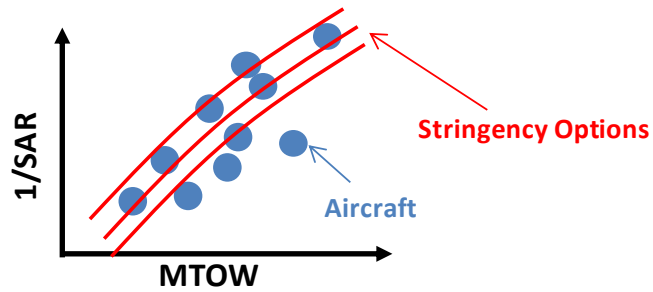
As identified throughout literature, the likely metric system for an aircraft CO<sub>2</sub> standard will be a measure of 1/SAR (specific air range) correlated against MTOW [119]. Subsequently, for each vehicle in the seed database SAR values are determined at 92% MTOW. This data is stored for all vehicles included in the inventory datasets. Given this data, the reciprocal of these SAR values are then plotted against the MTOW to visualize the expected metric system being considered, which is provided in Figure 4.21.





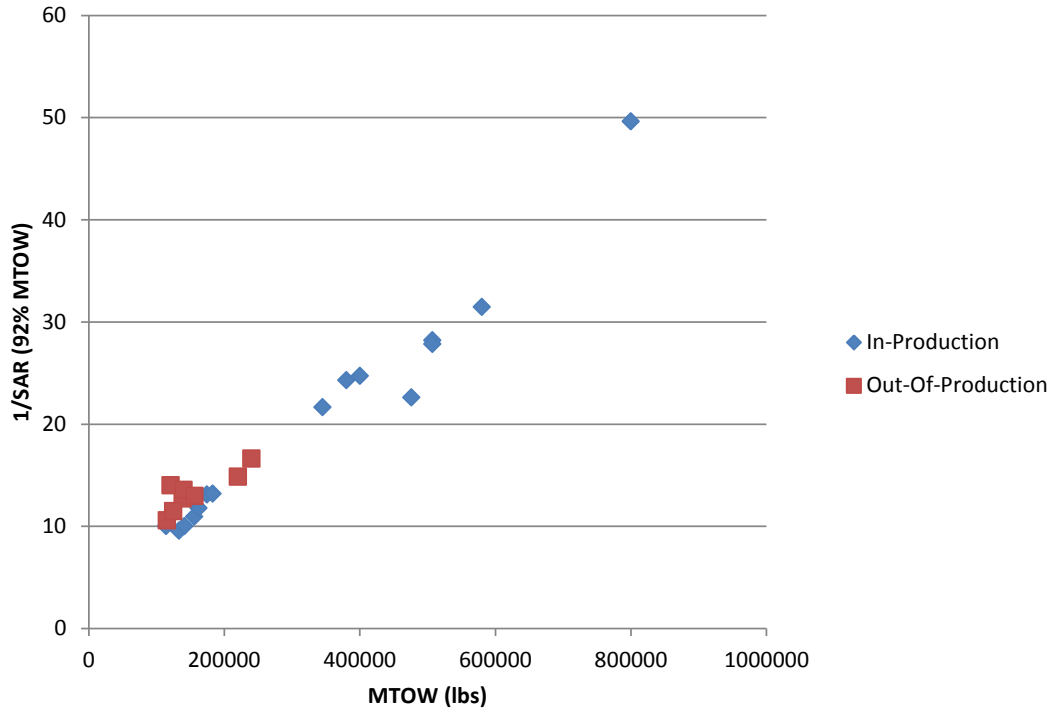
**Figure 4.21: Notional Aircraft CO<sub>2</sub> Standard Metric System**

As can be seen, the expected metric system is relatively linear. While it's unknown what the final metric system definition will be at this point, or how the stringency options will be fit, it's likely the stringency levels will follow the trends of the data. As such, it's assumed here that a linear fit of the data will produce a reasonable estimate for use in this study. The basic concept of stringency options has been explored more completely in 2.4.2.3.2, but as a reminder will likely result in limit lines distinguishing the level of technology insertion necessary to meet the standard. In order to describe this more concretely, a notional plot of a CO<sub>2</sub> metric system with corresponding stringency scenarios is presented in the Figure 4.22.



**Figure 4.22: Notional Aircraft CO2 Standard Stringency Options**

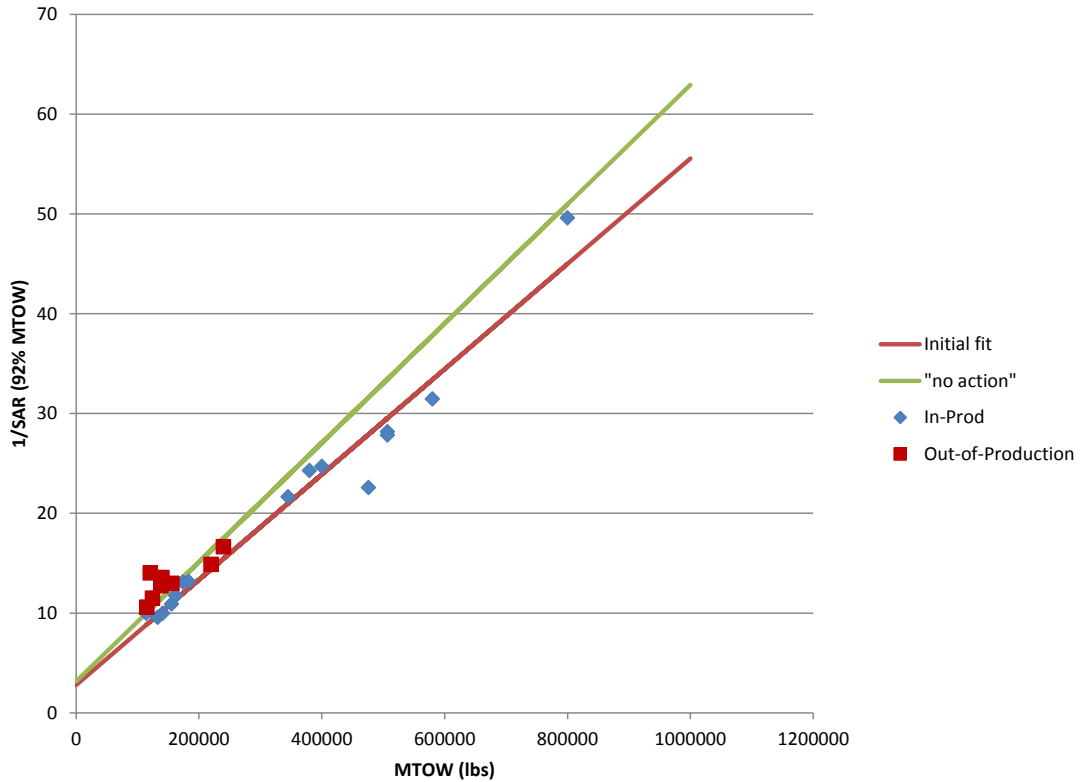
While stringency options can be defined within the module directly, in order to reduce computational effort when many different stringency options are considered, a baseline “no action” stringency option is defined. All future stringency scenarios will be based on percent reductions of this “no action” scenario. This “no action” baseline stringency option will be such that in-production aircraft are below the line, i.e., pass the level. However, the out of production vehicles will still be allowed to be impacted, as they would have to be replaced anyways by aircraft that are being produced in future years. In order to visualize the distinction of the in-production and out-of-production vehicles, Figure 4.23 is provided.



**Figure 4.23: Aircraft CO<sub>2</sub> Standard with Production Status**

Defining the baseline stringency option requires the determination of a stringency level where all in-production aircraft in the current fleet can pass a certification requirement. To accomplish this, the in-production aircraft metric value data is used to produce a linear fit using least squares regression. This initial fit is then increased to produce the “no action” stringency option serving as the baseline. The primary reason for only including in-production aircraft in the fitting of an initial stringency option is due to the fact that the out-of-production aircraft will need to be replaced by in-production aircraft regardless of the existence of standard. As such, an initial standard that does not impact in-production aircraft will not have an effect on the outcome of the simulation. Figure 4.24 is provided demonstrating the result of the initial fit of the data, as well as the corresponding “no action” stringency option. Additionally, the corresponding equation,

Equation 12, for the “no action” stringency option is also provided. It should be noted that producing the “no action” stringency option has been accomplished by increasing the initial in-production fit line by 13.28%.



**Figure 4.24: “No Action” Limit Line for the Aircraft CO<sub>2</sub> Standard**

**Equation 12: Limit Line Definition for “No Action” Aircraft CO<sub>2</sub> Standard**

$$\text{Baseline Stringency} = 5.9766 \times 10^{-5} \times \text{MTOW} + 3.158048$$

Given this initial stringency, stringency options can be defined. This is accomplished through a simple percent reduction from the “no action” baseline stringency option defined above. A more complete description of the ranges of stringency options studied are presented later in this document.

In addition to the metric system and stringency option, a notional aircraft CO<sub>2</sub> standard also requires definition of the scope of applicability. For this study, all aircraft included in the seed database will be subject to the standard, and the date of applicability can be defined by the user. The combination of aircraft subject to the standard and date of applicability finalizes definition of the notional standard. It was assumed that an initial implementation date is either 2017 or 2023. While these dates are notional, the methodology allows for any dates to be defined by the decision maker.

Given this definition for a notional CO<sub>2</sub> standard, a number of stringency scenarios can be generated. For each stringency option tested, aircraft introduced by manufacturers after the date of applicability will be required to meet the outlined certification requirement. As such, each CO<sub>2</sub> standard scenario will assess the specific aircraft meeting the requirement. Aircraft meeting the standard will be available for replacements in future forecasted years. However, all non-compliant aircraft will be required to meet the outlined standard by the date of applicability.

Meeting this requirement will necessitate the introduction of new technologies and other efficiency measures into design to improve the overall efficiency of the aircraft. Analysis of this technology integration is ideally completed using high fidelity vehicle level modeling tools, such as the Environmental Design Space (EDS). This has been accomplished for a number of new technology vehicles in other studies [173], but the engineering effort required to accomplish such a task for the number of vehicles represented in this database and the number of stringency options to be studied, is not feasible in the timeframe considered for this research.

As such, an approximation method has been developed in order to expedite creation of new technology replacements for aircraft represented in the seed database. This approximation will by nature be a normative forecasting technique, and future work will be necessary to determine the feasibility of producing vehicles meeting necessary metric value improvements. Despite this shortfall, the approximation will enable the high level policy tradeoff experiments planned in this research. The approximation technique for vehicle improvements is based on the needed margin to meet any given stringency option. This margin is a representation of the percent reduction in 1/SAR needed to be compliant with a potential CO<sub>2</sub> standard, and is based on Equation 13 presented below.

**Equation 13: Aircraft CO<sub>2</sub> Standard Margin**

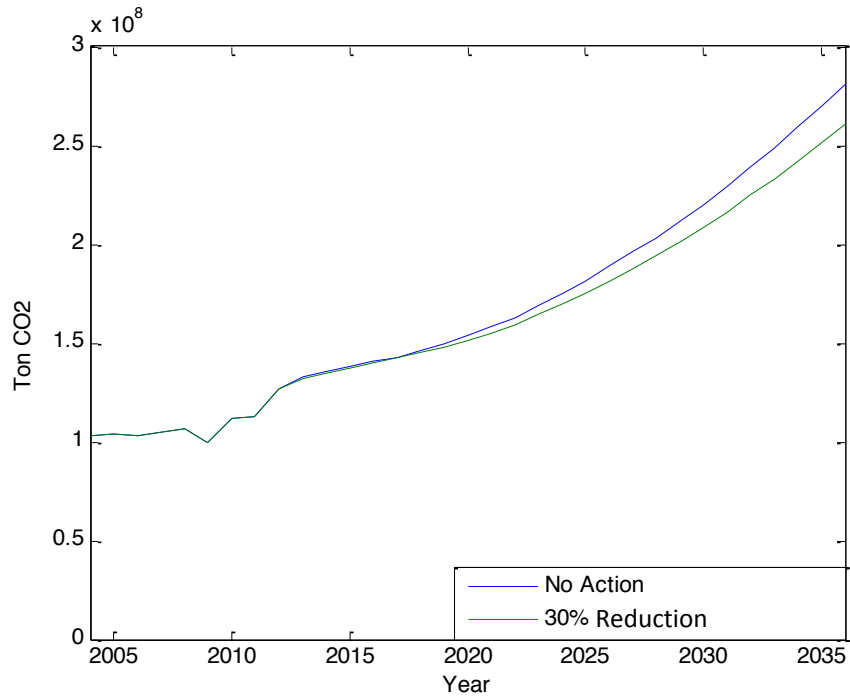
$$Margin = \frac{Aircraft\ MV - Stringency\ MV}{Aircraft\ MV}$$

In this equation, the aircraft metric values are those of the baseline aircraft, while the stringency metric value is calculated based on the given MTOW and reduction from the “no action” baseline stringency option defined in Equation 12. It is assumed that vehicles will be able to meet needed metric value improvements without specifically identifying individual technology packages or their impacts. Further, it is assumed that the fuel burn performance that will feed into the block fuel calculations will be impacted by the same extent as the impact in metric value improvement. This means that a 10% impact improvement will correspond to a 10% improvement in fuel burn characteristics. Implementing this in the fuel burn calculations of the main performance module is

accomplished by simply reducing the block fuel surrogates for a particular aircraft by the impact calculated.

While this method provides the performance for new vehicles as a result of certification requirements, the cost to produce these vehicles will also have to be established. This has been discussed previously in the non-recurring cost to manufacturers' module and capital cost calculations, where cost is also a function of metric value improvement and MTOW. As such, the impacts resulting from this module are also linked to the NRC and capital cost calculations. The formulation in this manner allows for generalization of metric value improvements, but can be modified if specific information or relationships are established.

Subsequently, for the notional CO<sub>2</sub> standard implementation module, the primary inputs are the percent reduction over a "no action" stringency scenario and the implementation date, and the output from the module is the impact to in production vehicles in the future. These impacts feed into the performance calculations, as well as the NRC and capital cost calculations. As a simple test to show how this method performs, Figure 4.25 provides a representation of the resulting CO<sub>2</sub> production given a reduction in the "no action" stringency of 30% with a date of applicability of 2017. As can clearly be seen, the trend in overall growth is fairly similar as there is no change in the demand forecast, however, due to technology insertion on new vehicles introduced to the fleet after 2017 there are measureable reductions in CO<sub>2</sub> emissions throughout the remainder of the simulation.



**Figure 4.25: Example Aircraft CO<sub>2</sub> Standard Emissions Reduction**

#### 4.10.2 Emissions Trading Scheme

As discussed previously, emission trading schemes have two major components, the cap setting process, and allocation of allowances. The impact of these trading schemes is to ultimately produce a real cost for CO<sub>2</sub> emissions, which are expected to be passed through to consumers, ultimately reducing demand. The following section will detail the method employed for cap setting and allocation of allowances. Additionally, the method by which demand is updated will also be discussed. It should be noted here that effort has been made to replicate many of the qualities of the EU ETS.

As with the EU ETS, the cap setting process typically involves defining a reference year for emissions. For the EU ETS, this reference emission level is the average



for years 2004 through 2006 [95]. In order to replicate this basic process, the user can specify the year on which the cap is based. In the existing ETS module this is set to 2005 by default in order to match the assumptions used for the EU ETS. The ETS module itself then assesses fleet fuel burn in the reference year and converts this fuel burn to CO<sub>2</sub> using the conversion of 3.15 lbCO<sub>2</sub>/lb Fuel. Additionally, the user can define the cap based on a fixed percent of the reference CO<sub>2</sub> output. For the EU ETS, this cap would be in the range of 97% to 95% depending on the year analyzed. As this study is meant to be more exploratory in nature, the level of the cap will be one of the main parameters to be varied.

Given determination of the cap set for the ETS, the allocation process must be defined. To begin this process, the user can define the date of applicability for the ETS. This date provides a starting point determining when allowances will be allocated. Following this, the method for allocation can begin. For aviation under the EU ETS, the allocation of allowances is based on the relative market share of air carriers, measured through revenue-tonne-kilometers [95]. To provide a similar methodology, the revenue-ton-miles (RTM) for each air carrier included in the study is tracked throughout the simulation, giving relative market share. This relative market share determines the level of allocated allowances to each air carrier. Further, the user can define the percentage of allowances allocated freely, and the percentage auctioned through the state. In a given year, the number of allowances needed over the cap for each air carrier is assessed, and it is assumed that these will be purchased through the ETS market linked with the EU ETS.

With the number of freely allocated, auctioned, and purchased allowances determined for each air carrier in a given year, the cost associated with the ETS can be

assessed. Due to the high volatility in allowance price observed in the EU ETS, this is kept as an input to the module to be varied for this study. As such, the market price of allowances is input, and an assumption for the auction price of allowances is provided. While it's not clear through literature what the auction price of allowances may be, it's assumed this price will be nominally lower than the market price of allowances. As such, the module assumes an auction price of half the input market price for allowances. The range of market prices studied is taken from numerous literature discussed previously, and will be introduced more completely again in the implementation section of this document. Further, due to the fact that it was observed that the lost opportunity costs associated with freely allocated allowances are typically passed through to consumers, an input is provided to the user to either pass through or not pass through these lost opportunity costs. The lost opportunity cost itself is calculated based on the level of allowances allocated freely and the market price input. Additionally, the cost associated with auctioned and purchased allowances are stored throughout the simulation to be added to overall recurring costs (RC) for aircraft owners and operators discussed previously.

The outcome of this method is an associated cost of the ETS to each air carrier in a given year. This cost must then be passed through to consumers in order to impact demand. The first step in accomplishing this is determining the cost pass through rate, which is a measure of the costs passed through to consumers over those absorbed by the air carriers. This cost pass through rate is provided as an input to the user, but is generally believed to be about 1 based on most existing literature, which implies all costs are

passed on to consumers. The cost that is determined to be passed through in a given year is reflected in the ticket prices in the following year, and it's assumed that the consumer behavior reacts immediately to increases in price. Updating demand in this way amounts to the creation of a partial equilibrium model of demand for the simulation. Since the impact to demand is not propagated to other sectors of the economy it does not classify as a general equilibrium model.

The demand updates are based on the price elasticities of demand (PED). The price elasticity of demand is a basic measure of how demand changes in response to a change price, and can be stated mathematically as in Equation 14. Here Q denotes the quantity of a good or service, while P denotes the price of that good or service. The principle provides a relationship for the change in quantity as price changes. Typically the PED is negative, barring Veblen and Giffen goods, demonstrating one of the key principles of economics, as price increases the quantity demanded will decrease.

**Equation 14: Price Elasticity of Demand**

$$PED = \frac{\frac{dQ}{Q}}{\frac{dP}{P}}$$

Estimates for the PED in aviation have been provided by a number of different studies, with IATA giving a good overview of those studies [137]. Due to the fact that it is identified earlier that there may be disproportionate impacts on low cost carriers over legacy carriers, estimates for PED are desired that differentiated between these basic carrier types. PriceWaterhouseCoopers provides just such an estimate based on a 2005

report [138]. For full service carriers it is -1.23, while for low cost carriers it is -1.38. These values demonstrate that there tends to be greater changes in demand due to price fluctuations for low cost carriers.

In order to calculate the relative change in quantity demanded, a base price for air travel must first be established. This is accomplished for the air carriers considered here through detailed analysis of the BTS Airline Origin and Destination Survey (DB1B) Ticket database, which provides reported air fares and coupons [150]. This database has been collected for each quarter of 2012 (the base year for forecasting), and analyzed using the statistical analysis software JMP<sup>®</sup>. The goal is to provide the average fare per revenue passenger mile (RPM) as a normalized measure of the price of air travel. This measure of price will allow for direct calculation of the change in price due to an ETS policy, without having to provide special consideration for changes in stage length and different routes. The fare per mile is reported directly in the DB1B database. All available data is used for each air carrier in the study, however, air fares identified as not credible were initially removed from the dataset. For this study, only the average ticket prices per RPM will be used in the determination of demand updates, however, it should be noted that there is a great deal of variability in this measure. While not considered explicitly in this study, the variability will be explored and documented to provide information for future work. The average fare per mile is presented below in Table 4.14, while Appendix F provides greater detail regarding the variability in fare per mile for each air carrier considered here. As can be seen in the standard deviation of fare per RPM and from the histograms in Appendix F, the variability can be greater than the average price. Despite

this fact, the average fare per RPM is determined to provide a good representation of air fares in this study.

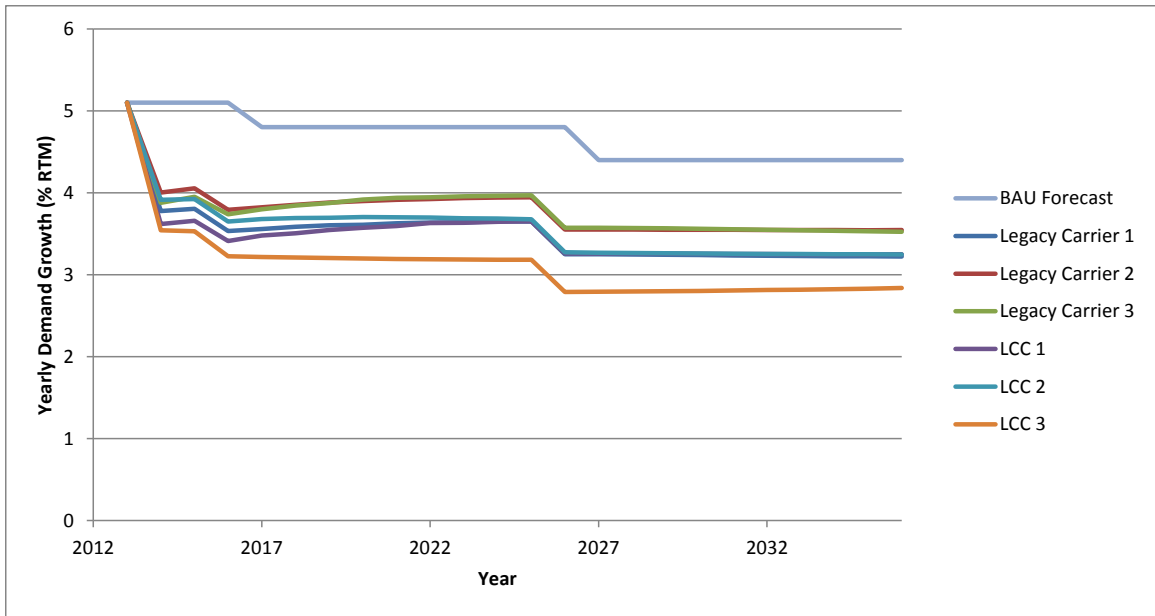
**Table 4.14: Average Fare Per Revenue-Passenger-Mile**

<b>Carrier</b>	<b>Average Fare Per RPM (\$)</b>	<b>Standard Deviation</b>
Legacy Carrier 1	0.2288	0.2041
Legacy Carrier 2	0.2537	0.2872
Legacy Carrier 3	0.2263	0.1882
LCC 1	0.2280	0.1407
LCC 2	0.2513	0.2151
LCC 3	0.2140	0.2021

With this average fare per RPM the price of air travel is set. Additionally, the operations database and expected growth can be used to calculate the RPM for each year and air carrier throughout the simulation. This RPM for each air carrier is used along with the calculated ETS costs passed through to consumers in applicable years to determine a relative increase in fare per RPM. This increase in the fare occurs in the year following the costs on air carriers as previously stated, but impacts demand in that year. As such the percent change in air fare from the previous year is equated to a percent change in demand through the PED estimates. This percent change in demand is applied to the growth forecast to determine the new demand under an ETS for all years of the simulation. These calculations occur on a year by year basis throughout the simulation, and the resulting increases in fare and demand are tracked.

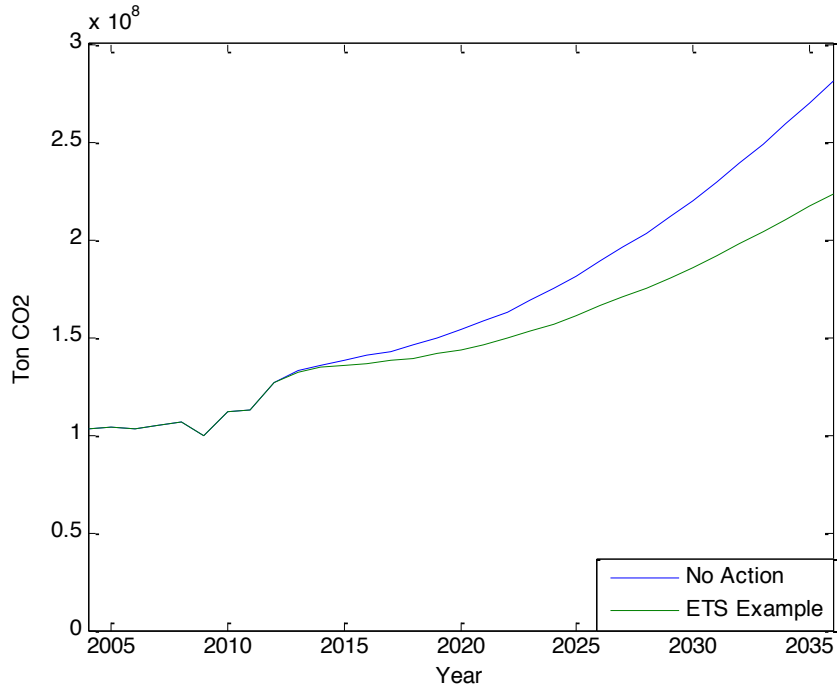
To demonstrate the impact of the ETS on the forecast, Figure 4.26 is provided. Shown here is the input demand forecast, and the resulting growth per year for each air

carrier included in the study. It should be noted that the steps occurring at 2016 and 2026 are due to the input demand forecast, which changes at those dates. In order to generate these results, a cap year of 2005 with a cap of 95% is chosen, replicating the cap setting process of the EU ETS. Further, an assumed market price of \$20 per ton CO<sub>2</sub> is input, which is within the bounds of most studies on the EU ETS surveyed, and full cost pass through is assumed. Finally, the ETS implementation date selected is 2014. As can be seen, there is a reduction in demand over the forecast of approximately 1% to 2% depending on the air carrier analyzed. This reduction is in line with a number of other studies on aviation's impact in the EU ETS [102, 106, 115]. The fact that these reductions are in line with other studies is a good indication that the model is behaving appropriately. Further, it's interesting to note that for the most part, the low cost carriers do show greater reductions in demand than the legacy carriers, barring the behavior of Legacy Carrier 1. This is also a good indication, that the hypothesis that there are disproportionate impacts on airlines based on carrier type is validated. The last piece of information to note is that the model tends to reach equilibrium demand within a few years. Due to the fact that PED estimates were greater in magnitude than -1 it is expected that demand corrections will overshoot the equilibrium value before resettling. This is quite obviously the case in the figure below.



**Figure 4.26: Example Yearly Demand Growth for an ETS**

The final check to ensure the ETS implementation is working appropriately is to analyze the impact to overall CO<sub>2</sub> production for the fleet. As demand has been shown to be reduced in accordance with estimates from literature, it's expected that the overall CO<sub>2</sub> emitted will also be reduced. Figure 4.27 provides the resulting CO<sub>2</sub> estimates for the example ETS corresponding to the demand growth rates seen above. As can be seen, there is an overall reduction in CO<sub>2</sub> emitted under the ETS scenario over the “no action” scenario described previously. This serves as a good indication that the modeling and simulation environment is working appropriately for this policy.



**Figure 4.27: Example Emissions Reductions for an ETS**

### 4.10.3 Summary of U.S. NAS Policy Cost-Effectiveness Modeling

As has been demonstrated, a cost-effectiveness model of the U.S. NAS has been created based on a framework and assumptions representative of other comparable models. This model has been validated against actual fuel sales, and has been shown to be a good predictor of overall fleet behaviors.

Further, modules representing the implementation of a notional CO<sub>2</sub> standard and emission trading schemes have also been developed and tested. The impact of these policies within the modeling framework has been shown to behave in accordance with previous literature, as well as expected outcomes. In order to provide a more complete mapping of information flow throughout U.S. PoInT, Figure 4.28 is provided.



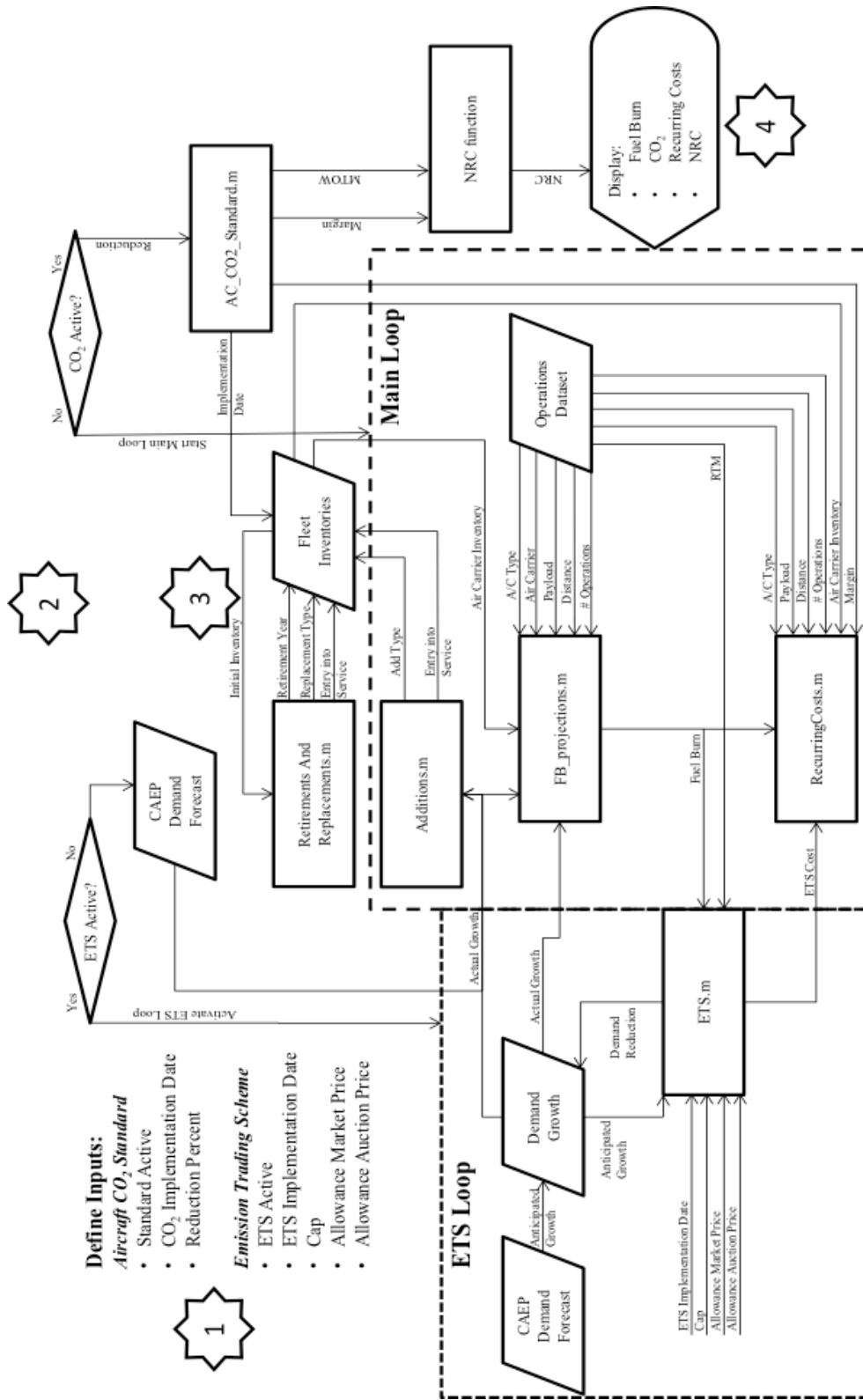


Figure 4.28: U.S. PoInT Information Flow Diagram

## CHAPTER 5

# IMPLEMENTING THE QUANTITATIVE POLICY SUPPORT PROCESS

### 5.1 Application of the Policy Analysis Process

In order to demonstrate the full capabilities of the proposed policy analysis process, it will be implemented to study the impacts of potential CO<sub>2</sub> certification standards and emission trading schemes on the U.S. NAS. Ultimately, the purpose of applying this process is to address the aforementioned research objectives:

1. Quantitatively assessing regulatory policy in the context of an acknowledged system-of-systems (SoS).
2. Demonstrating the ability to assess the concurrent implementation of multiple policies throughout a SoS.
3. Objective identification of effective policy space.
4. Reducing the regulatory uncertainty, and quantifying other forms of aleatory uncertainty in the presence of multiple regulatory policies.

The following sections will demonstrate the implementation of the policy analysis process outlined in Figure 3.6. As such, the utilization of the lexicon for systems-of-policy-systems will be employed, and the developed cost-effectiveness simulation environment of the U.S. NAS will provide quantifiable measures of costs and benefits. It should be noted here that all goals used in this process are purely notional, and are simply meant to discuss the resulting trends regarding effective policy space. Further, it is recognized that any policy implementation before 2017 is highly unlikely in the real world, however, policy implementation at earlier dates will be tested for the sole purpose of understanding longer term trends throughout the simulation. As such, **no policy**

**recommendations** are made in this work, and it serves as merely a demonstration of novel policy assessment capabilities.

## **5.2 Establish the Need**

As has been established, the mitigation of CO<sub>2</sub> emissions is a growing concern for policymakers throughout the world. The growing GHG emissions from commercial aviation are contributing approximately 2% [5] to anthropogenic climate impacts at much greater rates than has been seen in past decades, and the expected increases in demand will only exacerbate these problems. Ultimately, the fouling of our atmosphere in this way represents a classic tragedy of the commons, and the behaviors contributing to this must be addressed to reduce and help prevent catastrophic climate impacts.

In order to address this tragedy of the commons, regulatory bodies throughout the world are pursuing a number of policy options aimed at the mitigation of CO<sub>2</sub>. The International Civil Aviation Organization (ICAO) under the direction of the United Nations is leading this charge in commercial aviation, and through the GIACC is asking member states throughout the world to select “baskets of measures” to meet CO<sub>2</sub> mitigation goals established under the Kyoto Protocol. These baskets of measures ultimately represent a number of policy options directed at the mitigation of CO<sub>2</sub>, and are specified on a country by country basis through National Allocation Plans (NAPs). Despite such efforts, there has been little direction given to member states regarding the process by which baskets of measures ought to be selected. Further, the interdependencies of various policy options are rarely explored, even when interaction can be expected to be present. Two such policies that are widely cited throughout

submitted NAPs where interaction is expected to exist are a CO<sub>2</sub> certification standard and emission trading schemes, such as the EU ETS. These policies are both currently being studied widely throughout the world, yet there is no research directly studying both concurrently.

In order to fully understand how these policies will impact aviation and its associated GHG emissions, there is a need for a policy analysis framework to quantitatively assess concurrent policy making in air transportation systems. This framework must be able to account for how these policies impact aviation, how they may impact one another, how they can be pursued to work well together, and how uncertainty regarding their implementation can be quantified. By establishing this framework it will be possible to demonstrate the capability of concurrently considering baskets of measures in commercial aviation in the context of an acknowledged SoS.

In addition to this need for a policy analysis framework on which to concurrently study multiple policies, there are also specific issues with the policies themselves. For the certification standard this is largely due to the fact that a final agreement on a standard has not yet been reached. Further, even though a metric system framework has been established [118], it has yet to be publically disclosed regarding the specific functional form. As such, understanding the impacts of this CO<sub>2</sub> standard will require the ability to test a number of different potential standards in terms of costs and benefits.

Alternatively, emission trading schemes, especially the EU ETS, have been studied somewhat extensively in literature, and have also been applied directly to aviation

activities. Despite this relative wealth of information, there is a great deal of uncertainty regarding the implementation of emission trading schemes in the U.S. There has been strong opposition to inclusion in trading schemes such as the EU ETS [98, 99], while at the same time the Obama administration has indicated interest in cap and trade policy [188]. In large part this hesitance is likely a result of a lack of understanding of how emission trading schemes will impact aviation activities in the U.S. It's known that the primary impact of cap and trade policy in transportation markets is to reduce overall demand, however, due to a lack of studies regarding cap and trade policy in the U.S. NAS, the extent of these impacts domestically is not well understood. Subsequently, the study of potential emission trading schemes for U.S. aviation with linkage to other established ETS markets, such as the EU ETS, has yet to be studied.

### **5.3 Define the Problem**

In order to address this need, it's first necessary to fully understand the problem it represents. As aforementioned, from a conceptual level the mitigation of anthropogenic CO<sub>2</sub> from aviation activities represents a tragedy of the commons, where corrective behaviors are being sought through regulatory policy actions. As such, there are multiple pieces to this problem that must be understood. First, the policies being studied should be defined in order to establish the policy alternative space that exists to address CO<sub>2</sub> mitigation. Further, the structure of commercial aviation in the U.S. NAS must be understood in order to provide context to the inherent system-of-systems structure. Additionally, the structure of the system-of-policy-systems and its interaction with the physical SoS must also be established to provide the capability to analyze this potential

basket of measures as an integrated whole. The following sections will provide more detail regarding the policies considered, the physical SoS represented by the U.S. NAS, as well as the interaction of the SoPS with the physical SoS.

### **5.3.1 Regulatory Policies Considered**

Previously, a more formal lexicon was developed in order to help discuss systems-of-policy-systems (SoPS). The following sections will introduce definitions of the notional CO<sub>2</sub> standard and emission trading schemes utilizing the lexicon regarding metric systems, stringency levels, and compliance mechanisms. This lexicon will be discussed in reference to the cost-effectiveness simulation environment of the U.S. NAS created for the policy studies considered herein. It is implicitly assumed that the policy stakeholders will be regulatory bodies, such as the U.S. FAA and ICAO for both policies. Further, the notional CO<sub>2</sub> standard will also include aircraft manufacturers as stakeholders, and emission trading schemes will include air carriers.

#### **5.3.1.1 Aircraft CO<sub>2</sub> Standard**

The notional CO<sub>2</sub> certification standard considered herein is intended to be a command and control policy to push aircraft manufacturers to invest and infuse technology into new vehicle designs in order to improve the efficiency of the global fleet. It is unique in the sense that it will be the first internationally established fuel efficiency standard in the world, yet this standard is currently still under consideration and only considered as notional herein. There has only been limited information regarding the metric systems and potential stringency levels, and no formal agreements have been

reached. As such, the following discussion will highlight a potential form of this standard based on publically available information.

#### ***5.3.1.1.1 Notional Aircraft CO<sub>2</sub> Standard Metric System***

While ICAO CAEP has yet to publically identify the specific form of the metric system that will be employed in the final standard, there has been some indication as to what it may be through literature. Despite this fact, literature on the specific Aircraft CO<sub>2</sub> Standard is relatively limited, including just a few news releases from ICAO [116, 118], as well as a report from the U.S. FAA's PARTNER Project 30 and a conference paper from researchers at the Georgia Institute of Technology [117, 119]. What is clear from this literature is that the metrics considered are simple and will directly reflect the physical properties of interest for the given standard.

Instantaneous point performance measures of fuel efficiency have ultimately shown great promise for this purpose. The metric considered is known as specific air range (SAR), or nautical air mileage (NAMS), and is the air distance flown per unit fuel in steady-state flight [117]. In many ways this is analogous to miles per gallon (MPG) reported for automobiles. The advantage of such a measure is that it has been used historically in the aviation industry among operators and government agencies to classify aircraft fuel efficiency. SAR is often reported to airlines by manufacturers as a guarantee of product effectiveness. This measure is typically calculated as shown in Equation 1 and Equation 2 [117].

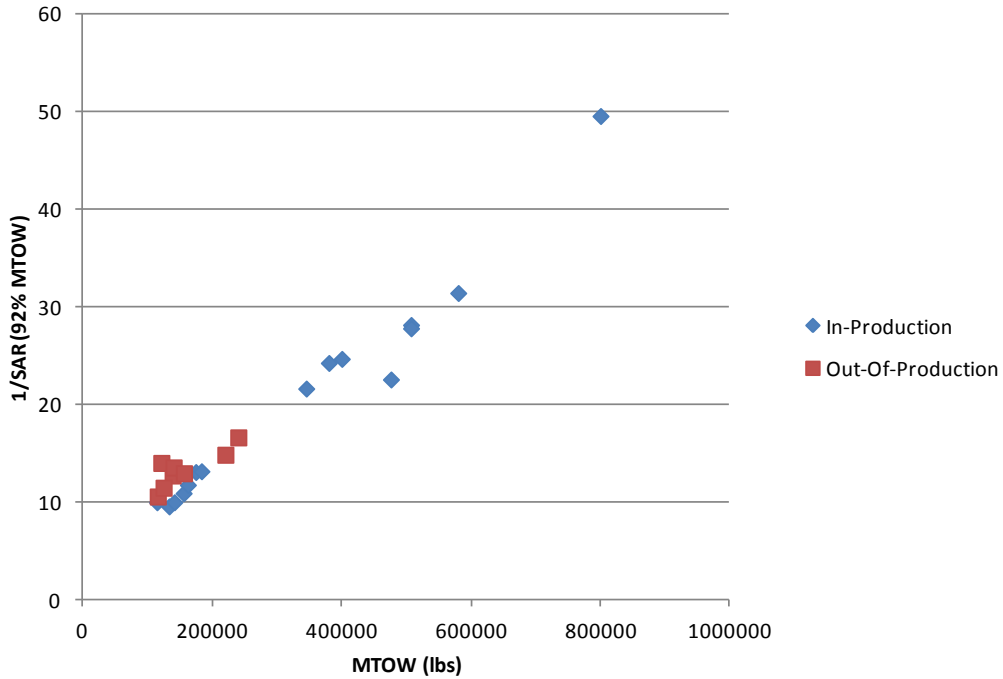
A recent news release from ICAO in 2012 indicates that the selected metric system is based on cruise point fuel burn performance, aircraft size, and aircraft weight [118]. While not explicitly stating this is the case, it seems quite apparent that the metric system chosen is based on a measure of 1/SAR, which would be consistent with the findings of Lim et. al. It should also be noted that the general observations of both types of metric systems indicated very similar characteristics between 1/SAR metrics and FB/R [117].

In addition to the actual metric, it has been shown that metric systems should also adopt a correlating parameter in order to normalize the differences in size or capability, allowing for uniform application [117]. These metric systems, including a metric and correlating parameter, are tested against the EC aforementioned in 2.4.2.3. As has been shown previously, 1/SAR correlated against MTOW is one of the most promising metric systems for the final standard. In the end, it's likely the metric system decided on by ICAO CAEP is some form of 1/SAR correlated against MTOW, as ICAO has stated that the overall design of the aircraft is represented in the CO<sub>2</sub> metric system by the certified maximum takeoff weight [118].

In order to provide a mapping for this metric system, the inventory databases of each air carrier considered are queried to produce a list of unique aircraft types. Estimates of SAR values are then determined at an evaluation condition of 92% MTOW, and the aircraft can be visualized in this metric system based on production status. The particular aircraft included in this study, and their corresponding metric system values are presented



in. Additionally, Figure 5.1 is reproduced below showing the metric system for the current study.



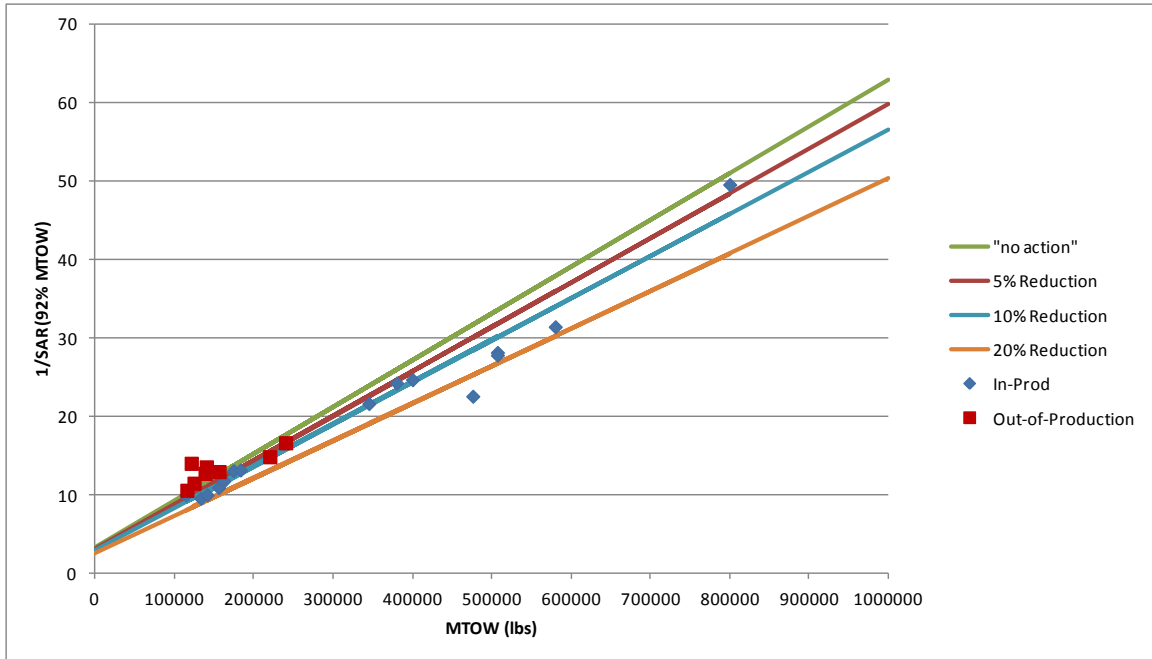
**Figure 5.1: Notional Aircraft CO<sub>2</sub> Standard Metric System under Consideration**

**5.3.1.1.2 Notional Stringency Options**

In addition to a metric system on which to evaluate fuel efficiency, some level of stringency must be placed on manufacturers in order to push technology development and integration. For the notional standard considered herein, insight into these stringency options is provided by the work of the FAA’s PARTNER Project 30, where in a findings report a number of notional limit lines (NLL) serve as the basis for analysis of a potential CO<sub>2</sub> certification framework [119]. In order to establish these NLL, a database of 192 vehicles is established, where aircraft are classified based on production status, and all

applicable parameters to various metric systems under consideration are also collected. Additionally, a number of fitting procedures for the initial stringency lines has been considered, and due to the fact that the 1/SAR based metric systems showed very simple trends, these fits tended to include linear and second order approximations of in-production vehicles [119]. Figure 5.1 showing the metric system under consideration follows these findings, and appears to have a very linear trend.

In order to provide a simple measure of stringency, an initial “no action” line can be defined and fixed percentage reductions can be analyzed from there. A more complete discussion of the initial limit line, known as a “no action” scenario, has been provided in 4.10.1. This initial limit line defines a standard that would not impact aircraft manufacturers, however, even small deviations from this line could create instances where manufacturers would have to respond through technology infusion. In order to provide a more visual representation of the metric system and stringency options, Figure 5.2 is provided. Here, the “no action” line is shown, as well as fixed percent reductions from there. These limit lines represent notional standards that could be applied, however, it should be noted that a wide range of stringencies will be studied here, with all applicable ranges for reduction percentages defined later.



**Figure 5.2: Aircraft CO<sub>2</sub> Standard Stringencies**

### **5.3.1.1.3 Aircraft CO<sub>2</sub> Standard Compliance Mechanism**

The last major component of the notional standard that has yet to be fully discussed is the compliance mechanism. The compliance mechanism is the application of intent meant to direct the activity of the entities involved under the CO<sub>2</sub> standard. In a sense, the compliance mechanism is the regulatory control authority's means of enforcing the standard. In order to fully define the compliance mechanism, the scope of applicability, including the entities covered under the standard and implementation timeframe, as well as the means of enforcement must be addressed. Here, the means of enforcement will most generally regard the type of standard, such as command and control or market based mechanism.

As has been noted, the primary industry affected by a standard will be aircraft manufacturers. As such, the PARTNER Project 30 findings report serves as a good starting point in defining the entities covered under the standard, with all manufacturers and vehicles represented in this study included.

As with any policy, timing can be very difficult to predict. However, it has been noted that the initial CO<sub>2</sub> NLL studied assumed an adoption of the standard in 2017 with introduction in 2018 [119] and an additional option for an adoption date of 2023 with introduction in the following year [52, 119]. As such, the likely implementation timeframe will be sometime between 2017 and 2023. That being said, due to the exploratory nature of this study, earlier implementation will also be studied to provide a best case scenario for overall CO<sub>2</sub> mitigation potential. A more complete discussion of the implementation dates considered will be provided when the ranges on the experiments run are discussed.

Finally, the general type of mechanism must also be discussed. As has been indicated in the PARTNER Project 30 findings report all covered aircraft manufacturers and vehicles would be subject to the standard, and failure to comply could result in the inability to bring an aircraft to the market [119]. This type of mechanism is generally considered a command and control approach to regulation, where the control authority, the U.S. FAA in the case of the NAS, would enforce the standard. As such, it is assumed here that if a standard is in place, aircraft manufacturers would be required to meet the limit line in order to comply.

### **5.3.1.2 Emission Trading Schemes**

Emission trading schemes (ETS), often referred to as cap and trade policy in the U.S., are market based regulatory policy mechanisms that attempt to create a real price for emissions. The purpose of creating a price for CO<sub>2</sub> is to internalize the cost of emitting anthropogenic GHGs, which are typically externalized by most industries. Typically, the effect of such schemes is to increase the price for a good created by the covered entities, thus reducing demand based on fundamental economic principles. As such, these ETS differ fundamentally from policy such as an aircraft CO<sub>2</sub> standard in the sense that they are generally focused on reducing demand as opposed to increasing efficiency. ETS are quite common throughout the world, and have been widely discussed in recent years, especially in the EU. With that said, they have been implemented in the U.S. as well through the Acid Rain Program, as aforementioned, and the Obama administration has indicated an interest in other cap and trade policy aimed at mitigating climate change. The following discussion will introduce ETS in the context of the SoPS lexicon developed. It should be noted here that the form of the ETS chosen for study is based on the structure of the EU ETS. The goal in doing this is to provide linkage correlation with a potential U.S. ETS and EU ETS, in order to provide a market of allowances for U.S. aviation activities. Without linkage, such a market would not exist, and it's unclear how air carriers would meet any cap, as they are expected to be net purchasers of allowances.

#### ***5.3.1.2.1 Emission Trading Scheme Metric System***

The metric system for emission trading schemes is quite different than for an aircraft CO<sub>2</sub> standard. It should be noted however, that these ETS interact with entities at a different hierarchical level of the air transportation SoS. Ultimately, the measurable parameters used for the ETS are the reported fuel sales, measured in this case through fuel burn to each air carrier. The fuel burn can be equated directly to CO<sub>2</sub> emissions as aforementioned, and will induce an associated cost that is likely to be passed on to consumers. The stringency setting process for these ETS provides the link between fuel burn and actual ETS costs, however, both the fuel burn and ETS cost represent the measurable parameters of the policy, and thus constitutes the metric system.

#### ***5.3.1.2.2 Emission Trading Scheme Stringency Options***

In order to provide intent to the ETS, stringency options can be defined utilizing the cap setting and allocation of allowances. As with the EU ETS, the cap setting process typically involves defining a reference year for emissions. For the EU ETS this reference emission level is the average for years 2004 through 2006 [95]. In order to replicate this basic process, the user can specify the year on which the cap is based. As stated in the modeling section of this document, in the existing ETS module this is set to 2005 by default in order to match the assumptions used for the EU ETS. Given this reference year for the CO<sub>2</sub> cap, the user can define the cap based on a fixed percent of the reference CO<sub>2</sub> output. As aforementioned, for the EU ETS, this cap would be in the range of 97% to 95% depending on the year analyzed. As this study is meant to be more exploratory in

nature, the level of the cap will be one of the main parameters to be varied, and the ranges analyzed will be introduced more completely in upcoming sections of this document.

With a cap in place, the allocation process must be defined in order to finalize stringency to each covered air carrier. For aviation under the EU ETS, the allocation of allowances is based on the relative market share of air carriers, measured through revenue-tonne-kilometers [95], and to provide a similar methodology, the revenue-ton-miles (RTM) for each air carrier included in this study is tracked throughout the simulation, giving relative market share. This relative market share determines the level of allocated allowances to each air carrier. Further, the user can define the percentage of allowances allocated freely, and the percentage auctioned through the state. In a given year, the number of allowances needed over the cap for each air carrier is assessed, and it is assumed that these would be purchased through the ETS market linked with the EU ETS.

#### ***5.3.1.2.3 Emission Trading Scheme Compliance Mechanism***

Finally, the compliance mechanism for the EU ETS can also be defined, which necessitates discussion of the scope of applicability, as well as the type and function of the policy. The scope of applicability includes the covered entities and implementation time frame. For the ETS under consideration in the U.S. NAS, the covered entities include all air carriers operating in the region. Due to the fact that only the top passenger air carriers have been included in the cost-effectiveness simulation environment however, only a subset of the air carriers operating throughout the NAS will be included. Despite

this limited set of covered entities, it's expected that the main effects of an ETS will be captured due to the large market share of the air carriers included.

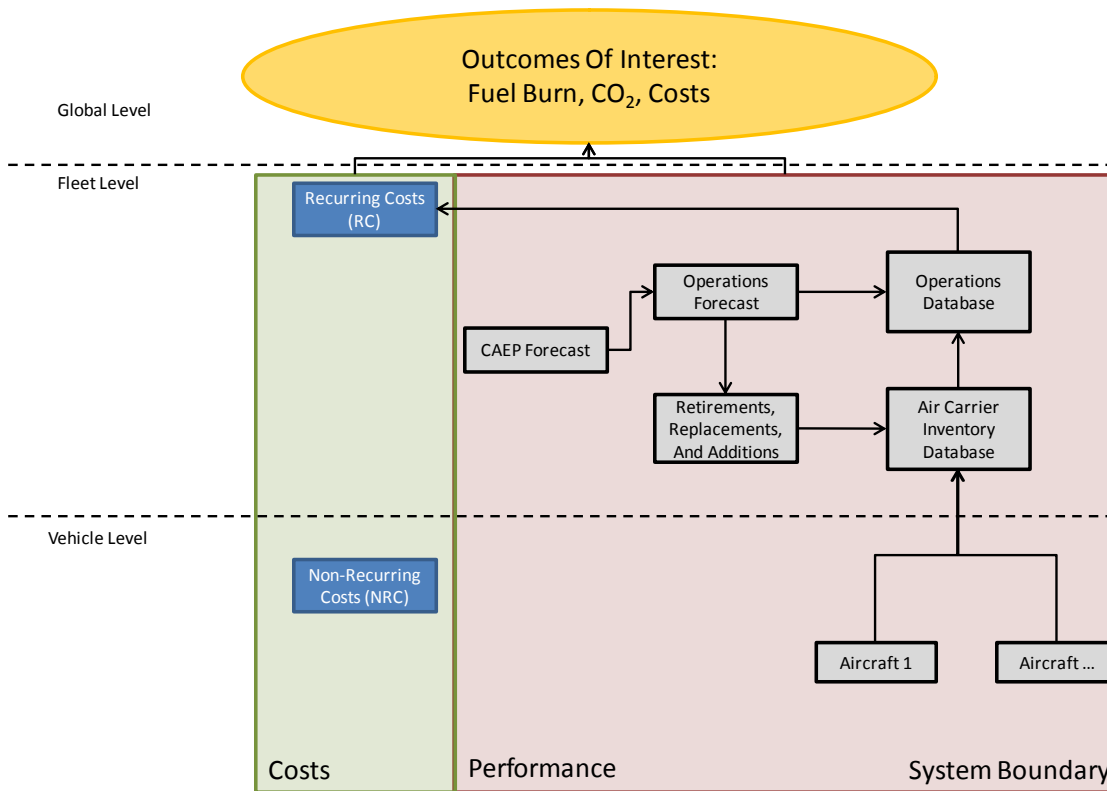
The implementation date of the ETS is an input to the cost-effectiveness simulation environment for the U.S. NAS. Due to the fact that the EU ETS has been in effect for aviation since 2012, it's currently possible to consider an ETS policy in the U.S. As such, implementation will be considered in the near future, however, due to the typically long timeframe for policy making, future implementation will also be considered. A more complete discussion on the actual dates of implementation will be discussed when feasible policy alternatives are generated.

Finally, as aforementioned, emission trading schemes represent market based policy mechanisms. As such, control authorities assess charges imposed to covered entities, and the market is allowed to respond to those charges. The mechanism through which these charges are passed on to consumers and consumer demand is updated has been discussed previously in 4.10.2. As a reminder though, with all allowances determined for each air carrier in a given year, the costs associated with the ETS are assessed, based on an input market and auction price of allowances. The user then defines the cost pass through rate, and whether the lost opportunity cost is also passed through, and the imposed charges are reflected in ticket prices the following year. Consumer demand responds immediately based on anticipated price elasticities of demand for commercial aviation, reflected through an increase in fare per revenue-passenger-mile.



### **5.3.2 Civil Aviation as a Transportation SoS**

In addition to defining the policies studied, the physical environment in which they operate must also be fully defined. The scope of this study is focused on the interaction of these CO<sub>2</sub> policies in the U.S. NAS. As such, the aviation transportation SoS represented by the U.S. NAS serves as the physical system of study. As has been previously defined, these transportation systems represent acknowledged systems-of-systems. The independently operating systems are each modeled separately, as discussed previously, and interact to perform a function that is greater than each system individually. Based on the current structure of this study, and the simulation of the U.S. NAS developed, this SoS can be illustrated as in Figure 5.3. This figure provides the basic structure of SoS presented by DeLaurentis, where the individual systems are grouped based on hierarchical level, and their interactions are traced. As can be seen, at the vehicle level, the aircraft included in the operations and inventory databases are modeled. These aircraft models, are ultimately utilized through the operations, inventory, and forecasting to produce estimates of the fleet fuel burn and costs. Finally, these fleet fuel burn and costs are aggregated to provide estimates of global CO<sub>2</sub> emissions and costs from the U.S. NAS.



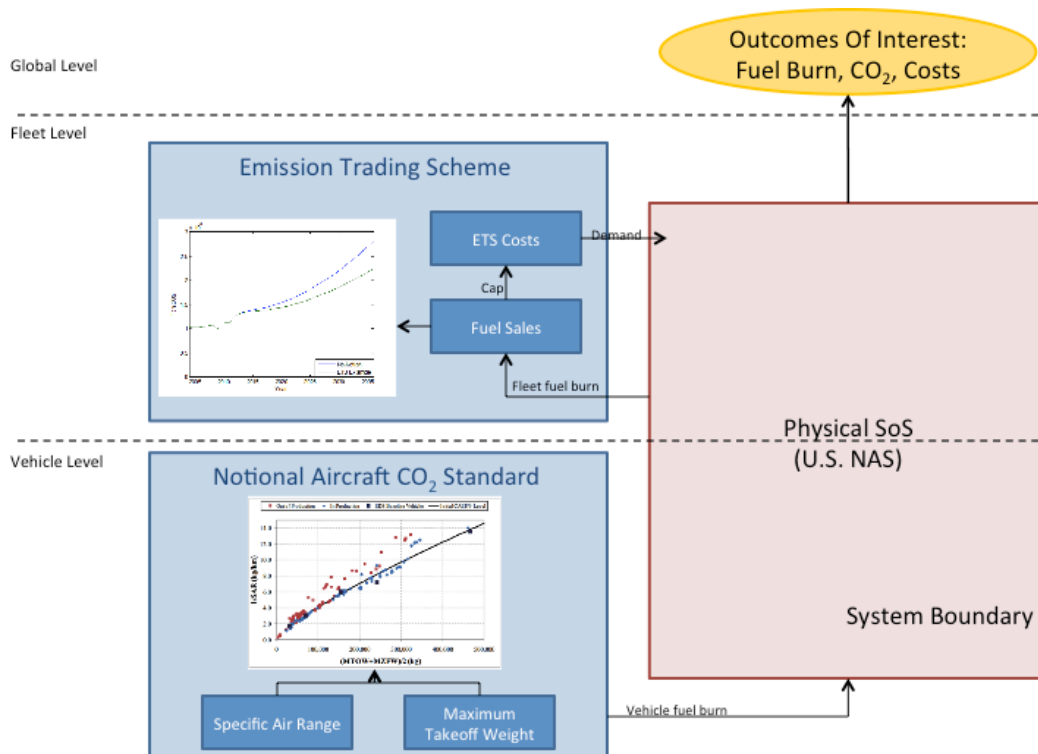
**Figure 5.3: U.S. NAS System-of-Systems Representation**

### 5.3.3 Regulatory Policies Constitute a SoPS

The case has also been made previously, that like the physical system itself, the policies themselves constitute an integral piece of the SoS and interact as a system-of-policy-systems (SoPS). For the policies being considered here, the metric system can be analyzed in this SoPS structure in much the same way the U.S. NAS has been. This basic representation of the SoPS utilizing a similar framework as previously established is presented below in Figure 5.4. It should be noted here, that typically, the metric systems do not directly interact as in the physical SoS, but interact indirectly through interaction

with the physical SoS. As such, interaction among the policies will exist, but it is ultimately a secondary effect dependent on the impact to the physical SoS.

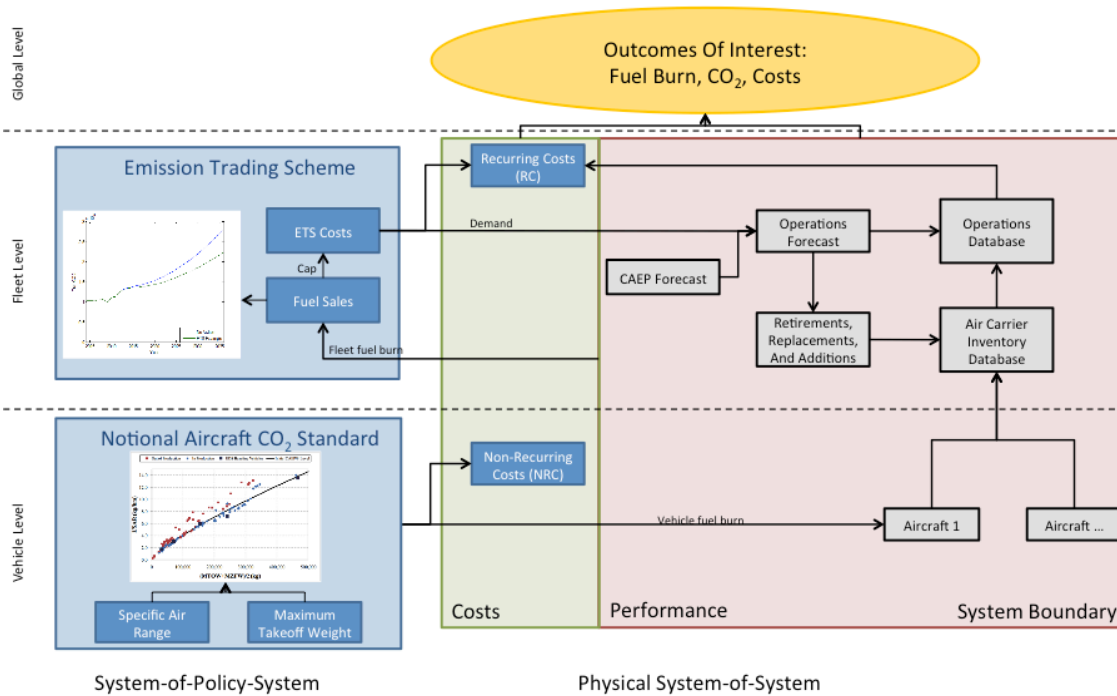
As can be seen in Figure 5.4, the notional aircraft CO<sub>2</sub> standard is at the vehicle level of the SoPS architecture, impacting the individual aircraft models in the physical SoS. These impacts are then aggregated through the modeling environment, as previously discussed, to produce fuel burn estimates for the air carriers in the NAS. This in turn, feeds into the ETS policy at the fleet level of the SoPS hierarchy, where charges can be assessed, modifying the behavior of consumers in the physical SoS. In this way, these individual policy metric systems induce behaviors at their respective levels of the SoPS hierarchy, and the impact to the global system can be tracked.



**Figure 5.4: U.S. NAS System-of-Policy-Systems Representation**

### **5.3.4 Interaction of the Physical SoS and SoPS**

Ultimately, both the SoPS and physical SoS interact in order to produce emergent behaviors for the entire U.S. NAS. As such, it's also important to understand the linkage between the SoPS and SoS representations. Figure 5.5 provides an illustrative representation of this linkage. As can be seen, the notional aircraft CO<sub>2</sub> standard interacts directly with the vehicle models at the base hierarchical level of the physical SoS. Additionally, this standard also impacts the non-recurring costs to aircraft manufacturers as previously discussed. As this information is propagated to higher levels throughout the SoS, the fleet fuel burn is ultimately input into the ETS and costs are fed back into the physical SoS. These costs are included in the recurring costs to the aircraft owners and operators, and also serve to update the input demand forecast. Ultimately, this interaction of the SoPS and SoS provides a complete representation of the system of study. Further, it should be noted that this representation also fits quite well into the GenPAF policy analysis framework developed to study these policies. The SoPS represent the “policies”, while the physical SoS represents the system boundary. At the global level of the U.S. NAS all outcomes of interest are tracked, and goals can be applied during further analysis.



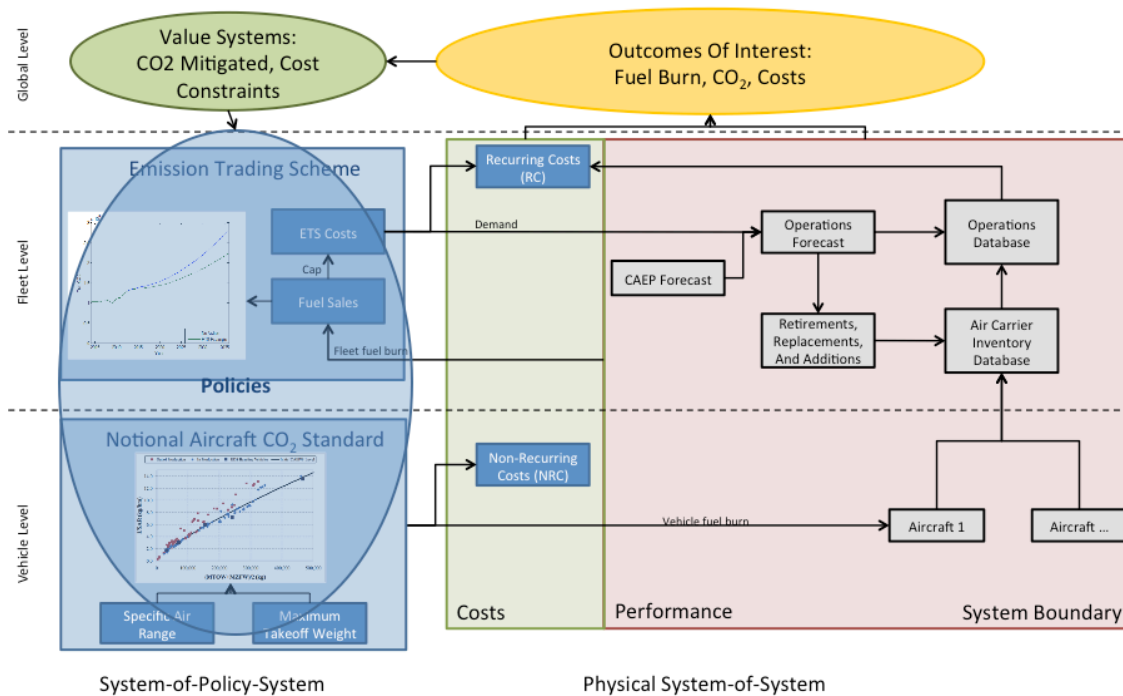
**Figure 5.5: U.S. NAS SoPS and SoS Interaction**

## 5.4 Establish Value

As aforementioned, establishing value for the impact of policy is solely in the policymakers domain. To remain objective throughout the policy development process the scientist simply provides the ability to apply value systems to the problem of study. As such, the role of the policy maker will be addressed here, however, the distinction of roles should be kept in mind.

In this step, the overall objectives of the problem are established. While the final setting of objective values does not need to occur here, at least the identification of parameters to be tracked for eventual down selection of alternatives should be the goal. This step will have a direct impact on the “Goals” used in the GenPAF policy analysis

framework. The measures of effectiveness established will serve as the basis on which effective policy space can be identified in the systems of policies studied throughout the process. As such, this step serves to establish the link between the measured outcomes of interest and policies under consideration, as seen in Figure 5.6. For the primary problem being discussed here, the measures of effectiveness used for eventual downselection of effective policy mixes will be total CO<sub>2</sub> emissions, and the costs incurred on aircraft manufacturers and air carriers. The idea is that these measures establish value in both the mitigation of harmful anthropogenic GHG, as well as the economic sustainability of the industry.



**Figure 5.6: Application of Value Systems to Policy in the U.S. NAS**

Ultimately, the desired level of CO<sub>2</sub> mitigation potential and acceptable costs incurred to the market actors involved is left to the policy maker. The subjectivity of their applied value systems can be made transparent through the visualization of the policy tradeoff selections. The process outlined here provides specific steps where a clear delineation of these roles can be applied. As such, the objectivity of the scientist can be maintained while including the subjectivity of policy makers. The following sections will overview the environmental and economic measures of effectiveness anticipated to be used for eventual downselection of effective policy space.

#### **5.4.1 Determining the Environmental Benefit**

Both policies under consideration here are aimed at the mitigation of anthropogenic CO<sub>2</sub>. As such, the overall level of mitigated CO<sub>2</sub> is the most direct measure of effectiveness regarding environmental benefit. Determining the level of mitigated CO<sub>2</sub> due to policy implementation necessitates an understanding of the overall CO<sub>2</sub> emitted in the absence of policy. This baseline emissions forecast serves as the benchmark on which to assess all other policy scenarios regarding environmental benefit.

The baseline emissions forecast is ultimately determined through the utilization of the simulation environment of the U.S. NAS, and air carrier and fleet level aggregate CO<sub>2</sub> effects have been introduced previously in Figure 4.18. As a reminder, these CO<sub>2</sub> emissions are based directly on fuel burn predictions using a conversion of 3.15 lb CO<sub>2</sub> per lb fuel consumed [119]. The simulation environment provides these estimates directly on a year by year basis out to 2036, however, they can also be aggregated throughout the

years to provide an overall level of CO<sub>2</sub> emissions that would occur in the absence of policy.

Given this benchmark for CO<sub>2</sub> emissions, the mitigation potential of implemented policy can also be assessed. This is accomplished by directly comparing the emissions estimates from policy experiments conducted in the cost-effectiveness simulation environment of the U.S. NAS to the benchmark emissions limits. Due to the fact that this simulation environment provides year by year estimates for each air carrier, this comparison can be done at the air carrier level on a year by year basis, or at the fleet level for cumulative emissions for any year out to 2036. Policy makers are responsible for determining the overall level of mitigation that is necessary, however, it should be noted that insight can also be gained from scientists as well regarding mitigation needed to avoid catastrophic climate events.

#### **5.4.2 Establishing the Economic Costs**

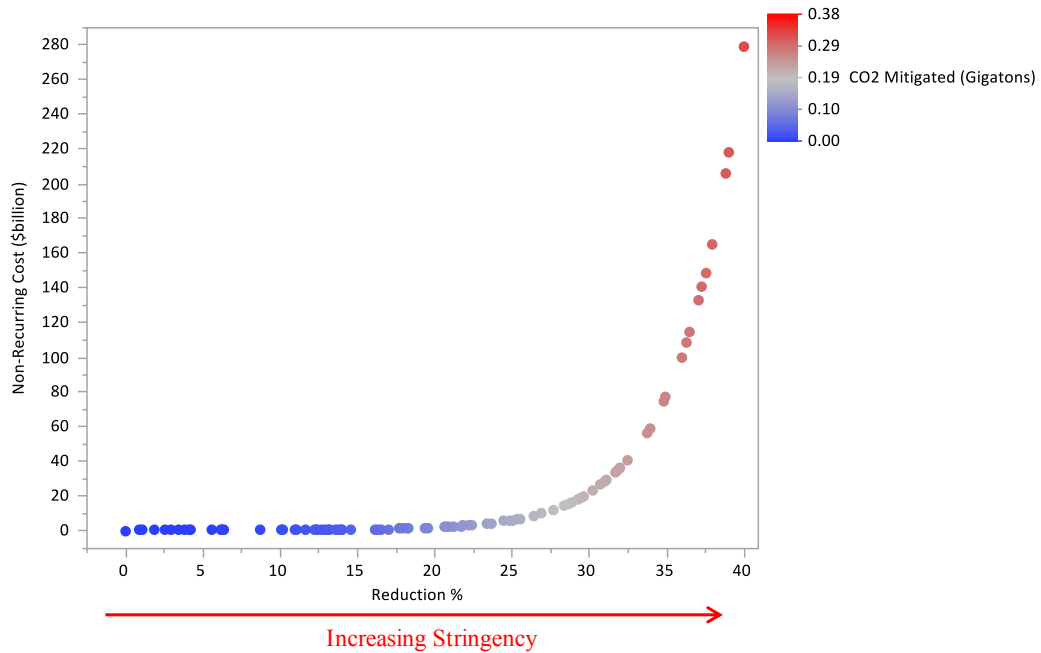
As aforementioned, costs are determined for both aircraft manufacturers and aircraft owners and operators. The notional aircraft CO<sub>2</sub> standard will impose non-recurring costs on aircraft manufacturers through requirements for technology investment and infusion, and ETS policy will produce CO<sub>2</sub> related charges to air carriers. The interaction of the policies with the SoS will also alter the recurring costs (RC) to aircraft owners and operators. Due to the fact that these costs are inherently unique and independent, they are treated separately. The following sections will provide a brief



overview of these economic costs, and will mention how policymakers may apply value systems using them.

#### **5.4.2.1 Non-Recurring Costs to Aircraft Manufacturers**

As aforementioned, the only non-recurring costs (NRC) considered in this study are those imposed on manufacturers in order to meet the notional aircraft CO<sub>2</sub> standard. The technique used to model this cost is based on both airframe and engine development costs for aircraft families, and utilizes the parameters included in the metric system assumed herein. This produces a cost estimating relationship for NRC to manufacturers that is part of the cost calculation module of the simulation environment developed. It should be noted that this method of NRC estimation is inherently a normative forecasting technique, and does not consider any specific technologies to meet a specific metric value. A more complete description of this estimating relationship and its validation can be found in 4.5.2, and the final form of the relationship can be viewed in Figure 4.15. Ultimately though, the resulting change in NRC to aircraft manufacturers is the result of an input reduction percent over the “no action” scenario. Thus, NRC can be mapped against the input reduction percent (which is also referred to as the improvement in margin in this document as well), as shown in Figure 5.7. As can be seen, the NRC to manufacturers tends to increase gradually up to a reduction percent of approximately 25, at which point costs tend to exponentially increase. This can be an indication of a potential technological limit for certain vehicles, but it’s ultimately a result of the specific form of the NRC estimating relationship utilized.



**Figure 5.7: Non-Recurring Cost (NRC) Variation with Reduction Percent**

Typically, the value system of the policy maker would desire a reduction in the economic burden of any established policy. As such, the value system of policy makers can be applied using this cost in two ways. NRC limits can be placed to filter economically viable policy options for aircraft manufacturers, or alternatively, a limit on the reduction percent over a “no action” stringency can be placed to filter technologically viable policy options for aircraft manufacturers. Due to the direct relationship seen between NRC and reduction percent, both approaches are equivalent, albeit from different value perspectives, the first being an economic viability perspective and the later being a technical feasibility perspective. With that said, it should be noted that the values of NRC shown in Figure 5.7 are purely notional, and do not reflect only feasible technology alternatives. It is fully recognized that reductions greater than approximately 20% are likely infeasible in the time frame considered, however, expanded ranges of

NRC are considered in this notional problem in order to provide trends for discussion of the outlined methodology.

#### **5.4.2.2 Recurring Costs to Aircraft Owners and Operators**

The recurring costs to aircraft owners and operators include both the direct operating costs (DOC), as well as policy induced costs due to emission trading schemes. The reason for inclusion of ETS related costs is the fact they would be assessed on a year by year basis, and are directly tied to fuel burn, thus operation of the vehicle. In this study, the specific costs included in these recurring costs are the fuel costs, capital costs, crew and maintenance costs, route and landing fees, and ETS related expenses.

As with estimating the environmental benefit of policy, the economic costs to aircraft owners and operators can be evaluated through benchmarking of the simulation environment in the absence of policy. In the absence of an emission trading scheme or an aircraft CO<sub>2</sub> standard, direct operating costs are provided on a year by year basis for each air carrier in 2012 USD. These costs can also be aggregated for the entire fleet. Examples of these benchmark direct operating costs are provided in Figure 4.20 for a single air carrier and Figure 4.19 for the entire fleet. It should be noted that there are no ETS related costs there due to the absence of policy.

Given this cost benchmark, the change in costs incurred under all policy scenarios can be determined. This can be accomplished for all recurring cost elements cumulatively, or specific elements, such as the ETS related costs, individually. Additionally, these costs can also be analyzed on a year by year or cumulative basis as

with CO<sub>2</sub> mitigation potential. The determination of which cost elements and level of aggregation to use for eventual down selection of effective policy space is solely in the domain of the policy maker. With that said, it will be shown that the fuel cost savings due to policy implementation tend to outweigh any increases in capital costs, thus DOC always tends to be reduced when policy is implemented. As such, the economic burdens associated with the increases in fees due to emission trading schemes may serve as a better measure of economic viability for the industry.

### **5.4.3 Providing the Ability to Tradeoff the Costs and Benefits**

Typically, cost-effectiveness analysis is accomplished by directly relating the costs and benefits as a ratio. This method provides a singular measure of cost-effectiveness for environmental policy such that the optimal policy can be identified numerically. While this form of cost-effectiveness analysis has precedent throughout regulatory policy analysis, directly relating the costs and benefits is difficult for policies impacting different actors throughout a SoS. Due to the fact that the non-recurring costs to manufactures and the recurring costs to aircraft owners and operators are accounted for independently and not directly related, they cannot be easily added to produce a singular measure of cost. This may be possible through the use of weighting functions, similar to concepts used for overall evaluation criteria, however, the most direct method of dealing with these distinct costs is to treat them independently. It's anticipated that the policymaker will be able to apply value systems directly through both costs and benefits independently utilizing filtering. As such, filtering of exploratory experimentation can occur on the NRC to manufacturers, RC to aircraft owners and operators, and

environmental benefits simultaneously. In this way, cost-effectiveness analysis can be completed, albeit in the absence of a singular measure of overall cost-effectiveness.

## **5.5 Generate Feasible Alternatives**

With potential values for policymakers identified, the policy alternative space must be fully explored in order to provide insight into the implications of competing value systems. This necessitates the generation of policy alternatives for the notional aircraft CO<sub>2</sub> standard and emission trading schemes. The generation of feasible policy alternatives will be used to address the research objectives in question, which will be reintroduced as they are addressed. Due to the fact that policy cannot be tested in the real world, computer simulations representing the SoS and SoPS must be used to predict overall behavior. For this study, the cost-effectiveness simulation environment developed for the U.S. NAS will be employed for the study of both policies. The following sections will detail the specific assumptions used in generating policy alternatives, and provide estimates of the environmental benefits and economic costs of the policies being studied.

This will be accomplished by first identifying the emissions and economic trends of the U.S. NAS in the absence of policy in order to benchmark policy implementation. Following this, the impact of each policy will be explored in isolation in order to demonstrate the primary effects of efficiency standards and trading schemes, and ultimately the interaction of these policies will be investigated through exploration of the concurrent implementation of both. Finally, the impact of aleatory uncertainty, in the form of changing fuel price, will be analyzed regarding the impact to the policy alternative space.

### **5.5.1 Predicting Costs and Benefits in the Absence of Policy**

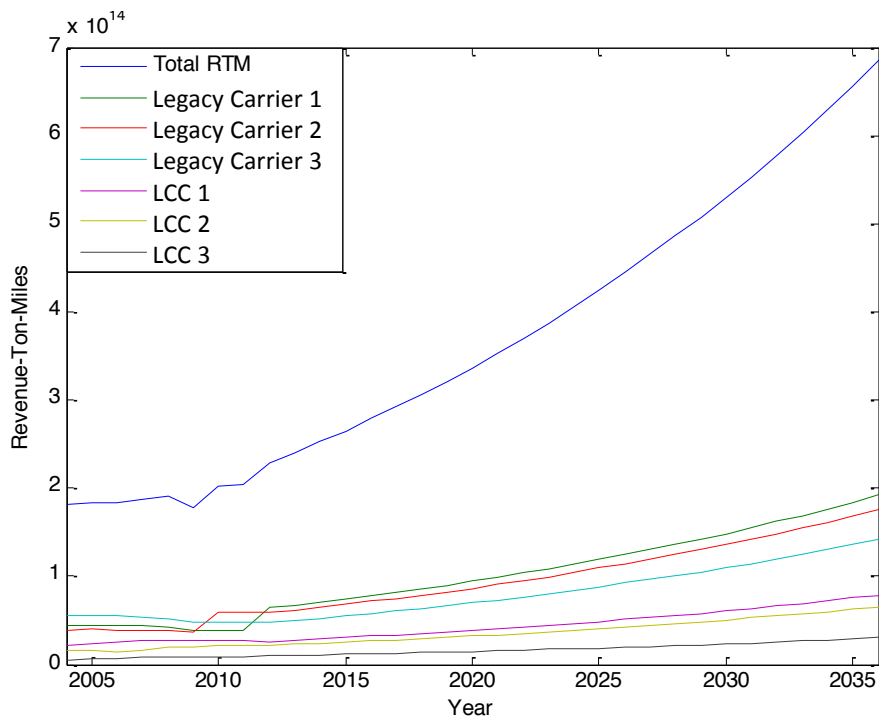
In order to provide a benchmark on which policies can be assessed, an understanding of the costs and benefits in the absence of policy is necessary. This “no action” scenario assumes a fixed technology fleet of vehicles, in which replacements and additions are chosen from existing in-production vehicles available in the cost-effectiveness model for the demand forecast assumed.

As aforementioned, the primary benefits being tracked in this policy study are CO<sub>2</sub> emissions, while the costs include the recurring costs to aircraft owners and operators, as well as the non-recurring costs to aircraft manufacturers. In the absence of a standard however, there will be no additional non-recurring costs to aircraft manufacturers. This is due to the fact that this benchmarking scenario only considers fleet evolution with current in-production vehicles. As such, there is no consideration of new vehicles entering the fleet, which is often referred to as a fixed technology fleet. Additionally, it should be noted that in the absence of emission trading schemes, the recurring costs tracked will be only the direct operating costs to air carriers, as there will be no emission trading scheme related costs.

The following sections will provide the results of this fixed technology fleet scenario in the absence of policy implementation. Growth of the industry will be examined through the revenue-ton-miles, emissions will be tracked through CO<sub>2</sub>, and the applicable recurring costs will also be presented.

### 5.5.1.1 Demand Growth in the Absence of Policy

For this study, a notional forecast is implemented, and provides an expected percent increase in revenue-ton-miles per year out to 2036. In the absence of a policy, namely emission trading schemes, this input growth is not modified throughout the simulation. As such, this forecast is applied directly to the measures of RTM for the fleet considered to provide estimates out to year 2036. The results of this forecast are provided in Figure 5.8. As can be seen, the forecasted growth tends to be exponential, as expected, and is consistent for all air carriers considered.



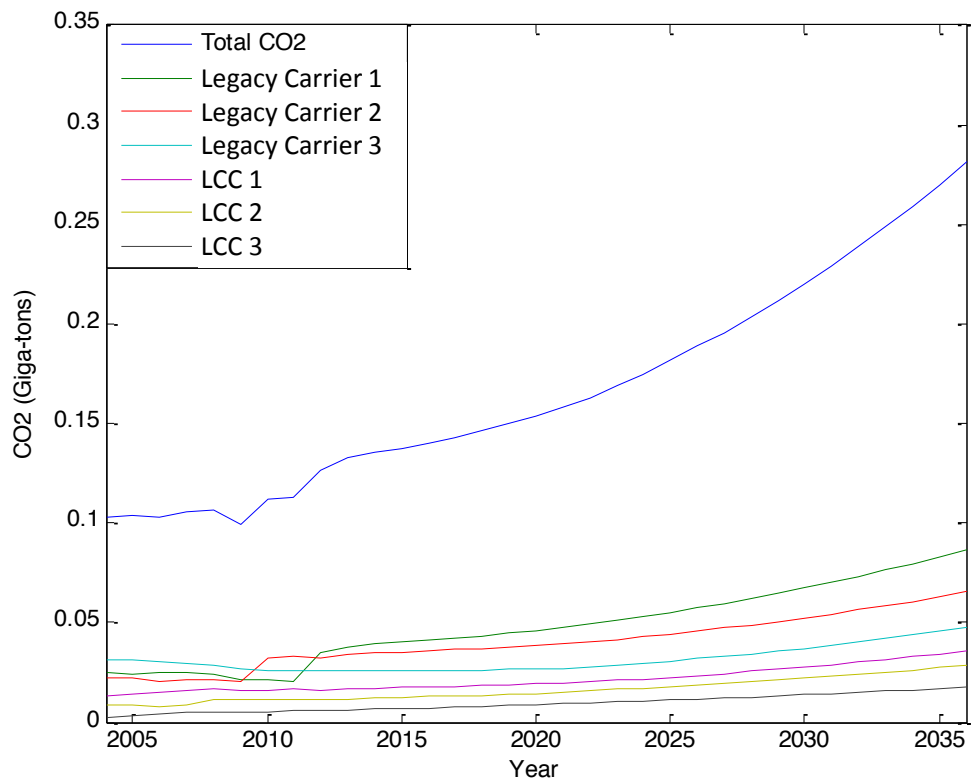
**Figure 5.8: Forecasted RTM in the Absence of Policy**

### 5.5.1.2 CO<sub>2</sub> Emissions in the Absence of Policy

Due to the fact that the benefits of policy implementation will be measured through direct comparison of predicted CO<sub>2</sub> emissions, an understanding of the emissions from the fleet considered in the absence of policy is necessary. As aforementioned, this is measured through predicted fuel burn and converted using an established multiplier from literature. The resulting CO<sub>2</sub> in the absence of policy is presented in Figure 5.9, where the total CO<sub>2</sub> for the fleet is presented in addition to the contributions from each air carrier considered.

While the trends observed in this figure follow those observed in RTM growth generally, there are some noticeable differences. The most prominent difference can be seen in the total CO<sub>2</sub> for the fleet between the years of 2013 and 2017, where CO<sub>2</sub> emissions grow much more slowly than the predicted growth in RTM. This delayed growth is due to the fact that as air carriers renew their fleet in the presence of increased demand, the overall efficiency of the fleet is improved. Ultimately this improvement in fleet efficiency produces a slower growth rate in emissions than RTM. With that said, the cumulative emissions over the course of the simulation for the fleet considered are approximately 5.5 Gt CO<sub>2</sub>.



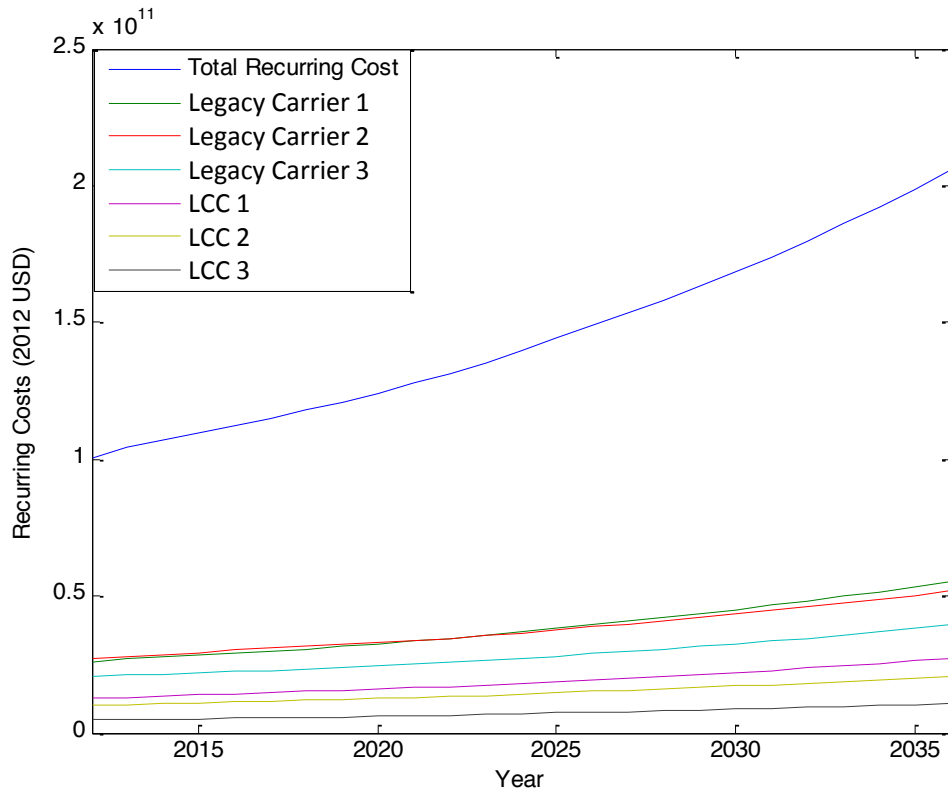


**Figure 5.9: Forecasted CO<sub>2</sub> in the Absence of Policy**

### 5.5.1.3 Recurring Costs in the Absence of Policy

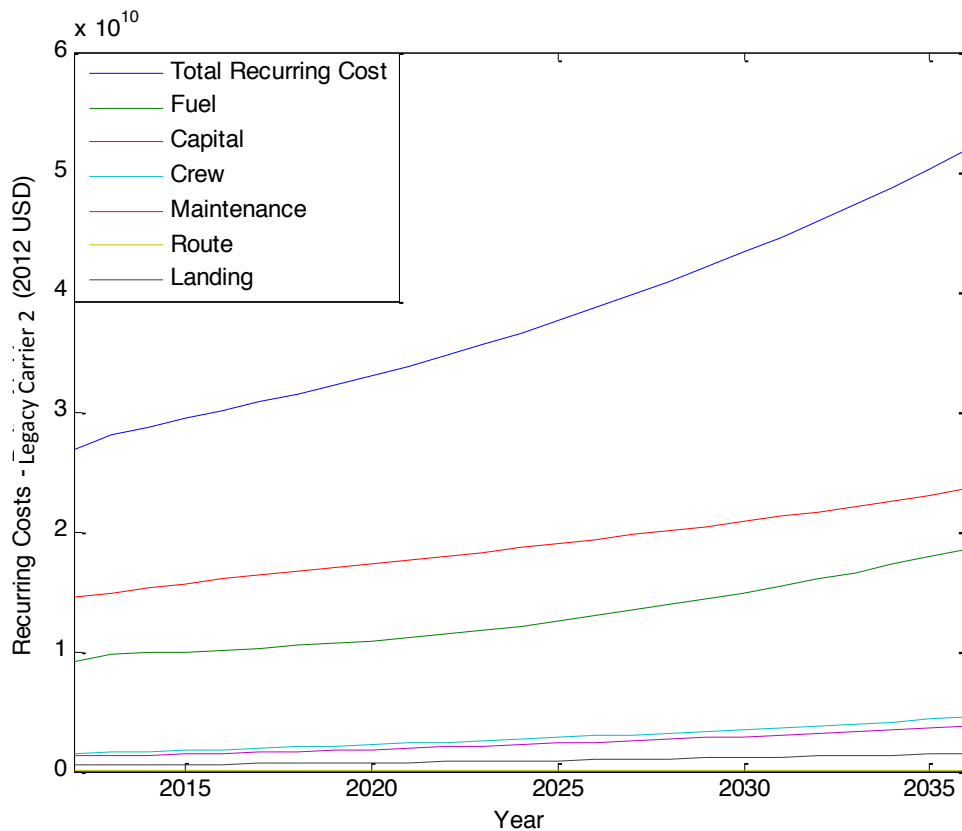
The other primary consideration in cost-effectiveness analysis is the associated cost of policy. Due to the fact that policy implementation will produce changes in the direct operating costs (DOC) for air carriers, these costs should be understood. The recurring costs considered in the absence of policy include the fuel costs, capital costs, crew costs, maintenance costs, route charges, and landing fees. The aggregate costs for each air carrier, as well as the fleet considered, are presented in Figure 5.10. As is expected, the total recurring costs increase throughout the course of the simulation as demand continues to grow. Additionally, it's interesting to note in this figure the relative

change in costs for specific air carriers, namely Legacy Carrier 1 and Legacy Carrier 2. As can be seen, the recurring costs for Legacy Carrier 2 tends to be higher than for Legacy Carrier 1 until about 2022, at which point the operating expenses for Legacy Carrier 1 outpace Legacy Carrier 2. This is a result of the fleet evolution for the two respective air carriers, and demonstrates that this simulation environment for the U.S. NAS predicts Legacy Carrier 2 will be operating a relatively more efficient fleet than Legacy Carrier 1 in the future. This prediction is based on the assumptions provided previously for the developed modeling environment.



**Figure 5.10: Total Recurring Costs for All Air Carriers in the Absence of Policy**

In addition to understanding the relative effect of each air carrier to the total recurring costs, the level of aggregation in this modeling environment of the U.S. NAS also allows for more detailed analysis of the DOC build-up for specific air carriers. In order to demonstrate this capability, Figure 5.11 is provided. Here the total operating costs for Legacy Carrier 2 are presented, along with the cost components comprising the DOC. As can be observed, the key contributions to overall DOC for Legacy Carrier 2 are the fuel and capital costs, with all other cost categories representing a much smaller fraction of overall DOC. This trend can be observed for all other air carriers considered, however, is not done here in the interest of succinctness.



**Figure 5.11: Recurring Cost Build-up for Legacy Carrier 2 in the Absence of Policy**

Ultimately, it is the relative change in costs and benefits due to policy implementation that will be used as a framework for effective policy identification. The preceding discussion of the costs and emissions in the absence of policy serve as the benchmark on which all policies will be evaluated for cost-effectiveness analysis.

## **5.5.2 Cost-Effectiveness Analysis of Individual Policies**

Given this understanding of the associated costs and emissions in the absence of policy, the relative cost-effectiveness of policy implementation can be assessed. While the ultimate goal of this research is to identify effective policy space in the presence of multiple concurrent policies, it's first necessary to understand the effects of the individual policies being studied. The following sections will address the effect of the implementation of the two policies in isolation in order to better understand their relative impacts. Ultimately, this analysis will be used to address research question 1, which is reproduced below.

*RQ1: What are the impacts to the U.S. NAS of a new certification standard or a trading scheme in isolation?*

### **5.5.2.1 The Notional Aircraft CO<sub>2</sub> Standard**

The purpose of an aircraft CO<sub>2</sub> standard is to push technology infusion on new vehicles developed by aircraft manufacturers. The result of creating new technology infused vehicles for the NAS will likely be a more efficient fleet for all air carriers. As a result, it has been predicted that implementing this standard will lead to a reduction in

fuel burn, thus CO<sub>2</sub> emissions, for air carriers. While emissions are expected to be reduced, this standard will primarily impact aircraft manufacturers, thus the expected growth in demand will not be impacted since the NRC incurred by the manufacturer to comply was not transferred to the operator. As a result, it's expected that the reduction in fuel burn will not be great enough to stabilize emissions. Further, due to technological limitations and economic considerations for aircraft manufacturers, the overall impact of such a standard will be limited. The overall benefit of the standard will be measured through a relative change in cumulative CO<sub>2</sub> from the "no action" scenario discussed previously.

While the notional aircraft CO<sub>2</sub> standard is expected to reduce emissions, this reduction will come at a cost to aircraft manufacturers. This NRC to aircraft manufacturers is a function of the necessary improvements needed for each aircraft included to meet the standard, as well as the size of the aircraft. A more complete discussion of the estimating relationship implemented to predict this NRC has been provided previously in 4.5.2. What is important to note however, is that there is expected to be an exponential increase in NRC with increasing stringency of the standard. The overall level of the NRC to aircraft manufacturers can ultimately be used to limit the ranges of viable stringency options. Additionally, as a reminder to the reader, the costs in this study are all purely notional, and the level of NRC considered is often economically unviable simply to discuss the resulting trends.

Finally, the standard is also expected to reduce operating costs for air carriers due to the fuel cost savings that are expected to occur through the implementation of more

efficient fleets. It's expected that these fuel cost savings will be greater than the relative increases in capital costs for the new technology vehicles under the fuel price scenario considered. This will be measured by considering the change in cumulative recurring costs between implemented standards and the "no action" scenario discussed previously. Ultimately, it's expected that it will be shown that there is a tradeoff in the costs imposed to aircraft manufacturers and the cost savings provided to air carriers.

#### ***5.5.2.1.1 Experiment Definition for a Notional Aircraft CO<sub>2</sub> Standards***

Populating the policy alternative space necessitates defining ranges on applicable inputs to the policy. For this policy, this is accomplished by defining the stringency of the standard, as well as the scope of applicability. The stringency level is based on percent reductions from a "no action" limit line defined previously. As such, defining the stringency level can be accomplished through a singular measure of reduction percent over the "no action" stringency limit. Ultimately, the maximum level of stringency will be dependent on the technical feasibility of meeting the standard for individual aircraft, as well as the economic viability to aircraft manufacturers. Due to the fact that the technology forecasting method implemented is normative, no specific technologies are identified to meet the standard, thus determining the maximum reduction from the "no action" limit line is not possible a priori.

Despite this limitation, the economic viability of these standards can be assessed through determination of the non-recurring costs to aircraft manufacturers through the estimating relationship established earlier. In testing a number of potential stringency

limits it has been determined that the NRC begins rapid exponential growth at a reduction of 25% to 30% below the “no action” limit line, and outpaces all other cost elements at 40% below this limit line. As such, the reductions to be tested are varied between 0% and 40% of the “no action” limit line defined previously on Figure 4.24. While the higher end of this range is likely well outside the realm of realistic policy alternatives, exploration beyond technical feasibility is expected to produce trends to be discussed in this notional implementation of policy.

The scope of applicability for this standard requires definition of the entities covered under the standard, as well as the date of implementation. As aforementioned, all manufacturers represented in the simulation environment created for the U.S. NAS would be subject to the standard based on current literature [119]. Thus, fully defining the scope of applicability for this study only requires definition of the date of implementation. As such, the assumed dates of implementation would occur in 2017 or 2023. Due to the ability to rapidly assess policy options however, implementation dates are varied from 2014 to 2023 on a yearly basis. While it is recognized that any implementation dates before 2017 are in reality extremely unlikely, earlier dates are tested to discuss the notional long term effects of these policies within the simulation. The ranges of the parameters varied for this policy option are summarized in Table 5.1.

**Table 5.1: Notional Aircraft CO<sub>2</sub> Standard DoE Ranges**

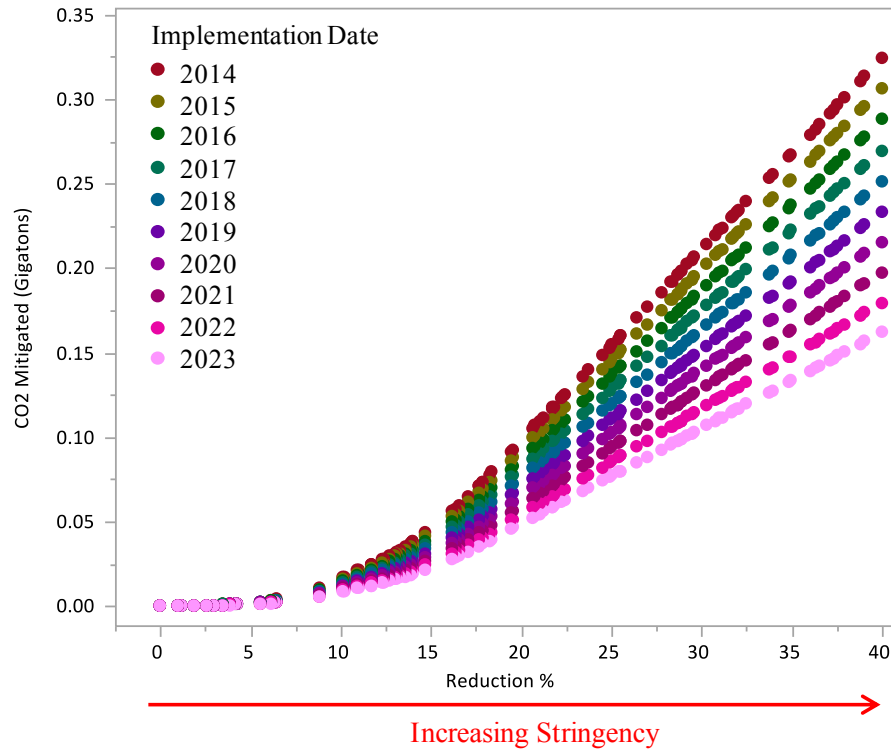
	<b>Minimum</b>	<b>Maximum</b>	<b>Type</b>
Reduction %	0%	40%	Continuous
Implementation Date	2014	2023	Discrete

Given ranges on the inputs to this policy option, the actual experiments to be run must be defined. This is typically accomplished through definition of design of experiments (DoE) [189]. The goal of this study is to explore the entirety of the policy alternative space through Monte Carlo Simulation, in order to fully populate all feasible alternatives. Due to the fact that the only parameter that can be continuously varied is the reduction percent defining the stringency, it has been determined that a randomized design on this variable with a full factorial of implementation date will adequately populate the space.

#### ***5.5.2.1.2 CO<sub>2</sub> Mitigation Potential of a Notional Aircraft CO<sub>2</sub> Standard***

For each experiment performed using the cost-effectiveness simulation environment of the U.S. NAS, fuel burn totals for each air carrier are collected. These fuel burn totals are converted to CO<sub>2</sub> emissions, and aggregated to estimate overall CO<sub>2</sub> emissions from the fleet. This provides a measure of emissions for the fleet on a year by year basis out to 2036. While the mitigation potential of these standards can be assessed yearly, the cumulative mitigation potential serves as a more illustrative measure of the effect of the policy. As such, the cumulative CO<sub>2</sub> emissions resulting from each policy experiment are compared to the cumulative emissions of the benchmarking scenario discussed previously. The resulting mitigation potential of the alternatives can then be viewed as a function of stringency level and year of implementation, as seen in Figure 5.12. This figure provides a visual representation of the policy alternative space explored for these standards, where implementation date is colored on a year by year basis.





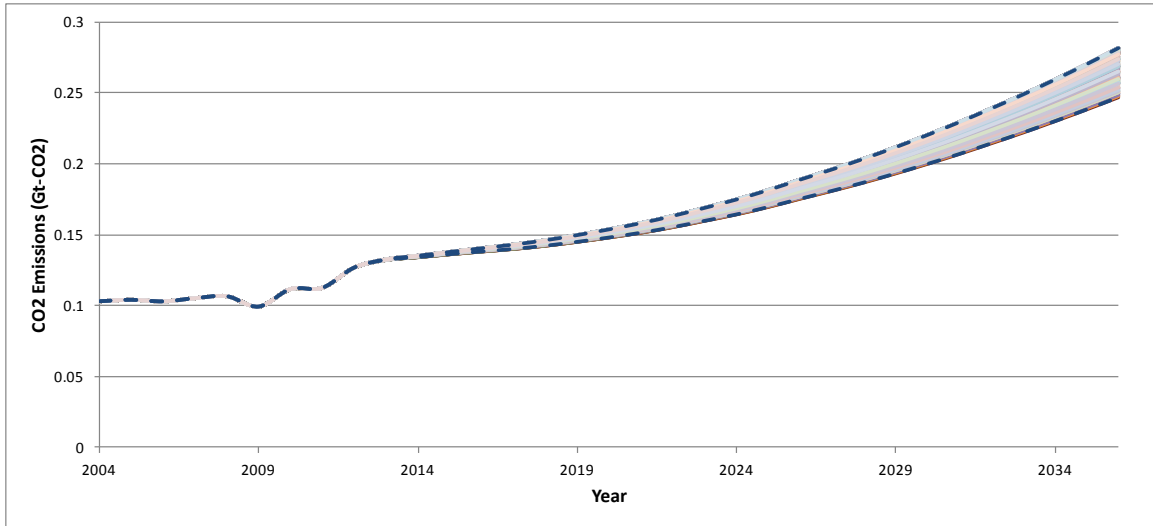
**Figure 5.12: CO<sub>2</sub> Mitigation Potential of the Aircraft CO<sub>2</sub> Standard**

As can be observed, the overall mitigation potential of the policy option in isolation is highly dependent on the overall stringency applied to the standard. While the impact of these standards can be quite significant, approaching 0.2 Gt-CO<sub>2</sub> at moderate stringency limits of approximately 30% below the “no action” limit line, the mitigation potential of stringencies at less than 10% produce negligible effects. As such, this figure serves to highlight the fact that a notional aircraft CO<sub>2</sub> standard under the definition provided in this study will only produce noticeable effects at stringencies above 10% reduction over the defined “no action” limit line.

Additionally, it can also be observed in Figure 5.12 that the overall mitigation potential of these standards is dependent on the year of implementation. As expected, the

sooner standards are implemented, the more mitigation potential exists. Further, at higher stringency levels, the range of mitigation potential becomes greater based on implementation date. This indicates that for moderate to strict levels, the ultimate date of implementation becomes more important for overall CO<sub>2</sub> mitigation potential. It should be noted that for all experiments run, none produce changes to the demand forecast. Ultimately, this confirms the hypothesis for research question 1 that these standards to aircraft manufacturers will produce reductions in CO<sub>2</sub> without impacting expected demand.

It was also predicted that these standards would not be able to stabilize emissions due to the fact that there is no impact to consumer demand. This prediction can be tested through direct observation of the CO<sub>2</sub> output for each policy experiment on a yearly basis, which is provided in Figure 5.13. The range of CO<sub>2</sub> emissions scenarios is presented in this figure, where CO<sub>2</sub> emissions are bounded by the scenario in the absence of policy and a 40% reduction over a “no action” limit line. It is clear from this figure that even under the most stringent option tested emissions will continue to grow in the future simply due to increasing demand.



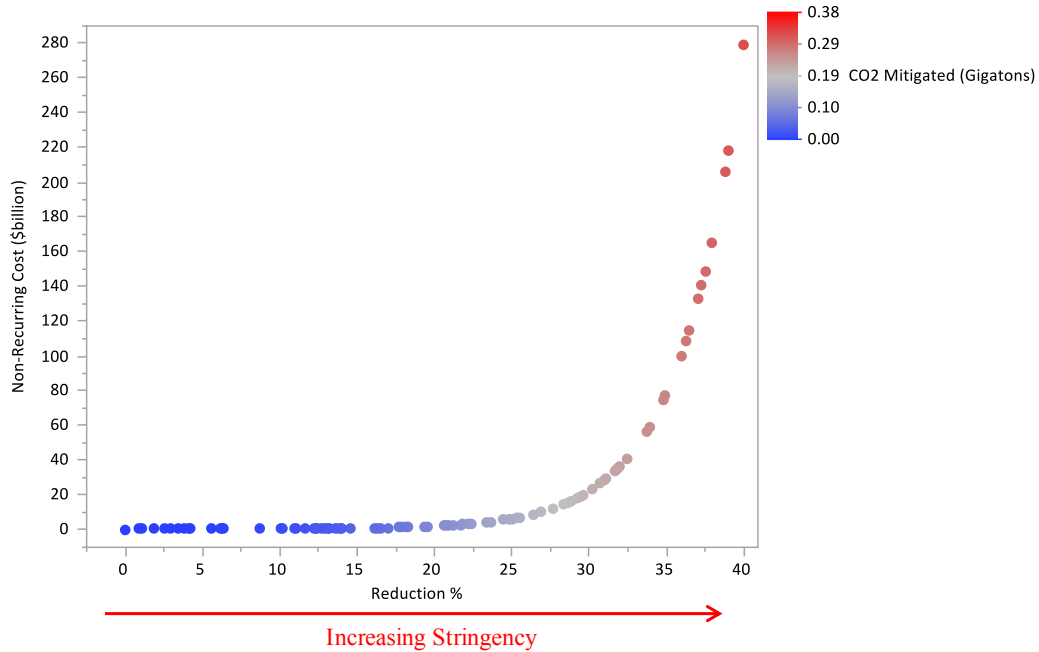
**Figure 5.13: Yearly Emissions for a Notional Aircraft CO<sub>2</sub> Standards**

#### **5.5.2.1.3 Variation of Non-Recurring Costs and Reduction Potential**

In addition to tracking the mitigation potential of the notional aircraft CO<sub>2</sub> standard alternative space, the non-recurring costs to aircraft manufacturers is also assessed. This is accomplished through the utilization of the NRC estimating relationship defined previously. Due to the fact that this is assumed to be a one-time cost, it is not affected by the date of implementation, but only the overall stringency limit of the standard. As such, policy makers should consider the date of implementation as well as the economic impact of these standards on aircraft manufacturers when determining economically viable policy alternatives.

It has been hypothesized that the effect of a notional aircraft CO<sub>2</sub> standard to aircraft manufacturers will be increasing NRCs associated with investments and infusion of technologies on new vehicle concepts. This increasing NRC is predicted to behave exponentially, showing low investment costs for less stringent policy alternatives, viable

costs for moderate policy, and economically unviable costs for very stringent policy. The variation in NRC to aircraft manufacturers with increasing stringency limits is repeated in Figure 5.14.



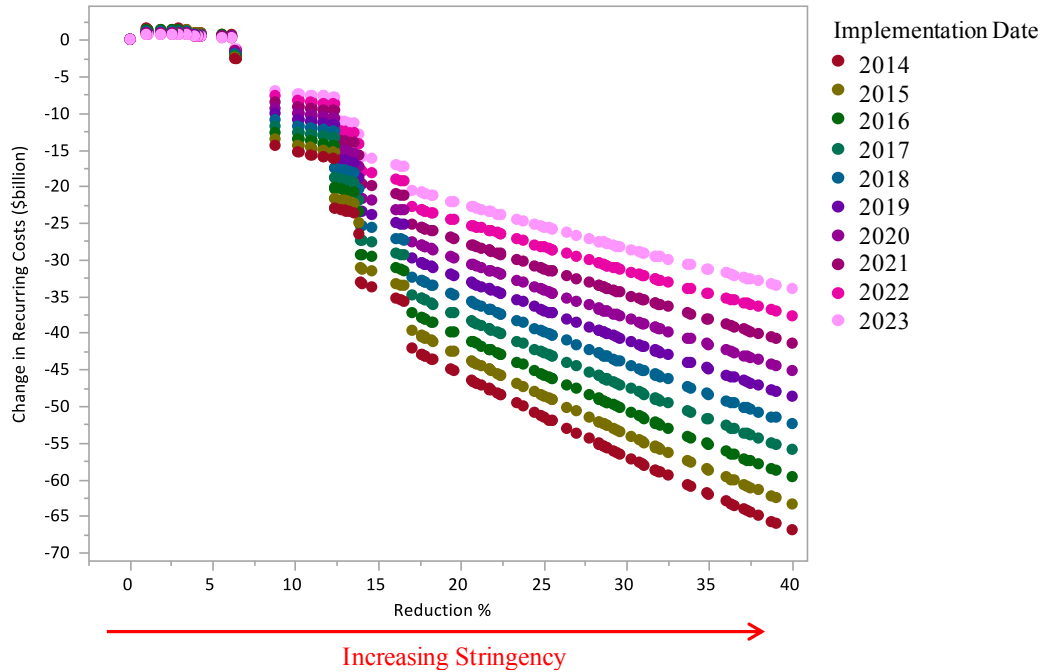
**Figure 5.14: Non-Recurring Cost Variation for the Aircraft CO<sub>2</sub> Standard**

As shown here, less stringent standards in the range of 0% to 10% reduction over a “no action” limit line incur negligible costs to all aircraft manufacturers on the order of tens of millions of dollars. Typically this level of cost would be within the level of investment uncertainty for any new development program. More moderate stringency limits, in the range of 10% to 30% below the “no action” limit line, have the potential to incur significant, but likely acceptable costs, to aircraft manufacturers, reaching a level of approximately \$20 billion. While this cost may seem high, it should be noted that the cost would be shared among all aircraft manufacturers represented. Finally, for very stringent

policy alternatives above 30% reduction over the “no action” limit line, the NRC to aircraft manufacturers exponentially increases, reaching levels well over \$200 billion. While it would be in the policy makers’ purview as to whether this level of cost would be acceptable for the industry to incur, due to the fact that it’s at a level above the valuation of the companies producing aircraft, it’s unlikely to be deemed economically viable.

#### ***5.5.2.1.4 Recurring Cost Savings***

In addition to impacting the costs incurred to aircraft manufacturers, the notional aircraft CO<sub>2</sub> standard is also predicted to reduce the recurring costs to aircraft owners and operators over the benchmarking scenario. This is due to the fact that anticipated reductions in fuel burn, and thus fuel cost, at the current fuel price are expected to outpace increases in capital cost due to premiums for more efficient aircraft. The recurring costs to aircraft owners and operators are tracked on a yearly basis for the U.S. NAS, and have been aggregated for all air carriers considered. As with actual emissions, these costs can be analyzed on a yearly basis, however, assessing the cumulative impacts of the standards to recurring costs provides a more illustrative understanding of the tested standards to potential recurring cost savings. As such, the cumulative recurring costs for each experiment are compared against the benchmarking scenario to provide an overview of the potential cost savings. The results of this analysis are provided in Figure 5.15.



**Figure 5.15: Recurring Cost Savings Due to Aircraft CO<sub>2</sub> Standards**

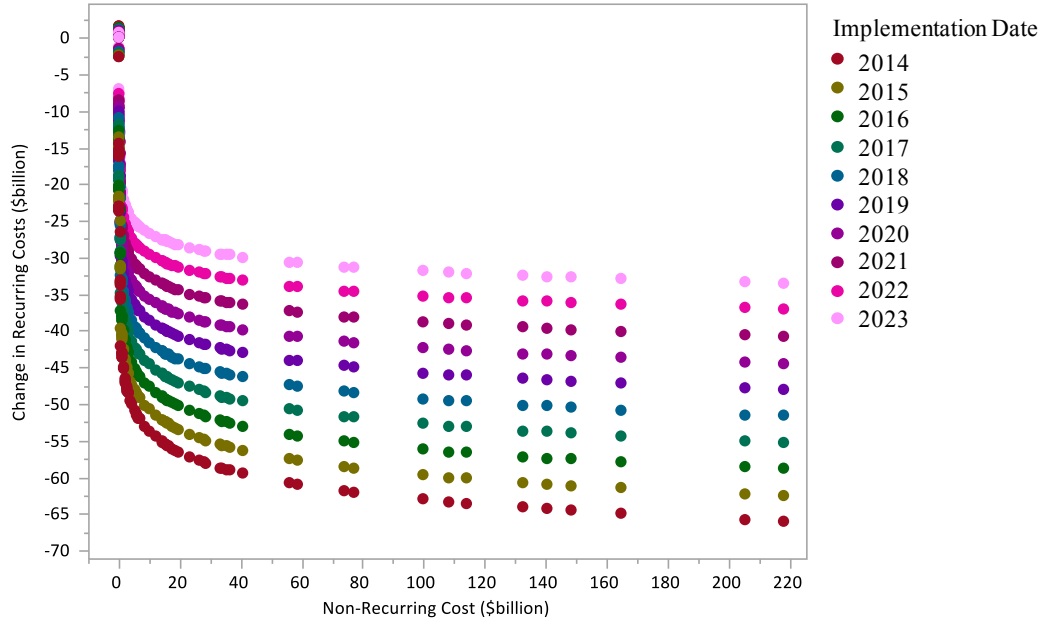
As can be seen, at less stringent policy alternatives in the range of 0% to 10% produce negligible cost savings. This is likely due to the fact that both the increases in capital costs and decreases in fuel costs are minimal in this region of the policy alternative space. However, for more moderate stringency limits, the recurring cost savings increase dramatically. While not shown here, further analysis reveals that this effect is due to the savings in fuel costs outpacing increases in capital costs. Ultimately, the cost savings continue to increase for more stringent policy alternatives. The reason for these decreasing costs is the fuel savings. It may be assumed that at very stringent policy options the high cost of investment to aircraft manufacturers would be passed on to aircraft owners and operators, ultimately accounting for the fuel cost savings. However, in the implementation of the pricing module for new aircraft it has been assumed that the price is market driven. As such, the premiums willing to be paid by air carriers for new

vehicles will not necessarily match the increases in costs incurred to aircraft manufacturers. It is this assumption that ultimately leads to the continual decrease in recurring costs for the policy alternative space explored here.

Additionally, it's also interesting to note that there are discrete jumps in the recurring cost savings for moderate policy options. These occur due to the nature of the CO<sub>2</sub> metric system assumed herein. Since this metric system produces a space that is not fully continuous, the standard tends to impact different vehicles at specific stringency levels. As such, there tends to be jumps in the recurring cost savings as highly utilized vehicles begin to be affected by the standard.

#### ***5.5.2.1.5 Manufacturer and Air Carrier Cost Tradeoffs***

Ultimately, what is demonstrated by the increasing costs to aircraft manufacturers and reduced costs to aircraft owners and operators over the benchmarking scenario in this policy alternative space is that there is a cost tradeoff inherent with this policy option. This tradeoff is illustrated in Figure 5.16, where the recurring costs to aircraft owners and operators is plotted against the non-recurring costs incurred by aircraft manufacturers. As can be seen, lower recurring costs to air carriers typically coincide with greater NRC to aircraft manufacturers. While this is generally true, it's also quite apparent that the implementation date has the potential to greatly impact the overall cost tradeoff between the air carriers and aircraft manufacturers.



**Figure 5.16: RC and NRC Tradeoff Due to the Aircraft CO<sub>2</sub> Standard**

#### 5.5.2.1.6 Summary of Impacts of a Notional Aircraft CO<sub>2</sub> Standard in Isolation

The hypothesis provided regarding the impact of a notional aircraft CO<sub>2</sub> standard has been shown to be reasonable in the preceding discussion. As a reminder, it was predicted that these standards in isolation would lead to:

1. A quantifiable decrease in CO<sub>2</sub> emissions.
2. No change in demand over the input forecast.
3. An inability to stabilize emissions.
4. Increases in non-recurring costs (NRC) to aircraft manufacturers.
5. Decreases in recurring costs (RC) to aircraft owners and operators.

#### 5.5.2.2 Emissions Trading Schemes

Emission trading schemes (ETS) are regulatory policies aimed at creating a real price for CO<sub>2</sub> emissions in order to internalize the costs associated with anthropogenic



climate impacts. As such, these ETS impact aviation through a different mechanism than an aircraft CO<sub>2</sub> standard previously discussed. The primary effect of an ETS is to reduce demand by passing additional costs on to consumers in the presence of the policy. This is primarily based on the anticipation that demand growth in civil aviation will outpace efficiency improvements, leading to a performance gap in emissions. This performance gap will have an associated cost based on the definition of the ETS, which is likely to be passed through to consumer ticket price. Any increase in price will necessarily alter the expected demand through established demand elasticities. As such, it has been predicted that the presence of an ETS will lead to CO<sub>2</sub> mitigation through decreased demand over the input demand forecast. Further, it's anticipated that demand reductions will reach equilibrium values on the order of 1% to 2% below predicted estimates for moderate ETS definitions, such as those established in the EU ETS. Further, the relative impact to different carrier types, namely low cost carriers and legacy carriers, is expected to be disproportionate, with low cost carriers reaching lower equilibrium demand values in general than the legacy carriers included in the fleet.

The following sections will detail the assumptions implemented in defining the cap setting and allocation process for ETS policy alternative space, and provide the impacts to the U.S. NAS based on computational experimentation. As was done for the prior policy option analysis, all applicable research objectives and hypotheses tested in conducting these experiments will be given specific mention.

#### ***5.5.2.2.1 Cap Setting and Allocation of Allowances for an ETS***

In order to define the metric system for an ETS, the cap setting and allowance allocation processes must be established. Due to the desire for linkage of the ETS studied here to the established allowance markets in the EU, the structure of the EU ETS is used to benchmark these processes.

Ultimately, the cap determines the level of allowable emissions under an ETS. Typically this is determined based on a percent of some reference year emissions, which for the EU ETS is on the order of 95% of the average emissions between 2004 and 2006. In order to replicate this cap setting process in the modeling environment developed for the U.S. NAS, the reference year is defaulted to 2005, and the cap is allowed to be varied by the user. While much of the forthcoming discussion considers a cap representative of the EU ETS, in order to fully populate the ETS policy alternative space, a range of caps is defined for experimentation from 50% to 100% of the 2005 fleet emissions.

With an established cap for the ETS, the allocation of allowances to the entities covered can be addressed. For the EU ETS this is accomplished through determination of the relative market share of air carriers based on the revenue-tonne-kilometers (RTK) flown. In order to replicate this process the revenue-ton-miles (RTM) are tracked for all air carriers included in this study, and allowances are allocated based on the relative market share from the measured RTM. While this ultimately establishes the total allowed emissions for each air carrier under an ETS, the number of allowances auctioned and those allocated freely must be defined. For the EU ETS, 15% of allowances can be

auctioned, with the remainder provided freely to covered entities. This assumption can be implemented directly in the framework of the developed modeling environment, however, due to unexpected observed behaviors in output CO<sub>2</sub> emissions when only a fraction of allocated allowances are auctioned, it is proposed that all allowances under the established cap be auctioned. As such, it's assumed that all allowances allocated under a given cap will be auctioned, and the performance gap in emissions will be covered through purchased allowances on the EU ETS allowance market.

#### ***5.5.2.2.2 Determining Allowance Prices***

While the cap setting and allocation processes outlined above provides the ability to determine the number of purchased and auctioned allowances under a given ETS, the associated cost is dependent on the price of the allowances allocated and purchased. Subsequently, the definition of allowance purchase and auction price is necessary for the determination of total ETS cost to be passed through to consumers.

A number of assumed purchase prices of allowances have been studied in aviation for the EU ETS throughout literature, and a review of these assumptions has been provided in Table 2.4. From these reviewed studies, the purchase price of allowances has been assumed to vary between €5 and €60 per tonne. Due to the fact that the modeling environment and all costs are in English units and USD, this allowance price range must be converted. Using the current exchange rate of \$1.35 per Euro [190] and 1.10231 short tons per metric ton, the allowances prices can be converted into commensurable units

with the developed modeling environment. This results in a range of allowance prices for purchased allowances between \$6.12 and \$73.48 per short ton of CO<sub>2</sub>.

While the existing literature provides a good estimate of the range of possible market prices for purchased allowances, there is generally no mention of the price for auctioned allowances. As such, it's unclear if auctioned allowances are assumed to have the same price, or be nominally lower. Due to the fact that assuming the prices are the same between purchased and auctioned allowances would negate the effect of a cap, it has been assumed that the price of auctioned allowances is nominally lower than the purchase price of allowances from the EU ETS market. In order to provide a first estimate of this price, an assumption is made that the auction price of allowances allocated under the cap will be 50% of the price of purchased allowances.

The next issue to address is that of the pass through of lost opportunity costs. As has been identified in literature, one potential solution to alleviate this problem is to define a set price for allowances under the cap that are passed through to consumers. This can either be accomplished by assuming that no lost opportunity costs are passed through to consumers, or that all allowances under the cap are auctioned. Due to the established belief that air carriers will likely pass on lost opportunity costs to consumers, a strong argument can be made that all allowances under a cap ought to be auctioned. For this study, all allowances allocated under a cap will be auctioned based on this reasoning.

### 5.5.2.2.3 *Experiment Definition for Potential Emission Trading Schemes*

Up to this point, the cap setting and allocation processes have been established, the allowance prices have been determined, and a case has been made for the auctioning of all allowances under a specified cap. This information provides the full definition of potential ETS policy, which can be implemented in any future year. In order to fully define the policy alternative space, ranges on all input parameters will be established, and a discussion of the design of experiments to be run will be discussed.

For this study, it has been determined that the cap will be set based on a 2005 reference, and will vary from 100% to 50% of those emissions. The market price of emission allowances will be varied based on estimates from literature between \$6.12 and \$73.48 per ton. Both the cap and market price can be continuously varied between the minimum and maximum values established here. As with the notional aircraft CO<sub>2</sub> standard, the implementation date is a discrete input to the simulation environment. In order to provide some consistency between the two policy options discussed here, the implementation date will be varied between 2014 and 2022. Table 5.2 provides a summary of the input parameters for this ETS policy alternative space study.

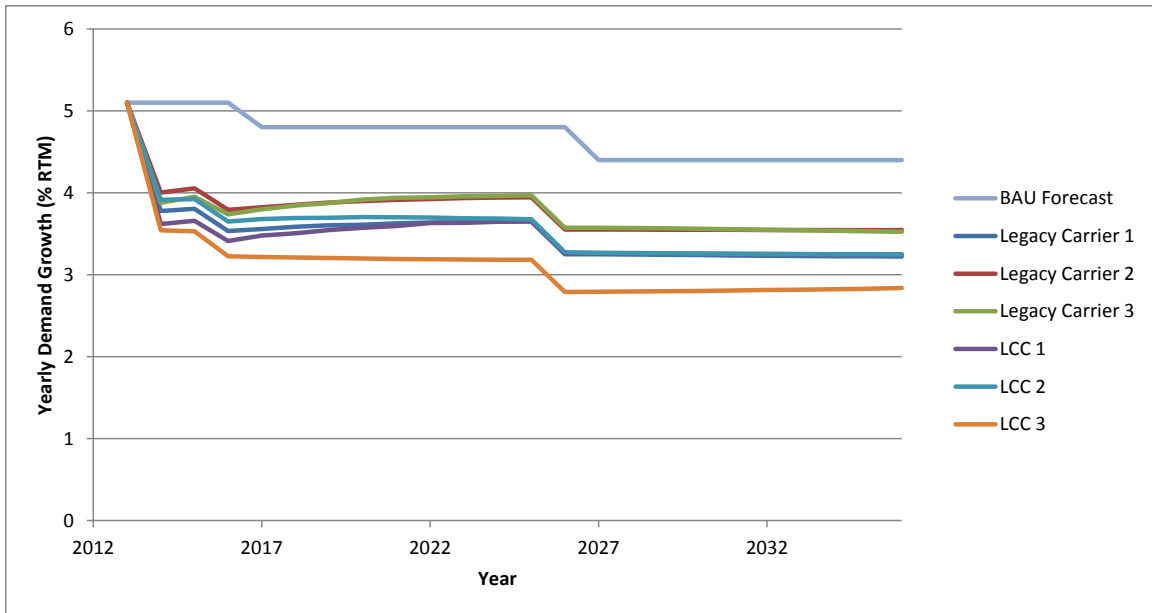
**Table 5.2: Emission Trading Scheme DoE Ranges**

	<b>Minimum</b>	<b>Maximum</b>	<b>Type</b>
Cap	50%	100%	Continuous
Market Price (per ton)	\$6.12	\$73.48	Continuous
Implementation Date	2014	2022	Discrete

As with the notional aircraft CO<sub>2</sub> standard analyzed previously, the purpose of defining ranges on these input parameters for an ETS is to fully populate the policy alternative space. Due to the fact that there are two continuous and one discrete variable, a different approach for the design of experiments (DoE) is taken here than for the previous study. In order to capture the extremes of the policy alternative space, a central composite design on the continuous variables is employed, and the internal policy alternative space is populated by supplementing this DoE with a large number (hundreds) of Latin Hypercube and randomized experiments [189]. This DoE is then repeated for a number of implementation dates in the range studied. Specifically, the continuous variables are tested for potential implementation in 2014, 2016, 2018, 2020, and 2022.

#### ***5.5.2.2.4 The Impact of an ETS to Demand***

Before discussing the results of the outlined experiments, the impact of emission trading schemes to consumer demand will be analyzed. This can be done for any of the planned experiments; however, the general trends in demand impact remain the same. Further, analyzing all experiments simultaneously in respect to demand equilibrium proves very difficult to visualize. As such, an ETS policy is defined that is comparable to the EU ETS in order to address RQ1.1, which is concerned with the general impacts to demand for passenger transport, and RQ1.2, which explores the relative impacts to different air carrier types. The ETS that is defined to address these objectives is based on a 2005 reference year with a cap of 95%. An allowance price of \$20/ton is assumed, and all costs are passed through to consumers. Further, it's assumed that the date of implementation would be 2014 in order to fully explore the effects to passenger transport.



**Figure 5.17: Emission Trading Scheme Impact to Consumer Demand**

Given this definition for the ETS, the yearly demand growth as a percent of revenue-ton-miles (RTM) can be extracted from the results. It should be noted that the steps in demand growth are a result of the input forecast, which anticipates yearly demand growth changes in 2016 and 2026. The resulting yearly demand growth for each air carrier can then be compared to the input business as usual (BAU) forecast, as in Figure 5.17. As can be seen, the resulting demand growth under an ETS comparable to the EU ETS in the U.S. NAS produces demand that is 1% to 2% lower than the input forecast. This result is within the same range as previous studies regarding the impact to air carriers in the EU [102]. Further, it is noted that the resulting demand for all air carriers reaches a new equilibrium value within 3 to 5 years. Subsequently, the hypothesis proposed for RQ1.1 is confirmed, as it was expected that equilibrium demand would be reached and be comparable to previous research efforts.

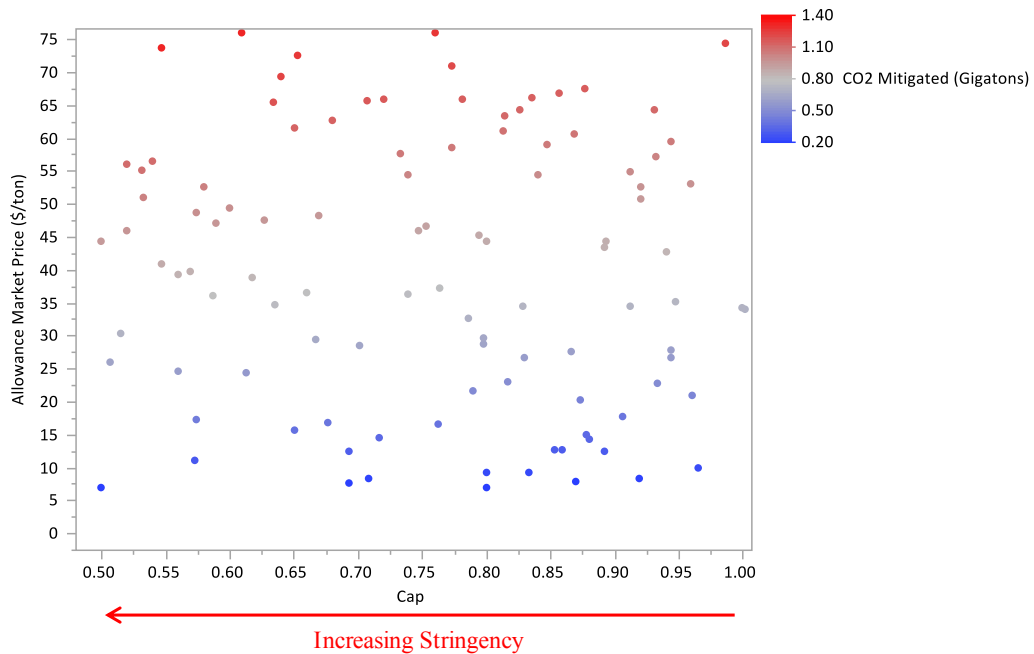
In addition to understanding the general impact to demand under an ETS, this figure also demonstrates the relative impact to specific air carriers. It has been predicted that low cost carriers would be impacted more greatly than the legacy carriers due to their relatively lower ticket prices and higher demand elasticities. As can be observed, this is generally the case, barring Legacy Carrier 1 whose equilibrium demand closely matches that of LCC 1 and LCC 2. Subsequently, it can be stated that the hypothesis for RQ1.2 was partially confirmed. Generally, the relative impacts to low cost carrier demand under an ETS will be greater than for legacy carriers, however, a full understanding of the impacts to demand equilibrium will ultimately occur on a case by case basis.

#### ***5.5.2.2.5 The Relative Influence of Market Price and Cap Definition to CO<sub>2</sub> Mitigation Potential***

With this understanding of the impacts of emission trading schemes to consumer demand, the experiments defined previously can be analyzed more thoroughly. Due to the fact that the market price and cap are varied in this experimentation, it's important to identify the relative influence of each variable to overall CO<sub>2</sub> mitigation potential. In order to accomplish this, the cumulative CO<sub>2</sub> emissions from each experimental run are compared against the benchmarking scenario to provide a measure of mitigation potential. The specific experiments can be visualized based on market price and cap with overlaid colors showing CO<sub>2</sub> mitigation potential, as seen in Figure 5.18. This is accomplished for each potential implementation date, and was determined to demonstrate similar trends regardless of date of implementation. It can be observed in this figure that the coloration is relatively constant across the defined cap, but changes drastically across



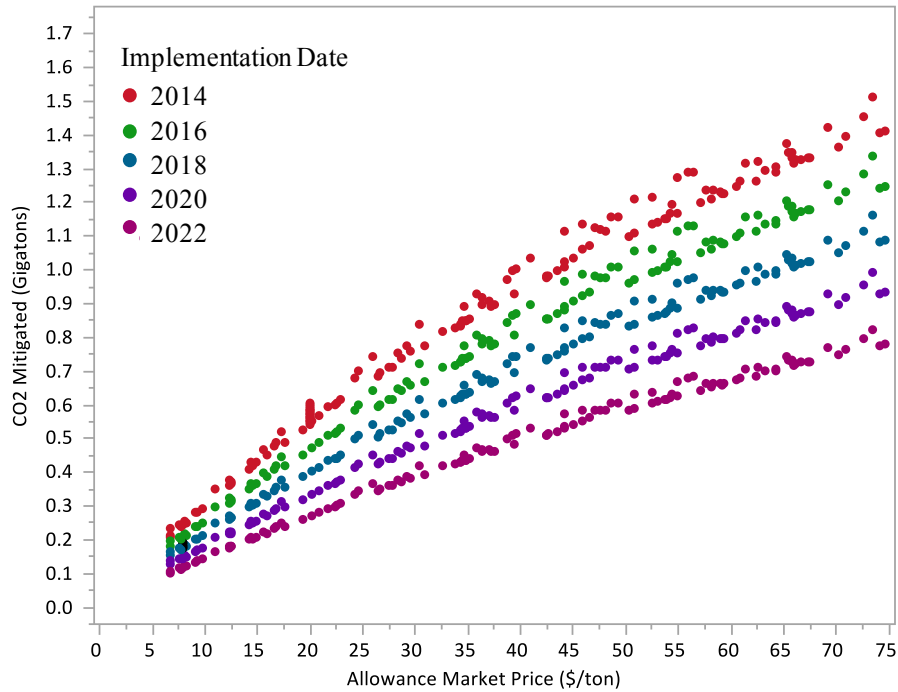
the input market price. This indicates that the market price of emissions allowances is more influential than the defined cap in terms of overall CO<sub>2</sub> mitigation potential. It should be noted that this result is likely dependent on the assumed definition of the cap setting process, which was made consistent with that of the EU ETS. Due to the fact that the reference year was chosen as 2005 and caps up to 50% below this limit were tested, the actual range of the caps tested is somewhat limited. Future studies of such standards not linked to the EU ETS may explore a wider definition of the emissions cap, resulting in trends different than those seen below.



**Figure 5.18: Relative Influence of Market Price and Cap to CO<sub>2</sub> Mitigation Potential**

In addition to looking at the cap and market price simultaneously, the impact of changing market price to overall CO<sub>2</sub> mitigation demonstrates the results shown previously. To provide an illustrative view of this, Figure 5.19 is provided, where all

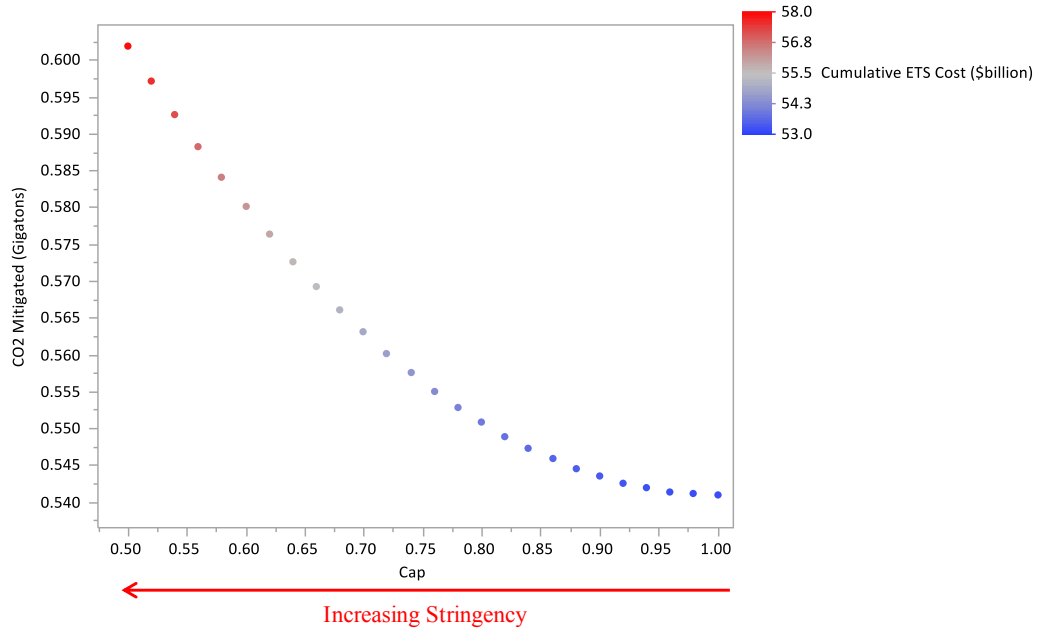
experiments performed to populate the ETS policy alternative space are provided based on CO<sub>2</sub> mitigation potential and market price. Here, the implementation date is colored in a similar fashion to the analysis performed for the notional aircraft CO<sub>2</sub> standard. As can be observed, the market price and date of implementation have the greatest impact on cumulative CO<sub>2</sub> mitigation potential in the time frame considered for this simulation. The effect of the cap controls where in each colored band the CO<sub>2</sub> mitigation potential will fall. Ultimately, the cap produces much smaller changes in emissions mitigation than either the market price or date of implementation, although, this is not to say the impact of the cap is negligible. As was the case for the prior policy option, the overall CO<sub>2</sub> mitigation potential of these ETS are highly dependent on the year of implementation. The sooner the ETS is implemented, the greater the mitigation potential. Ultimately, for very high market prices the difference between implementing an ETS immediately and waiting until 2022 can mean an additional 1Gt-CO<sub>2</sub> mitigated by 2036; however, the effect is less pronounced at low market prices. Finally, it's also important to note here that the CO<sub>2</sub> mitigation potential of these tested ETS is typically much higher than for the notional aircraft CO<sub>2</sub> standard in isolation based on the assumptions of each policy implementation.



**Figure 5.19: CO<sub>2</sub> Mitigation Potential of ETS with Varying Market Price**

#### 5.5.2.2.6 *Effect of Cap Setting to ETS Related Costs and CO<sub>2</sub> Mitigation*

While the effect of the cap is less pronounced in these experiments than either the market price or implementation date, the impacts to overall CO<sub>2</sub> mitigation potential and emission trading scheme related costs can still be substantial. In order to demonstrate the isolated effect of the cap set, a reference scenario is selected among the policy alternatives previously identified. A range of cap definitions is run through the developed modeling environment for an allowance market price of \$20/ton with an implementation date of 2014. The resulting mitigation potential and ETS related costs are visualized in Figure 5.20.



**Figure 5.20: Effect of Cap on ETS Cost and CO<sub>2</sub> Mitigation**

As can be observed in the above figure, as the cap is reduced, and the policy is made more stringent, the overall level of CO<sub>2</sub> mitigation potential increases. Additionally, the costs associated with the ETS also tend to increase with more stringent ETS policy. It's interesting to note in the figure that the CO<sub>2</sub> mitigation potential seems to have a second order polynomial relationship with the cap level. This may indicate that the mitigation potential of further reductions in the cap may increase more rapidly than at moderate definitions of the policy. Additionally, it should be noted that although the cap does have a less pronounced effect on mitigation potential than market price or implementation date, the demonstrated policies shown at this market price represent a change in mitigation potential on the order of 0.1Gt-CO<sub>2</sub>, which is still very significant.

#### ***5.5.2.2.7 Summary of Impacts of an ETS in Isolation***

As with the analysis of the notional aircraft CO<sub>2</sub> standard, the study of ETS in isolation is aimed at addressing RQ1, which concerns the impact of these policies to the U.S. NAS. It has been predicted that emission trading schemes will impact demand, reaching new equilibrium values that can be quantified. These demand changes are expected to be different depending on air carrier type. In order to address these needs, ETS policy alternative space is populated for a number of cap definitions, potential market prices of allowances, and implementation dates. In analyzing the results of these experiments with the given assumptions it has been determined that an ETS tends to:

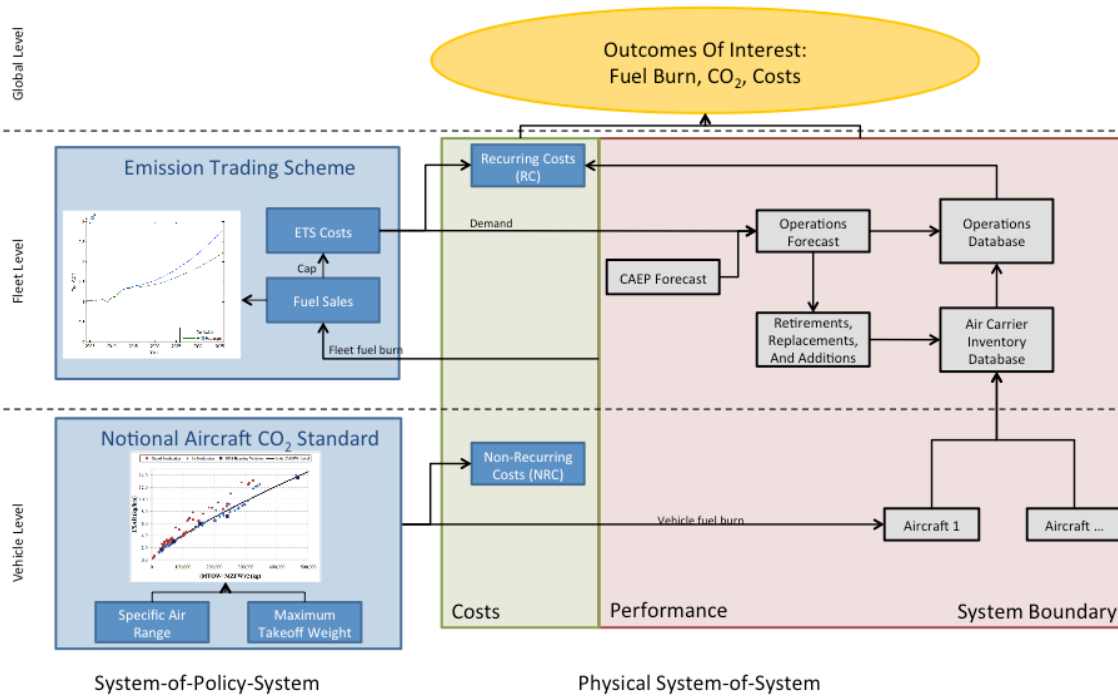
1. Reduce demand over the input demand forecast.
2. Produce new equilibrium demand values.
3. Impact low cost carrier demand more than legacy carrier demand, typically.
4. Incur policy induced costs to aircraft owners and operators.
5. Produce greater CO<sub>2</sub> mitigation potential than Aircraft CO<sub>2</sub> Standards.

### **5.5.3 Concurrent Policy Implementation**

With an understanding of the individual impacts of the two policy options, the exploration of feasible policy alternative space can be continued concerning the concurrent implementation of these policies. It has been shown that previous policy analysis studies typically pursue regulatory policy analysis for one policy at a time. Despite this fact ICAO's GIACC has tasked EU member states with the determination of "baskets of measures" aimed at the mitigation of emissions. The concurrent implementation of the policies pursued in this study represents a potential "basket of

measures”. It has been predicted that the effects of this basket of measures cannot be predicted solely based on the individual assessment of the policies included due to their complex interactions within an established SoS. This realization has prompted the definition of systems-of-policy-systems, where policy tradeoffs are likely to occur.

The following sections will explore the determination of policy tradeoffs between the two options considered herein. In order to accomplish this, a benchmarking research objective has previously been established (RQ2.1) where it is posited that the XPIROV policy analysis framework implemented previously can be expanded for the study of multiple policies implemented concurrently. This expansion of the established policy analysis framework has been termed the GenPAF framework, and a representation of the policies considered in this framework is presented in Figure 5.21. As can be seen, the individual policies constituting the SoPS can be mapped to the specific systems within the physical SoS at their respective hierarchical levels, and ultimately the interaction of these policies to overall outcomes of interest can be tracked. As such, the GenPAF policy analysis framework ought to adequately represent and track the interactions of these policies.



**Figure 5.21: Concurrent Policy Analysis in the GenPAF Framework**

Ultimately, the purpose of conducting policy alternative exploration for multiple policies in this SoPS context is to understand how the combined effects of the policies differ from their impacts in isolation. Due to the fact that the notional aircraft CO<sub>2</sub> standard will improve the overall efficiency of the fleet, the impact to demand of emission trading schemes are expected to be lessened. Further, it has been predicted that meeting an established environmental goal can be accomplished through a mix of these policies, and there will be an inherent tradeoff among them in doing so. Finally, by exploring a policy tradeoff instead of a single policy to address environmental goals, it's expected that the associated policy induced costs will be lessened over any policy in isolation. Studying these effects will address RQ2, which is reproduced below.

*RQ2: How will the combined effect of these policies differ from their implementation in isolation?*

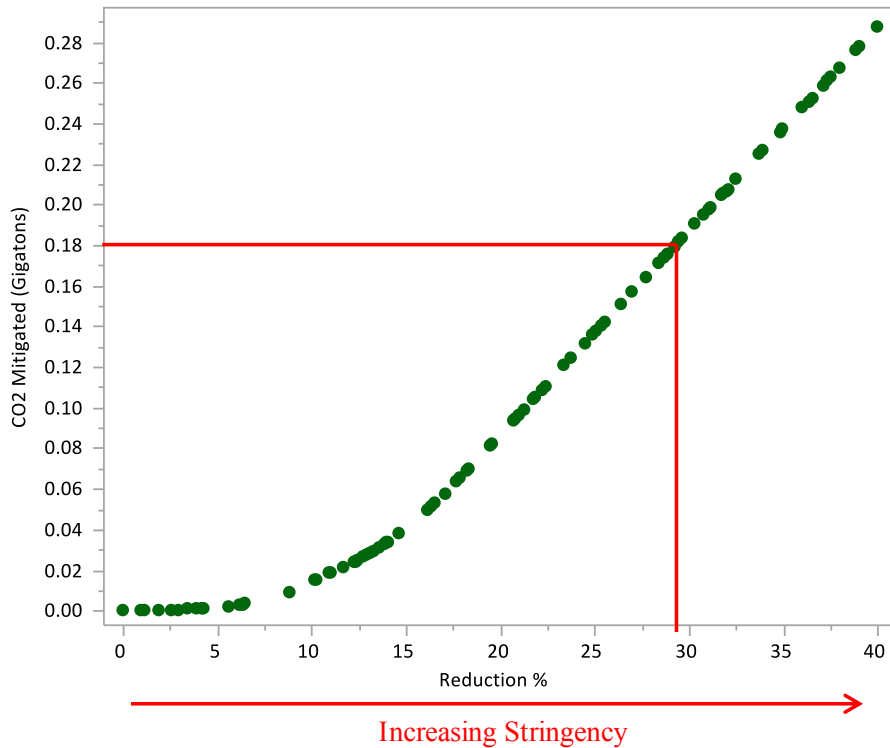
### **5.5.3.1 Cost-Effectiveness of Policy in Isolation**

In order to explore the inherent policy tradeoffs and potential reduction in costs of concurrent policy implementation, it is first necessary to understand the cost-effectiveness of meeting established environmental goals with either policy in isolation. This will provide a benchmark against which policy mixes can be compared in order to address the research objective aforementioned. Understanding the cost-effectiveness of meeting an environmental mitigation goal with either policy option studied here can be accomplished by utilizing the results of the individual policy results previously discussed. In order to illustrate this process, a notional value system from a policy maker will be applied on desired CO<sub>2</sub> mitigation, and the cost-effectiveness of each policy in isolation will be explored. For this example, consider the notional goal in question to be the mitigation of approximately 0.18 Gt-CO<sub>2</sub> by the year 2036.

Based on the results previously presented, this mitigation potential can be achieved with either policy option. For the notional aircraft CO<sub>2</sub> standard, meeting this environmental goal can be achieved with an implementation in 2016 and a reduction of approximately 30% over the “no action” limit line. In order to illustrate this assessment, a subset of the results presented in Figure 5.12 have been extracted and are presented in Figure 5.22. The needed reduction over the “no action” limit line is quite apparent in this figure, and this reduction can be used to predict the non-recurring costs (NRC) incurred



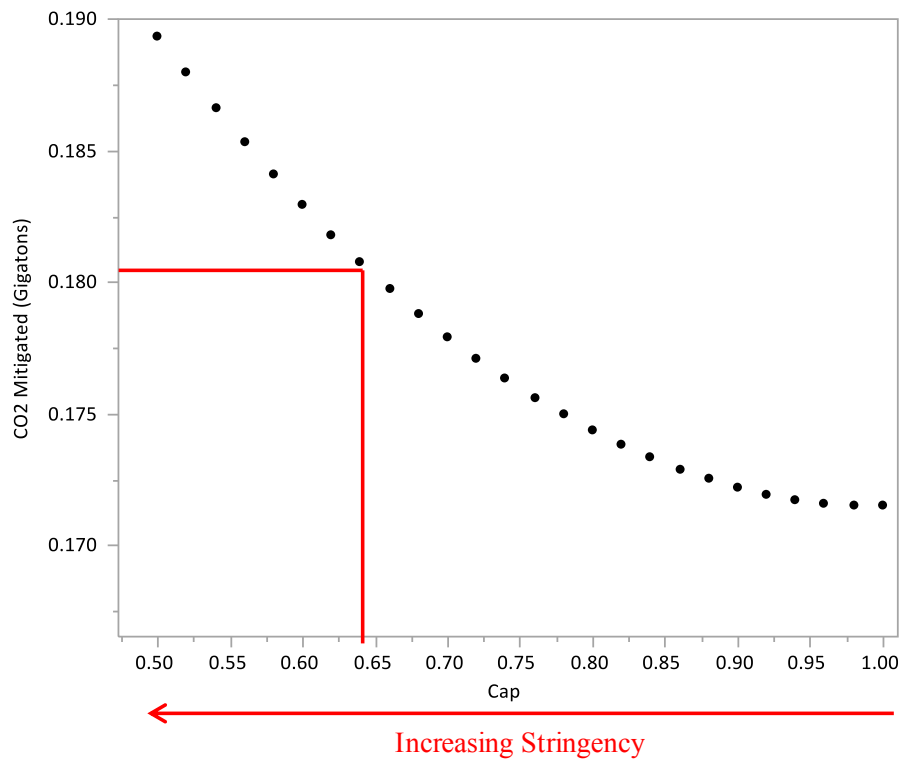
by aircraft manufacturers to meet the standard through the relationship shown in Figure 5.14. Doing so provides an estimate for NRC in the range of approximately \$20 billion for technology investment needed to meet this goal.



**Figure 5.22: Notional Aircraft CO<sub>2</sub> Standard Stringency to Meet Notional Goal**

Similarly, emission trading schemes can also be implemented to meet this established goal. In order to remove the effect of allowance market price from this analysis, a market price of \$8/ton is considered here. Based on closer examination of the results presented in Figure 5.19, it is determined that meeting this mitigation goal at the market price considered can be accomplished with an implementation of the ETS in 2018. Given the establishment of the market price of allowances and implementation date, the impact of the cap can be isolated to determine the level of cap necessary to meet

the mitigation potential outlined here. To provide a more visual representation of this cap determination process Figure 5.23 is presented. As can be seen here meeting the goal of approximately 0.18 Gt-CO<sub>2</sub> by 2036 can be accomplished with a cap in the range of approximately 65% of 2005 emissions. The costs associated with the implementation of this ETS can then be assessed using the cost-effectiveness simulation of the U.S. NAS. Doing so demonstrates a cumulative cost associated with this ETS of approximately \$23billion.



**Figure 5.23: Emission Trading Scheme Stringency to Meet Notional Goal**

As is shown here, meeting a notional emissions mitigation goal may be possible with either policy option, but doing so may produce large costs on the order of \$20 billion. Further, it should be noted that pursuing either of these policies in isolation will produce disproportionate effects on market actors throughout the U.S. NAS. If the

notional aircraft CO<sub>2</sub> standard is implemented, the burden will be primarily placed on aircraft manufacturers, while the implementation of emission trading scheme will burden aircraft owners and operators. Producing a more fair and balanced approach to the market actors included in the U.S. NAS will likely require a tradeoff of the two policies considered here.

### **5.5.3.2 Discovering a Policy Tradeoff**

Understanding this policy tradeoff is accomplished through concurrent policy implementation using the framework presented in Figure 5.21. Due to the fact that it's not possible to know the exact definitions of the notional aircraft CO<sub>2</sub> standard and emission trading schemes that will meet the policy goal of 0.18 Gt-CO<sub>2</sub> a priori, the alternative space of these concurrently implemented policies must be explored. Filtering can then be used to illustrate the effective policy mixes that meet this goal.

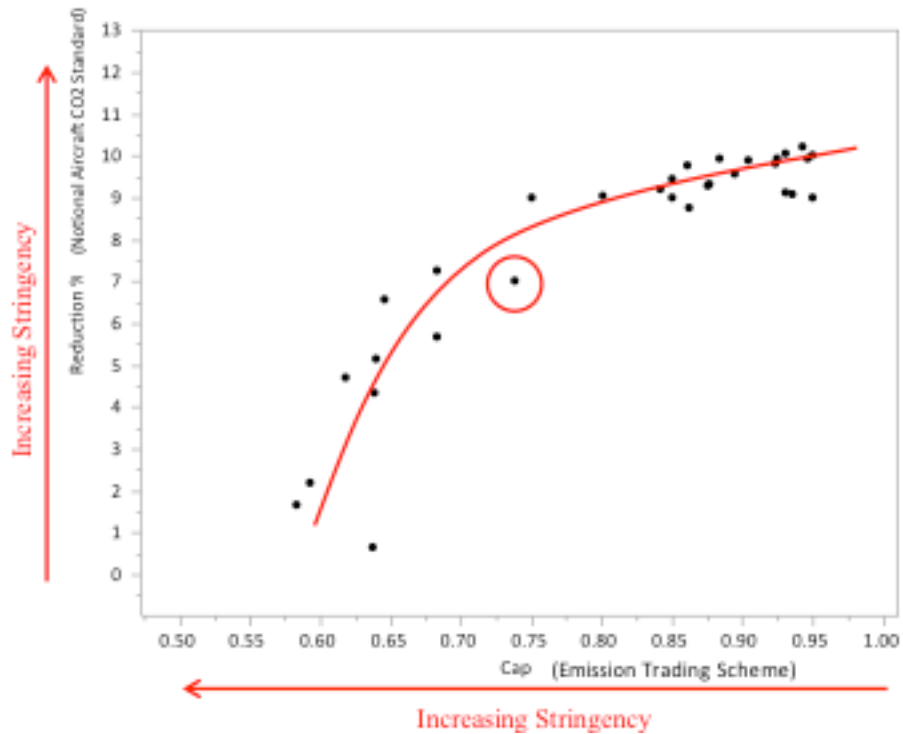
Accomplishing this necessitates definition of the ranges of each policy to be run in conjunction. The implementation of each policy has already been established, with the notional aircraft CO<sub>2</sub> standard occurring in 2016 and an ETS in 2018. Further, the market price of allowances under an ETS have been assumed to be \$8/ton. Subsequently, studying the combined effect of this policy tradeoff at this stage will be accomplished through the variation of stringencies for both policy options. For the notional aircraft CO<sub>2</sub> standard, the reduction percent over a "no action" limit line is varied, and for the ETS the cap definition is the parameter to be changed. Table 5.3 provides the ranges of the

stringency parameters varied in this study. These ranges are based on those established previously for each of the policies in isolation.

**Table 5.3: Policy Tradeoff Parameter Definition**

	<b>Minimum</b>	<b>Maximum</b>	<b>Relevant Policy</b>
Reduction %	0%	30%	Aircraft CO <sub>2</sub> Standard
Cap	50%	100%	Emission Trading Scheme

These ranges on the individual policies are varied through a randomized DoE to populate the policy alternative space, which is ultimately filtered for a notional mitigation goal of 0.18 Gt-CO<sub>2</sub> by 2036. The stringency parameters of each policy can then be viewed simultaneously, and effective policy mixes can be identified, as seen in Figure 5.24. It is readily apparent in this figure that a tradeoff among the policies exists. If a less stringent notional aircraft CO<sub>2</sub> standard policy is desired, the ETS must be made more stringent to meet the established goal and vice versa.



**Figure 5.24: Policy Tradeoff of the Aircraft CO<sub>2</sub> Standard and ETS**

Ultimately, it is in the policymaker’s purview as to what specific mix of these policies is optimal, but it would likely be an intermediate policy along the policy tradeoff curve identified. While the scientist is not able to predict what specific policy mix will be selected, the costs for all policy alternatives are stored from the results of the experimentation and can be analyzed dynamically. To demonstrate this capability, consider the policy mix circled in Figure 5.24 and it is assumed to be a desired policy mix to be implemented. This SoPS alternative consists of a notional aircraft CO<sub>2</sub> standard with a reduction of approximately 7% over the “no action” limit line and an ETS with a cap of 75% of the emissions from 2005. Analyzing the costs of this policy mix reveals an associated NRC to manufacturers of approximately \$60 million and a cumulative cost of the ETS on the order of \$20 billion to aircraft owners and operators. While this cost is

still substantial, it represents a savings of billions of dollars to both of these market actors over either policy in isolation. In this way, the inherent tradeoff in this concurrent policy alternative space demonstrates the potential for sharing the economic burden of meeting environmental goals at a reduced cost to both aircraft manufacturers and owners/operators.

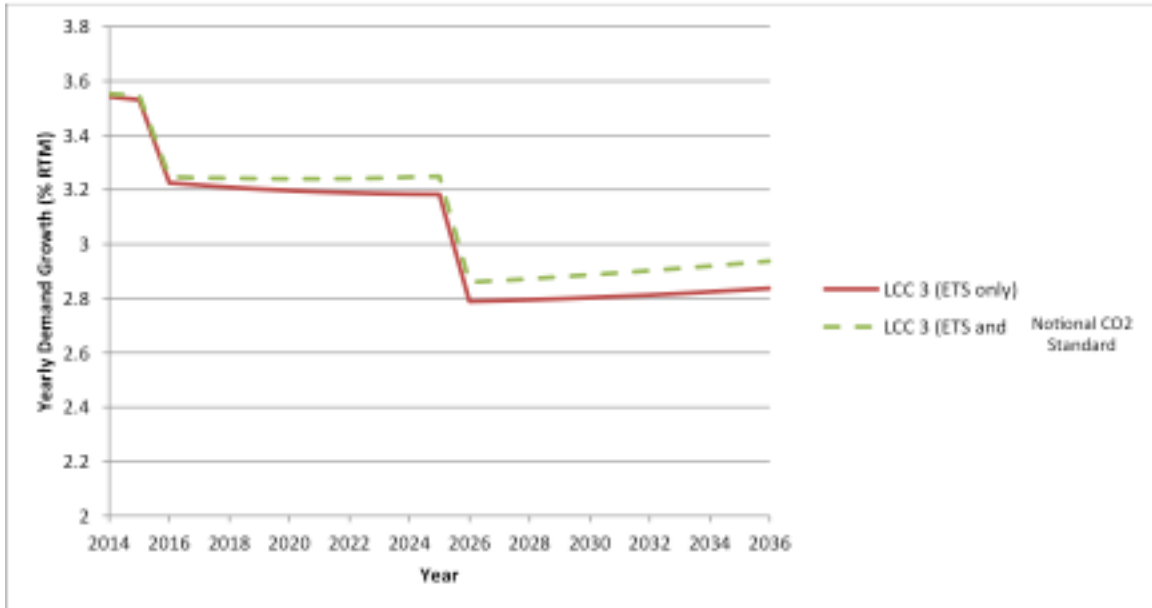
### **5.5.3.3 The Influence of a Notional Aircraft CO<sub>2</sub> Standard to Demand Under an ETS**

In addition to analyzing the effects of this policy tradeoff in reducing the associated costs to market actors included in the U.S. NAS, the interaction of these concurrent policies should also be explored. As aforementioned, it has been hypothesized that the inclusion of a notional aircraft CO<sub>2</sub> standard in the presence of an ETS will lessen the effect of demand reduction. In order to test this hypothesis, the emission trading scheme studied earlier that is comparable to the EU ETS is implemented in addition to a relatively stringent notional aircraft CO<sub>2</sub> standard. The specific definitions of parameters for each policy are presented below in Table 5.4. It should be noted that the implementation dates selected are in a time frame that would be politically and technically infeasible; however, the purpose is to understand the combined effects to demand of these policies. As such, earlier implementation allows for longer durations of time to be considered in this study.

**Table 5.4: Policy Interaction Definition**

<b>Emission Trading Scheme</b>	
Cap Year	2005
Cap	95%
Allowance Price (per ton)	\$20
Implementation Date	2014
<b>Notional Aircraft CO<sub>2</sub> Standard</b>	
Reduction %	30%
Implementation Date	2014

The results on demand growth for this policy mix are compared against those for the ETS in isolation. As a reminder, the impacts to demand for this particular ETS have been presented previously in Figure 5.17. As expected, in the presence of a notional aircraft CO<sub>2</sub> standard, the impact to demand of the emission trading scheme is lessened. This occurs for all air carriers considered, and to illustrate this effect Figure 5.25 is provided. Here, the impact to LCC 3's demand is presented under an ETS in isolation, and with a policy mix. As can be seen, the presence of the notional aircraft CO<sub>2</sub> standard leads to higher equilibrium demand than under an ETS in isolation. While a similar result can be viewed for all air carriers, it is not necessary for the illustration of this effect. Subsequently, this hypothesis on the impact to demand under a policy mix has been confirmed using the modeling environment developed.



**Figure 5.25: Impact to Equilibrium Demand Under Policy Mix**

#### 5.5.3.4 Summary of Concurrent Policy Implementation

It has been shown here that for an established environmental goal, effective policy mixes can be identified at a reduced cost to either policy in isolation. In pursuing these effective policy mixes there is an inherent tradeoff among the notional aircraft CO<sub>2</sub> standard and emission trading schemes, and the identification of an optimal policy mix would be based on a policy maker's assessment of the relative burden to be placed on aircraft manufacturers and air carriers. While these policy mixes have the ability to more fairly distribute the associated costs of meeting environmental objectives, the interaction of the two policy options produces effects to equilibrium demand growth. Subsequently, understanding the inherent tradeoffs and implications of concurrent policy implementation necessitates studying these policies as a SoPS.



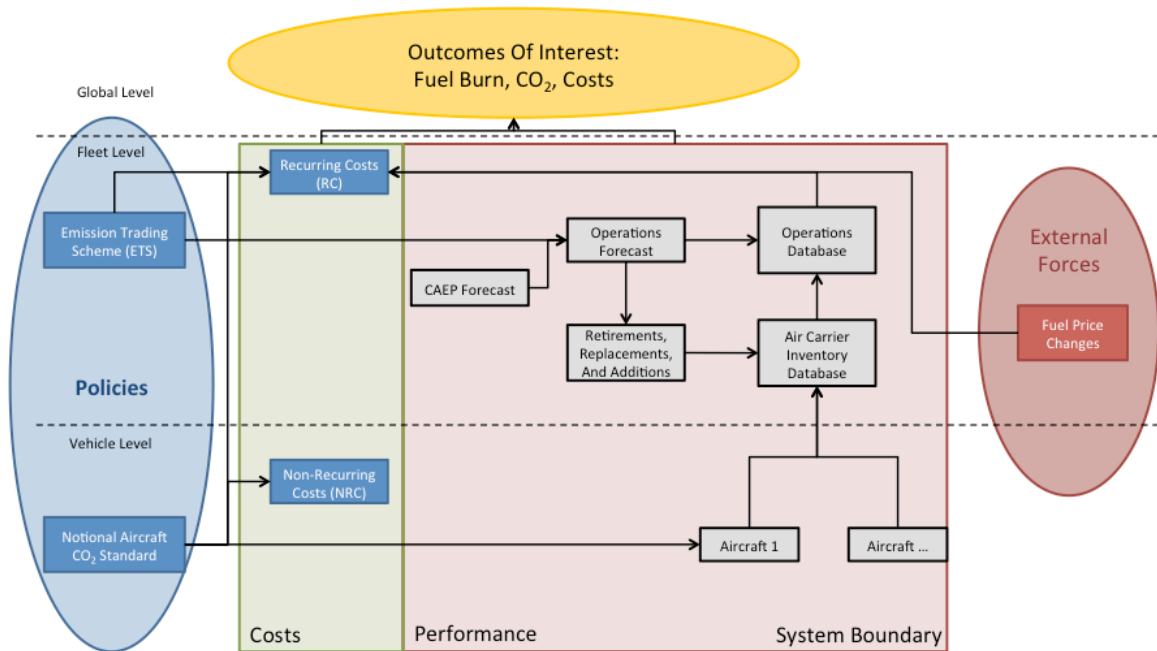
#### **5.5.4 Quantifying the Effects of Aleatory Uncertainty**

In addition to understanding the potential tradeoffs among multiple concurrently implemented policies, the ability to quantify aleatory uncertainty in this framework is also desired. This is due to the fact that many uncertainties in the physical SoS cannot be reduced through policy implementation, and may have an impact on the policies themselves. As such, quantifying the impact of these uncertainties can provide valuable insight to policymakers. One example where this is likely the case is in the potential volatility of fuel price. While an underlying assumption of \$3/gallon has been applied to this problem, and is consistent with other analyses, future fuel prices may be substantially lower or higher based on factors outside the control of commercial aviation.

To demonstrate the capability of quantifying the effects of aleatory uncertainty in the physical SoS, such as fuel price volatility, the GenPAF policy analysis framework will be employed through the mapping of exogenous factors to the specific systems of interest within the physical SoS. Doing so for the purpose of studying the impact of fuel price changes can be visualized in this framework in Figure 5.26. As can be seen here, the fuel price is treated as an exogenous factor, which will impact the recurring cost calculations. It's anticipated that the impact of fuel price volatility will be most pronounced in the study of the notional aircraft CO<sub>2</sub> standard, where there is a tradeoff in the increases in capital costs and reductions in fuel costs. As the fuel price assumption changes the relative influence in fuel cost to capital costs will change, and may lead to instances where the increases in capital costs outweigh the reductions in fuel costs. It has been hypothesized that this will occur at low fuel prices and more stringent notional

aircraft CO<sub>2</sub> standards, will will be to address the research objectives outlined by RQ4.2, which is reproduced below.

*RQ4.2: How can specific forms of aleatory uncertainty be quantified in the presence of regulatory policy for commercial aviation?*



**Figure 5.26: Exploring Aleatory Uncertainty in the GenPAF Framework**

#### 5.5.4.1 The Impact of Fuel Price Volatility

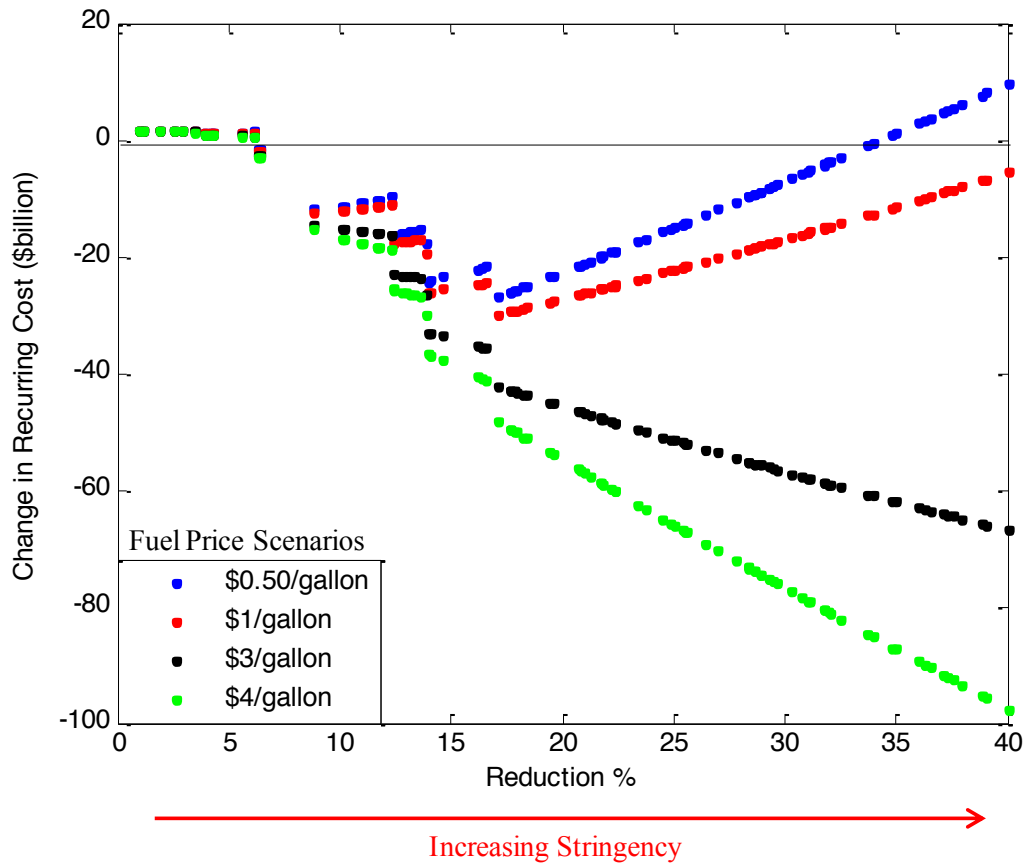
The main effect of changing the assumed fuel price will be to alter the relative influence of fuel costs to the calculation of the recurring direct operating costs outlined in 4.5.1. As a reminder, at the assumed fuel price of \$3/gallon, which is based on previous regulatory analyses and estimates from the Energy Information Administration, the recurring capital costs and fuel costs accounted for the majority of all DOC, and were of

approximately the same magnitude. Changing the fuel price assumption to account for fuel price volatility will ultimately change the relative level of the fuel cost. As the fuel price is reduced, the relative influence in fuel costs to DOC will also be reduced.

While studying the effect of varying fuel price to the benchmarking scenario is possible, the main purpose here is to illustrate implications to potential regulatory policy. As such, the impact of varying fuel price will be studied here in the presence of notional aircraft CO<sub>2</sub> standards. This provides a more interesting case for analysis, as one of the main effects of the policy is to increase capital costs, and reduce fuel consumption, thus fuel costs. As such, there is an inherent cost tradeoff occurring in the DOC due to this standard. While it has been shown that under the current fuel price scenario all potential standards lead to a reduction in DOC due to decreases in fuel costs, this result may change as the fuel price is varied. In fact, it's expected that a cost tradeoff will become more apparent as the fuel price is reduced, ultimately, reaching a level where increases in capital costs outweigh fuel cost savings.

In order to demonstrate this, the notional aircraft CO<sub>2</sub> standard is considered for an implementation in 2014, and a large number of reduction percentages over the “no action” limit line are tested based on previously established ranges. This is accomplished for four fuel price scenarios of \$0.50/gallon, \$1/gallon, \$3/gallon (default assumption), and \$4/gallon. The cumulative recurring costs over the course of the simulation are then aggregated and compared to the benchmarking scenario aforementioned. This produces a measure of cumulative change in recurring costs due to a notional aircraft CO<sub>2</sub> standard under different fuel price scenarios. The results of this analysis are presented in Figure

5.27. As previously established, the default fuel price of \$3/gallon results in continual decreases in recurring costs as the standard becomes more stringent. This is due to the fact that at this level of relative fuel costs, the fuel burn savings outweigh the marginal increases in capital costs due to the premiums air carriers pay for more efficient vehicles. This trend is further exaggerated at higher fuel price scenarios, where the fuel costs become more influential. While this is true for the higher fuel prices tested, as the relative influence of fuel costs is reduced the trend in recurring cost savings can become quite different. As can be seen in the lower fuel price scenarios tested, there tends to be a reduction in recurring costs only as the increases in efficiency outweigh the marginal increases in capital costs. As the notional aircraft CO<sub>2</sub> standard becomes more stringent under these scenarios though, the increases in capital costs can become more influential than the reductions in fuel cost. While this doesn't lead to actual recurring cost increases for the \$1/gallon scenario, under the \$0.50/gallon fuel price scenario, a notional aircraft CO<sub>2</sub> standard with a reduction of 35% or more over the "no action" limit line is shown to produce higher recurring costs than the benchmarking scenario. This increase in the recurring costs is due to the greater capital costs, and their relative influence in overall DOC. Additionally, it should be noted that as with recurring cost savings observed earlier, there are discrete jumps in this data. These occur due to the nature of the metric system assumed, as previously described.



**Figure 5.27: Change in Recurring Costs Under Different Fuel Price Scenarios**

While the main focus of this research is in the identification of effective policy space when multiple policies are implemented concurrently, many of the underlying assumptions to this analysis may alter the results of this analysis, as shown here. Subsequently, it's deemed important to demonstrate that the established policy analysis framework is capable of quantifying the impacts of aleatory uncertainty within the physical SoS. This has been accomplished here through the analysis of the effects of fuel price volatility to the overall change in recurring costs to aircraft owners and operators. As has been shown, the effect of a substantially lower fuel price may lead to instances

where the notional aircraft CO<sub>2</sub> standard produces greater recurring costs over the benchmarking scenario despite fuel burn savings.

## **5.6 Make Decision**

With the ability to concurrently implement both a notional aircraft CO<sub>2</sub> standard and emission trading schemes, greater insight into the potential implications of effective policy mixes can be provided to policy makers in the decision making process. As has been explicitly stated, the final decision of an effective policy mix is solely based on the applied value systems from policy makers. With that said, the scientist can provide the ability to identify a quantitative policy space through inverse design principles. It has been predicted that this can be accomplished through Monte Carlo Simulation and filtering based on value heuristics established previously.

In order to address CO<sub>2</sub> mitigation policy in commercial aviation, it's expected that likely measures of effectiveness will include CO<sub>2</sub> mitigation potential, and the economic costs associated with policy implementation. In the case of the notional aircraft CO<sub>2</sub> standard, the economic viability of policy is measured through the non-recurring cost (NRC) incurred to aircraft manufacturers, and for emission trading schemes, the associated recurring ETS costs can be used. Further, it is anticipated that the identification of effective policy space is also highly influenced by the value systems applied using these measures of effectiveness. As such, the assessment of effective policy mixes will be dependent on the desires of each individual policymaker to mitigate CO<sub>2</sub> or reduce economic burdens to aircraft manufacturers and air carriers.

While this method will allow policymakers to apply their value systems to identify an effective policy space, in the same vein, it will also provide traceable insights into the value systems themselves. This is due to the fact that such an approach is expected to reveal Pareto frontiers of effective policy space, and the selection of policy mixes will highlight the tradeoff among the feasible policy alternatives studied. As such, this approach of applying value systems through filtered Monte Carlo Simulation is expected to provide traceability to policymakers' decisions.

Ultimately, it's expected that implementing filtering using the heuristics selected will reveal reductions in effective policy space as either greater CO<sub>2</sub> mitigation potential is desired, or through reduced economic burdens to aircraft manufacturers and air carriers. This will be accomplished by demonstrating the use of filtering to identify effective policy space, which can be used to uncover policy tipping points. Additionally, the use of visualization to communicate the impacts of policy identification will also be discussed, as well as the usefulness of this method in the reduction of regulatory state uncertainty. Demonstrating these capabilities is expected to address the objectives outlined in RQ3, which is reproduced below.

*RQ3: How can this knowledge of a policy tradeoff be used to help meet goals, such as those established under the Kyoto Protocol?*

### **5.6.1 Utilizing Filtering to Show Effective Policy**

As previously stated, the identification of effective policy space can be achieved by applying value systems to the policy alternative space being studied. While this would

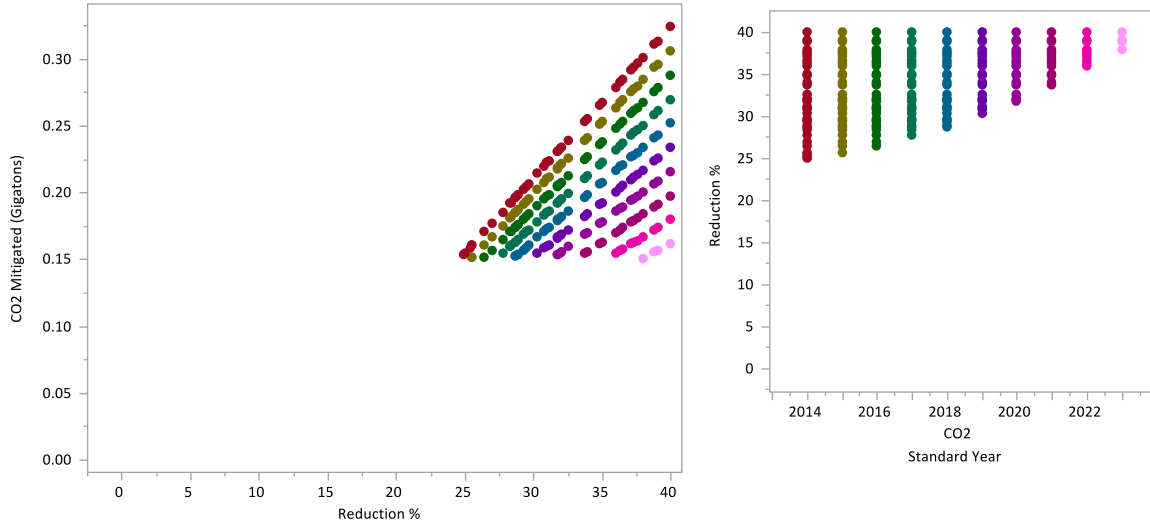
be accomplished by the policymaker, the capability to identify an effective policy space will be demonstrated here through the consideration of notional CO<sub>2</sub> mitigation goals and levels of economic viability. This will be accomplished using the results presented previously for the two policy options. Following this demonstration, a more thorough mix of these policies will be analyzed by generating an expansion of the policy alternative space using concurrent policy implementation in the GenPAF framework. Filtering principles will then be used on the policy alternative space to demonstrate the ability to identify effective policy mixes that can be considered feasible candidates for “baskets of measures” to address CO<sub>2</sub> mitigation in the U.S. NAS.

#### **5.6.1.1 The Aircraft CO<sub>2</sub> Standard**

A number of potential notional aircraft CO<sub>2</sub> standards have been run in isolation based on the inputs provided in Table 5.1, and the resulting CO<sub>2</sub> mitigation potential has been presented in Figure 5.12. Further analysis of the policy alternative space for this policy option can be accomplished by considering the application of value systems through filtering. To demonstrate this capability, consider a notional scenario in which a policymaker desires an overall CO<sub>2</sub> mitigation potential of 0.15 Gt-CO<sub>2</sub> by the year 2036. This value system can be reflected in the provided results by filtering the policy alternative space to an effective policy space where only policies resulting in at least 0.15 Gt-CO<sub>2</sub> or greater are observed, as is the case in Figure 5.28. As evident, this particular value system results in the requirement of a notional aircraft CO<sub>2</sub> standard with a minimum reduction of 25% below the “no action” limit line. Additionally, the impact to



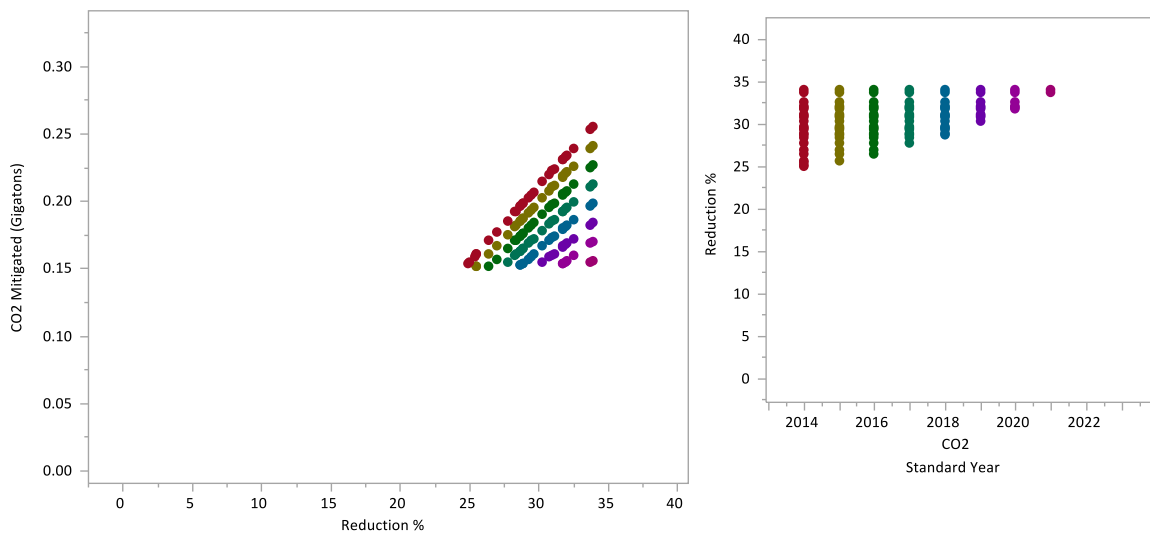
implementation date can also be observed, and it becomes apparent that the later the standard is put in place the more stringent it will have to be to meet this goal.



**Figure 5.28: Assessment of a Notional Aircraft CO<sub>2</sub> Standards to Achieve 0.15 Gt-CO<sub>2</sub> Mitigation**

In addition to applying values on the environmental aspects of the problem, the policymaker may also choose to express their value system through economic considerations, such as the non-recurring cost (NRC) incurred to aircraft manufacturers. If it is determined by the policymaker that a NRC greater than \$60 billion may overburden aircraft manufacturers, this consideration can also be included as a part of the applied value system. Doing so for the notional aircraft CO<sub>2</sub> standard studied here results in a maximum reduction over the “no action” stringency limit line of approximately 35%, as seen in Figure 5.29. Given this applied value system to both the environmental and economic considerations of the problem, the effective policy space is greatly reduced from the policy alternative space presented earlier. Further, it can be seen that this value

system requires the implementation of a notional aircraft CO<sub>2</sub> standard before 2023, with very few policy options available the later the standard is implemented. If this notional value system is reflective of the actual value system of policymakers, it becomes quite clear that waiting until 2023 to pass a standard will not produce the desired results. The power of this approach is that any policy maker value system can be implemented and the options to achieve that value are readily obtained.



**Figure 5.29: Assessment of a Notional Aircraft CO<sub>2</sub> Standards to Achieve 0.15 Gt-CO<sub>2</sub> at an NRC Less Than \$60 billion**

As a result of this applied value system to the experiments performed for the notional aircraft CO<sub>2</sub> standard in isolation, it can be seen that effective policies will likely have an aggressive stringency level and be implemented prior to 2023. Further, the more rapidly the standard can be implemented, the less stringent it needs to be to meet the environmental goals established herein. Subsequently, this analysis points out the need

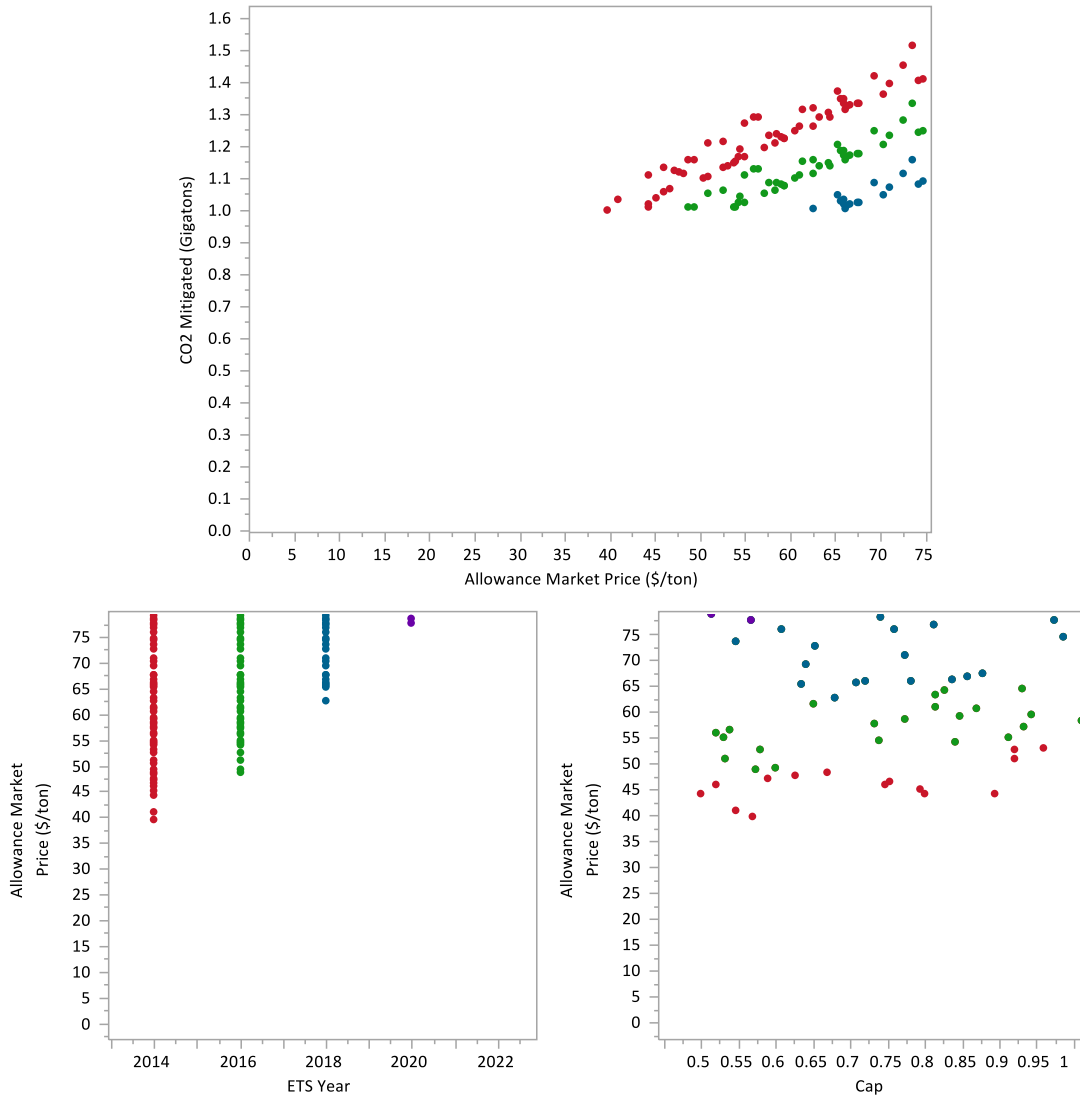
for a response in the coming years in order for the standard to be effective based on the applied value system.

#### **5.6.1.2 Emission Trading Schemes**

As with the notional aircraft CO<sub>2</sub> standard in isolation, the results presented previously for emission trading schemes can also be used to study the effects of applied value systems. This is done for the experiments performed based on the ranges presented in Table 5.2. The results of these experiments to the overall mitigation of CO<sub>2</sub> have also been presented previously in Figure 5.19. It should be noted here that for this demonstration of the application of value systems to the policy in question, the market price of allowances is varied within the ranges provided by literature. Due to the fact that this market price was the dominant factor in overall CO<sub>2</sub> mitigation potential, it's expected that applying value systems on the environmental goals will primarily impact the necessary market price of allowances. Additionally, as has been noted previously, the CO<sub>2</sub> mitigation potential of the emission trading schemes studied tended to be much greater than for the notional aircraft CO<sub>2</sub> standard, thus, it's expected that policymakers would likely desire greater reductions in CO<sub>2</sub> given the implementation of an ETS.

To demonstrate the impact to the ETS studied in isolation, consider the notional desire of a policymaker to be the mitigation of 1 Gt-CO<sub>2</sub> by the year 2036. Application of this value system can be accomplished through filtering as was done previously, and the resulting effective ETS policy alternatives can be visualized in Figure 5.30. As can be seen, achieving the value system of the policymaker with an ETS would necessitate a

market price of allowances of at least \$40 per ton-CO<sub>2</sub>. Further, this goal can only be achieved if an ETS is implemented by 2020, and the later the implementation date the higher the necessary allowance price would need to be.



**Figure 5.30: Effective Emission Trading Schemes to Achieve 1 Gt-CO<sub>2</sub> Mitigation**

In analyzing the impact of these applied value systems to the two policy options previously studied, some general trends are readily apparent. For a desired reduction in

overall CO<sub>2</sub> emissions, policies implemented sooner can be less stringent, while those planned for implementation further into the future will have to be more stringent to achieve the same desired mitigation values in the forecasted period. Further, it's quite apparent that the impact of applying both environmental and economic desires is the reduction in effective policy space, as hypothesized. Finally, it has also been shown that by applying the value systems in this way, many dates of implementation can be seen to be infeasible, which is an important consideration for policymakers.

### **5.6.1.3 Identifying Effective Policy Space Under Concurrent Policy Implementation**

In addition to analyzing the implications of applied value systems to the policies considered in isolation, the two policy options implemented concurrently can be analyzed for effective policy mixes. The ability to implement these policies concurrently in the GenPAF policy analysis framework has been previously demonstrated, and will be used here to populate the policy alternative space. Doing so requires definition of the ranges used, as well as the DoE to populate the policy alternative space.

In order to remove the effect of allowance market price from the ETS, a singular market price is selected within the ranges identified from literature. For this study, it's assumed that allowances can be purchased on the market for \$20 per ton-CO<sub>2</sub>, and would be auctioned at \$10 per ton-CO<sub>2</sub> under the cap. Further, due to the combinatorial nature of including multiple implementation dates on multiple policies, only a subset of dates are applied. For this study, the likely dates of implementation of the notional aircraft CO<sub>2</sub>

standard are included, 2017 and 2023, as well as 2014 to demonstrate the mitigation potential given immediate implementation of the standards. Due to the fact that the implementation date is a discrete input to the problem, a full factorial of these dates is run for the two policies. Given these assumptions, the cap for the ETS, and reduction over the “no action” limit line for the Aircraft CO<sub>2</sub> standard can also be varied. The ranges for these continuous parameters are provided in Table 5.5, and a central composite design supplemented with Latin Hypercube and randomized points are generated to populate the space. It should be noted that the ranges selected to populate this policy alternative space have been selected based on the previous studies of the two policy options in isolation.

**Table 5.5: DoE Ranges for Concurrent Policy Implementation**

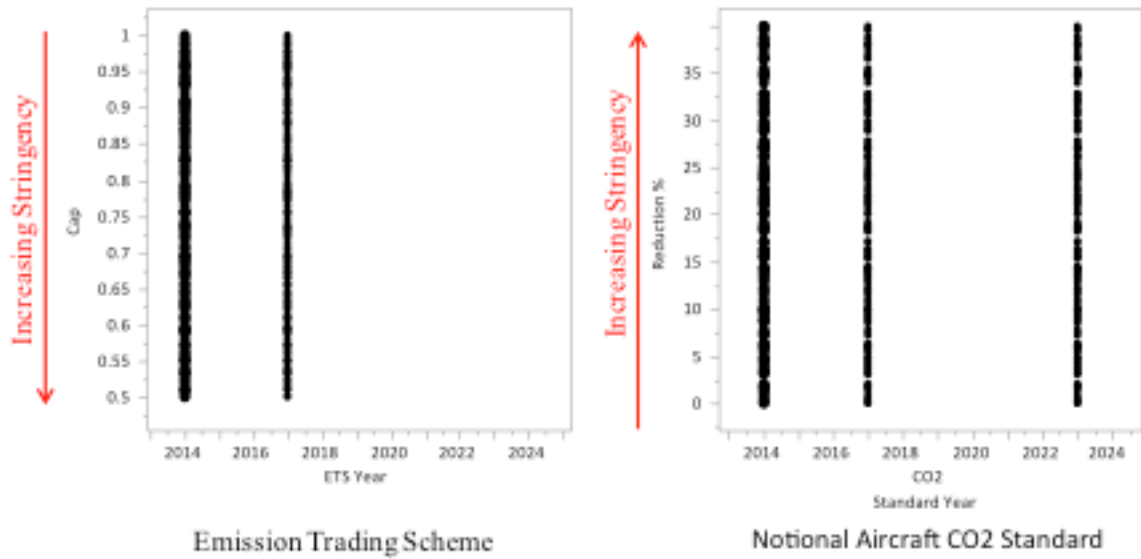
	<b>Minimum</b>	<b>Maximum</b>	<b>Relevant Policy</b>
Reduction %	0%	40%	Aircraft CO <sub>2</sub> Standard
Cap	50%	100%	Emission Trading Scheme

The resulting policy alternative space can be visualized in Figure 5.31. As can be seen, the alternative space is well covered for all applicable years for both policies. Subsequently, it is assumed that these experiments will provide the necessary information to analyze the impact of an applied value system.



**Figure 5.31: Concurrent Policy Alternative Space**

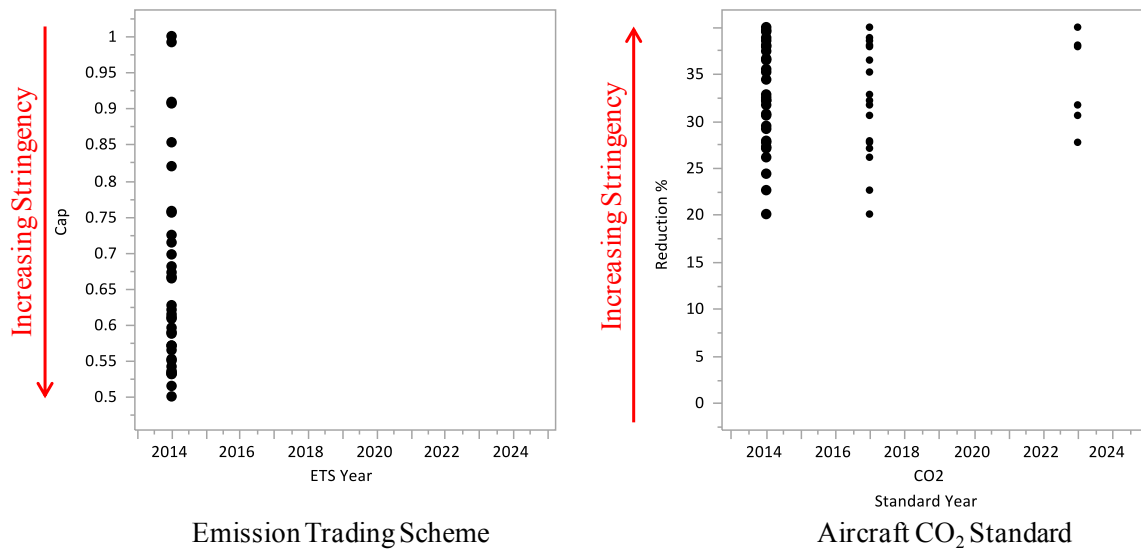
With the policy alternative space fully populated through Monte Carlo Simulation, the application of value systems can be considered. As was the case for the policies in isolation, this is achieved through filtering of the policy alternative space. For this notional example, consider a scenario where the policymaker desires an overall reduction in CO<sub>2</sub> of at least 0.7 Gt by the year 2036. Filtering all infeasible policies from the alternative space shown above, results in an effective policy alternative space provided in Figure 5.32. As can be observed, this environmental goal produces little impact on the implementation date or overall stringency of the notional aircraft CO<sub>2</sub> standard, however, it demonstrates that an emission trading scheme would need to be implemented by 2017. The fact that greater mitigation potential can be achieved by an ETS means that achieving goals in this range necessitates early implementation of such policies.



**Figure 5.32: Effective Policy Mixes to Achieve 0.7 Gt-CO<sub>2</sub> Mitigation**

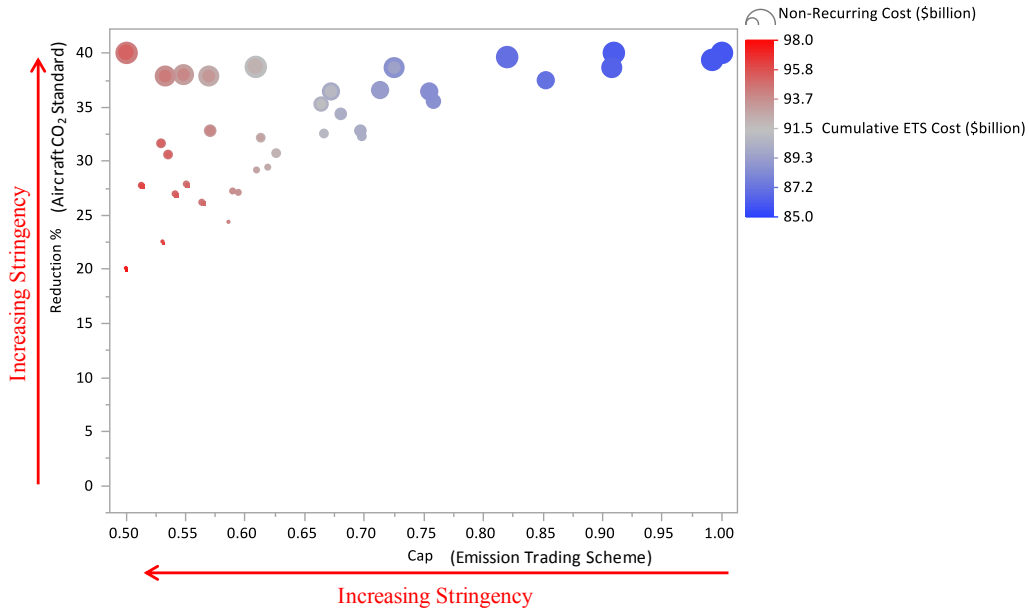
One of the main benefits to this approach is that the value systems can be dynamically changed, and the resulting effective policy space can be visualized in real time. As such, if the policymaker were to decide based on the previous results that greater mitigation potential is possible, they may increase their desired reduction. In this case, consider the desired mitigation potential is increased to 1.1 Gt-CO<sub>2</sub> by 2036. The resulting effective policy space is further reduced as presented in Figure 5.33. As can be seen, as the desire for greater reductions in emissions is placed on the policy alternative space, the need for ETS implemented immediately becomes clear, and more stringent notional aircraft CO<sub>2</sub> standard would have to be put in place.





**Figure 5.33: Effective Policy Mixes to Achieve 1.1 Gt-CO<sub>2</sub> Mitigation**

The reduced effective policy space can also be visualized as a tradeoff between the two policy options, as discussed in 5.5.3.2. For the effective policy space based on the value system applied here, this can be accomplished as in Figure 5.34. Here, in addition to filtering based on the environmental goals established by the policymakers, the costs associated with the policy mix can also be analyzed. This is accomplished for the NRC to aircraft manufacturers through the size of the dots, and for the ETS related cost through the color scheme described. In order to pick the most cost-effective policy to achieve the stated CO<sub>2</sub> mitigation goals, it's desired that the policy mix selected be represented by a small blue dot. In this way, the tradeoff in costs to aircraft manufacturers and air carriers can be made readily apparent to the policymaker.



**Figure 5.34: Effective Policy Mix Tradeoff**

## 5.6.2 Demonstrating Policy Tipping Points

One of the most valuable insights that can be gathered from this filtering approach as the absolute measure of a heuristic is varied, is the identification of policy tipping points. Policy tipping points can be classified as the applied value systems that eliminate effective policy space that may be desired by policymakers. This situation is quite apparent considering the desired implementation dates of effective policy, both in isolation and as a policy mix.

As an example, consider the value system applied to the notional aircraft CO<sub>2</sub> standard in 5.6.1.1. It has been expressed in literature regarding these efficiency standards that potential dates of implementation may occur in 2017 or 2023 [119]. As such, it is assumed that policymakers are looking at 2023 as a possible date for implementation.

However, if the notional value system applied to the problem previously is reflective of the actual value systems of the policymakers, there would be no feasible policy alternatives available for implementation in 2023. In this way, the desires expressed by the notional policymaker in terms of CO<sub>2</sub> mitigation potential and viable non-recurring costs (NRC) imposed to manufacturers creates a policy tipping point that excludes implementation in 2023. As such, this analysis can illustrate the need for more immediate action in the 2017 timeframe.

Ultimately, the heuristics used as the measurable parameters for the applied value systems can be varied to more fully understand the tipping points of the regulatory policies in question. The advantage of this approach, filtered Monte Carlo Simulation, is that this analysis of policy tipping points can be completed dynamically and shown in real time with policymakers present. In this way, this proposed method for policy analysis represents a contribution to concurrent policy analysis that has not yet been demonstrated in the literature.

### **5.6.3 Utilizing Results to Discuss Regulatory State Uncertainty**

As discussed previously in Chapter 2.5.1, regulatory state uncertainty is the uncertainty associated with the level and extent of regulatory policy implementation in the future. The case has been made that reducing the regulatory state uncertainty of policy mixes will inherently mitigate the impacts of regulatory effect and response uncertainty, as it is a precursor to both of these forms of uncertainty. As such, the regulatory state uncertainty of the systems of policies in question can be treated as a form

of epistemic uncertainty due to the potential for reduction in the existence of greater knowledge. Further, it has been posited that this form of epistemic uncertainty can be quantified through the relative size of effective policy space. As effective policy space is reduced, this form of uncertainty will also be reduced. This will be demonstrated considering the identification of effective policy space for the Aircraft CO<sub>2</sub> Standard. The purpose of doing so will be to address RQ4.1, which is reproduced below.

*RQ4.1: How can regulatory state uncertainty be reduced in the context of policy implementation?*

#### **5.6.3.1 Regulatory State Uncertainty in the Context of Current Policy Analysis**

As has been discussed throughout this document, the final state of policy is often unclear to regulated entities until the passing of the final standard. This is largely due to the political nature of policymaking, and the lack of a standardized framework on which to illustrate potential effective policy space with multiple policies implemented. As shown utilizing literature for the notional aircraft CO<sub>2</sub> standard, there is an indication of how the standard will be measured, but there is limited information regarding the final state of the standard. Subsequently, there is a great deal of uncertainty for aircraft manufacturers in the coming years regarding fuel efficiency regulations. This may produce instances of waiting to release new technologies until after the standard is established, in order to ensure their products will be available for purchase. Such delays, may create increased expenses for manufacturers, and will certainly result in delays in the release of more efficient vehicles.

### **5.6.3.2 Assessing Regulatory State Uncertainty in the Integrated Policy Analysis Process**

Despite this limitation in current policy analyses, the methodology for the integrated policy assessment techniques developed here allows for the determination of effective future policy states given applied value systems from policymakers. As an example of this capability, consider the notional aircraft CO<sub>2</sub> standards examined in 5.6.1.1, where the initial applied value system was based on a desired mitigation potential of 0.15 Gt-CO<sub>2</sub> by 2036. The application of this value system under the policy analysis framework established can be accomplished very early in the policy design process, and produces a more limited set of future policy states illustrated in Figure 5.28. This effective policy space can be easily conveyed to aircraft manufacturers, providing them with information regarding the full definition of feasible standards. Ultimately, this would allow manufacturers to bound the needed improvements in their products as more information and greater definition becomes available throughout the policy analysis process.

Further, as other values are added to the applied value system, such as a determination of maximum economic burden to aircraft manufacturers, the effective policy space is reduced, as seen in Figure 5.29. Subsequently, as the applied value system becomes more defined, so does the effective policy space. As such, the addition of alternative criteria, as well as increases in policy makers desires, has been shown to lead to reductions in the effective policy space. These reductions in effective policy space equate to a more limited set of future policy states, which provides useful information to

the regulated entities. Ultimately, this information, which is not typically produced under current cost-effectiveness approaches, produces greater information on the feasible regulatory states being considered. As such, it can allow entities, such as the aircraft manufacturers for the notional aircraft CO<sub>2</sub> standard, to plan accordingly for the expected standards in terms of both stringency and implementation timeframe. Subsequently, it stands to reason that the policy support process developed here inherently provides for the ability to identify and reduce the regulatory state uncertainty of the policies in question. This has been demonstrated implicitly through the analysis provided here, and is now explicitly stated.

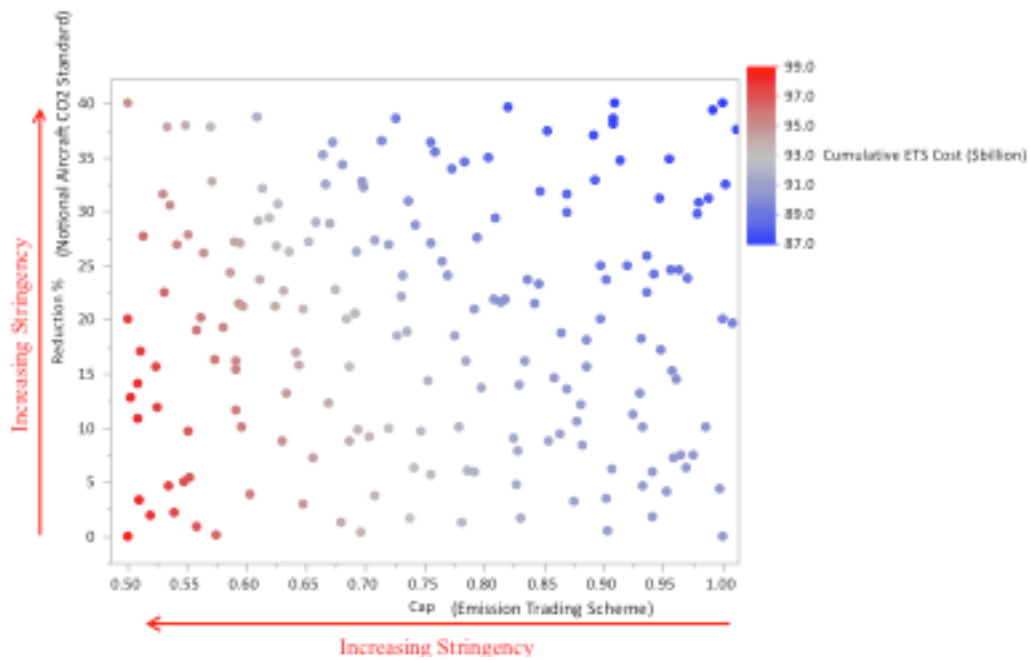
#### **5.6.4 Summary of Contributions to the Identification of Effective Policy Space**

Ultimately, the purpose of developing this integrated policy support process is for the systematic and quantitative identification of effective policy space considering multiple interacting policies earlier in the policy analysis and design process. It has been demonstrated that the policy analysis framework implemented for the study of these policies adequately captures the main effects in the U.S. NAS, as well as their interaction as a system-of-policy-systems (SoPS). Further, the ability to quantitatively capture the effects of aleatory uncertainty in the physical SoS has been demonstrated, and the potential for reducing regulatory state uncertainty has also been discussed.

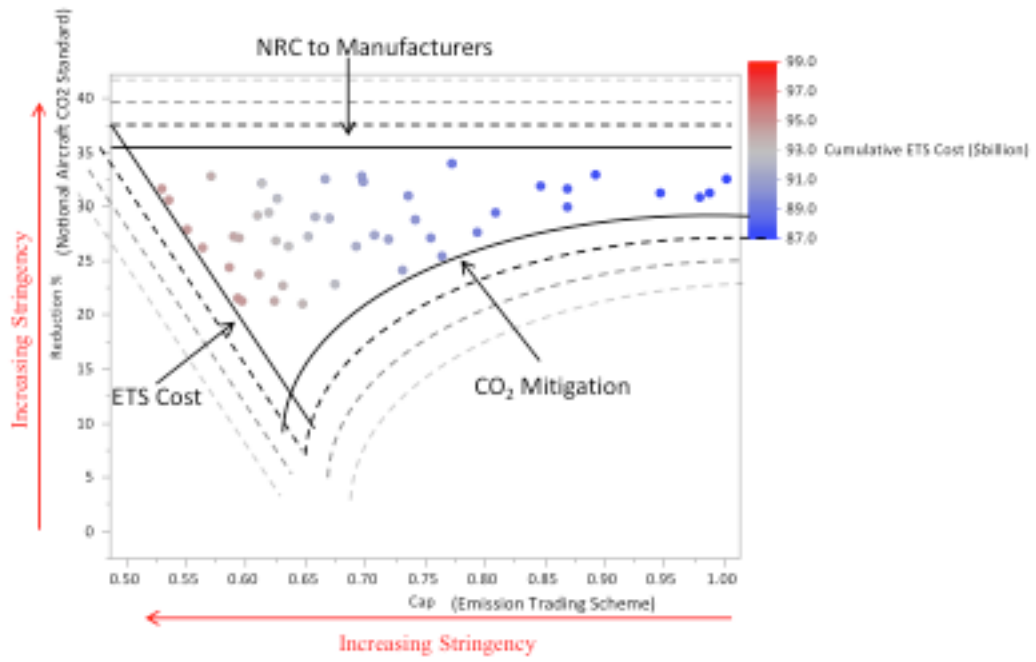
The primary advantage of the methodology employed here is that it formalizes a process for the study of multiple policies impacting a SoS concurrently, which provides

more information to policymakers earlier in the policy design process. Further, due to the systematic nature of this process, it provides traceability to the policy decisions made by policymakers, and ensures objectivity of the scientist providing policy analysis.

In the most general sense, it allows the scientist to fully populate the policy alternative space in an objective manner, so that the policymaker can subjectively apply value systems, going from policy alternative space (Figure 5.35) to effective policy space (Figure 5.36).



**Figure 5.35: Notional Policy Alternative Space**



**Figure 5.36: Notional Effective Policy Space**



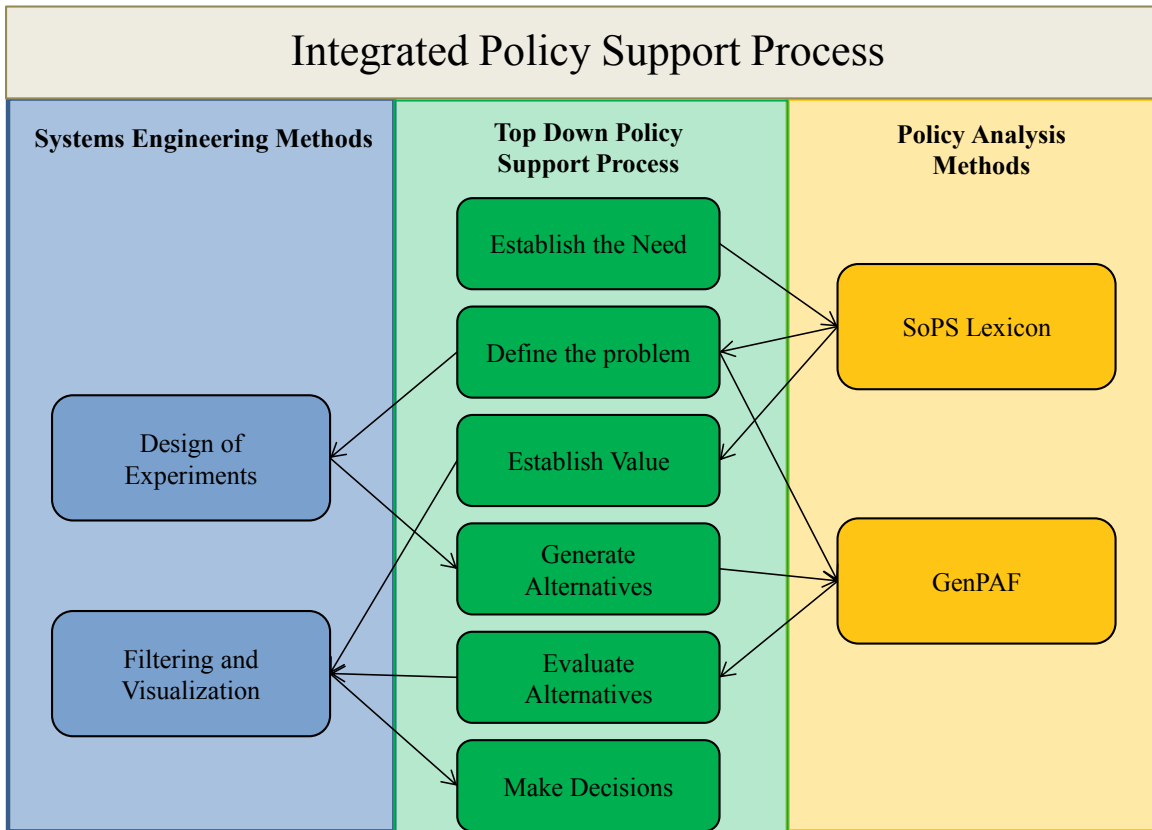
## **CHAPTER 6**

### **CONCLUSIONS AND FUTURE WORK**

As concern over the release of anthropogenic greenhouse gases continues to grow throughout the world, so too will our reliance on regulatory policy to induce behavioral and technological changes that can ensure the sustainability of our activities. This fact is well recognized in the global aviation community, and has led organizations such as ICAO to call on world member states to begin to address the climate change concerns associated with aviation through the identification and selections of baskets of policy measures. While this proactive approach to create binding policy agreements throughout the world is a promising sign of a strong commitment to create sustainable behaviors in aviation, there has been little guidance on how each member state should determine their respective baskets of measures. Further, there has been no established framework on which to evaluate and bring transparency to the submitted National Allocation Plans, and as a result, it is unclear whether the submitted regulatory policy measures will meet the goals for each region. This has ultimately created an atmosphere of ad-hoc policy decision making in the context of a highly complex system-of-systems (SoS), where policy is typically pursued one at a time even if there are known policy interactions.

In order to address the inevitable shortcomings associated with this web of policymaking in a complex SoS, a top down integrated policy support process has been formalized based on research in the product and process design fields. This integrated policy support process provides the ability to systematically analyze multiple

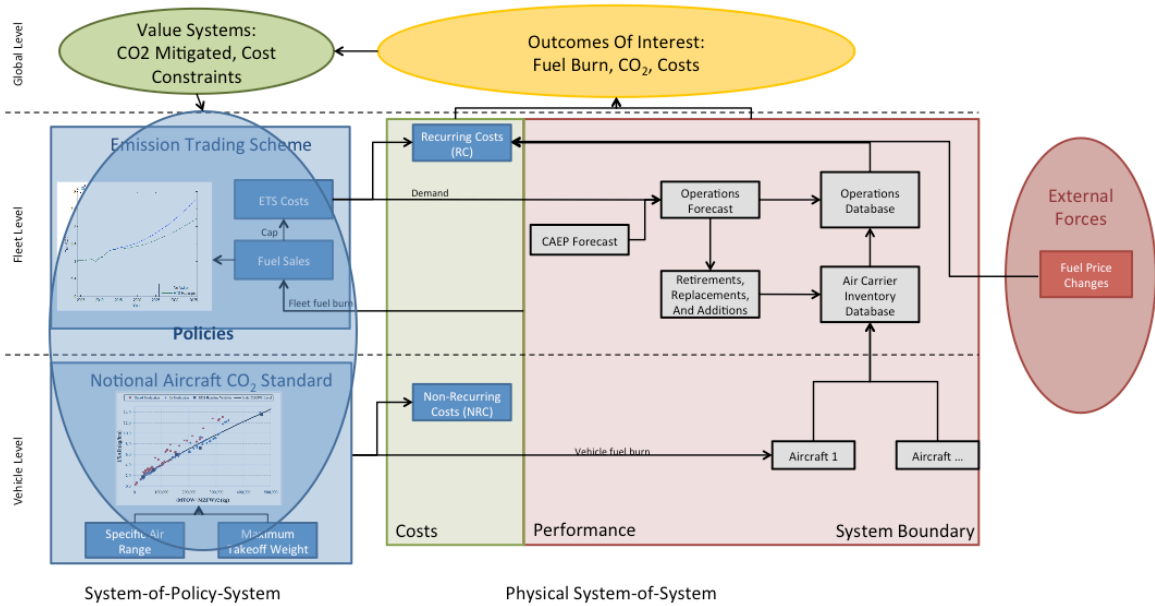
concurrently implemented policies in a holistic manner. It has been shown that concurrent policy analysis must be done in the context of the air transportation SoS holistically, as the policy implications are not additive and may have secondary effects on one another. Further, this formalized process brings traceability to the policy decisions and assumptions used to reach those decisions. Finally, the primary contribution of this research is the ability to identify and visualize areas of effective policy space. This policy support process can be visualized as shown in Figure 6.1.



**Figure 6.1: Integrated Policy Support Process**

As can be seen in the representation of the integrated policy support process, this systematic methodology for effective policy space identification integrates a number of

established systems engineering methods with developed policy analysis methods. These policy analysis methods are ultimately based on existing literature within the regulatory policy field, however, significant modification has been necessary to enable their use in the context of complex SoS problems, such as that posed by commercial aviation. The main contributions in the policy analysis field established by this research are the development of a lexicon that can be used to describe policy in the context of SoS, or as has been termed here, system-of-policy-systems (SoPS). Additionally, applicable policy analysis frameworks have been researched and modified for their inclusion in the study of multiple regulatory policies that are planned to be concurrently implemented in a physical SoS. This expanded policy analysis framework is largely based on prior research and has evolved herein as the GenPAF policy analysis framework. It has been shown to be sufficient in regards to concurrent policy implementation, and has been tested using a notional aircraft CO<sub>2</sub> standard and potential emission trading schemes in the U.S. NAS as a test case. The full implementation of these policies in the established policy analysis framework can be viewed in Figure 6.2. Based on the work presented in this document, it's expected that this policy analysis framework will be useful for expanded policy studies including other relevant GHG mitigation measures and also noise. Further, it's also expected that this framework can be applied to other industries throughout the world, and its application can extend beyond the civil aviation industry.



**Figure 6.2: Visualization of the GenPAF Policy Analysis Framework**

Ultimately, what has been demonstrated by the work presented in this dissertation is that areas of effective policy space can be identified through the application of value systems on policy alternative space. By providing a systematic method for populating and down selecting the policy alternative space the objectivity of the scientist can be maintained. Further, insights regarding the value systems of policymakers can be made readily apparent through the visualization of the policy mix selected in the context of the effective policy space. It is anticipated that this methodology, or something similar, can help formalize policymaking for organizations like ICAO, as well as other regulatory bodies throughout the world.

## 6.1 Summary of Contributions

In addition to providing the ability to identify effective policy space, the research conducted for this dissertation also provided a number of contributions to policymaking

for commercial aviation and beyond. These contributions to the regulatory policy and civil aviation fields are a result of the research objectives outlined in this document. As a reminder, there were four main research objectives, which include:

1. Quantitatively assessing regulatory policy in the context of an acknowledged system-of-systems (SoS).
2. Demonstrating the ability to assess the concurrent implementation of multiple policies throughout a SoS.
3. Objective identification of effective policy space.
4. Reducing the regulatory uncertainty, and quantifying other forms of aleatory uncertainty in the presence of multiple regulatory policies.

For each of these research objectives, associated research questions and hypotheses have been provided. Further, the results of attempting to answer these research questions have been identified through experimentation of a notional aircraft CO<sub>2</sub> standard and emissions trading schemes in the U.S. NAS. To provide a summary for the reader, the research questions and corresponding findings will be reintroduced here.

In order to provide an understanding of the main effects of the two policy options considered, the ability to quantitatively assess these policies in the context of the U.S. NAS was ultimately desired. This has been accomplished through the implementation of a cost-effectiveness model of the U.S. NAS, and specific policy implications have been mapped using the XPIROV policy analysis framework. The details regarding the implementation of these policies can be found in Chapter 4 and Chapter 5 of this document. These research efforts are aimed at addressing the first research objective, and as such the following research question was originally posed.

*RQ1: What are the impacts to the U.S. NAS of a new certification standard or a trading scheme in isolation?*

Through detailed analysis of the implementation of these policies in isolation, the primary effects of each have been identified. It has been shown that the notional aircraft CO<sub>2</sub> standard primarily affects the efficiency of individual aircraft available to air carriers, and thus the fleet efficiency can be improved. As a result, these standards produce quantifiable reductions in CO<sub>2</sub> emissions without impacting demand. Despite the mitigation potential of such measures, they have been shown to be unable to stabilize emissions, and can ultimately result in large non-recurring costs to aircraft manufacturers that may not be economically viable. The implementation of emission trading schemes have also been shown to induce reductions in CO<sub>2</sub> emissions, although from a different mechanism than the notional aircraft CO<sub>2</sub> standard. The ETS tends to create a real price for CO<sub>2</sub>, which is passed onto consumers, thereby reducing demand. It has been shown that the ETS produces new equilibrium demand values, and that there may be disproportionate effects based on air carrier types (ie. low cost carriers or legacy carriers). Additionally, it has been shown that these ETS create induced costs to air carriers that can be in the billions of dollars depending on the market price of emissions allowances, however, they have no measurable impact on aircraft manufacturers when implemented in isolation. Finally, the exploration of these policies in isolation also revealed that ETS have greater CO<sub>2</sub> mitigation potential than a notional aircraft CO<sub>2</sub> standard depending on the level of costs incurred.

With an understanding of the main effects of each of these policies in isolation, it was then desired to understand the impact of concurrent implementation of these policies as a notional basket of measures. This has been deemed necessary due to the fact these baskets of measures are meant to be a whole that is greater than each policy in isolation. As such, policy mixes consisting of the notional aircraft CO<sub>2</sub> standard and emission trading schemes have been tested concurrently in the U.S. NAS in order to address the second research objective. More detailed considerations regarding the concurrent implementation of multiple policies in the U.S. NAS is provided in Chapter 5 of this document. Conducting this research was ultimately aimed at addressing RQ2, which is reproduced below.

*RQ2: How will the combined effect of these policies differ from their implementation in isolation?*

It has been shown that the implementation of multiple policies concurrently in the U.S. NAS can be accomplished through the utilization of the expanded GenPAF policy analysis framework. The results of this implementation show that there are secondary effects that produce interaction between the two policy options that would not be evident if the policies were to be considered in isolation. The primary interaction of these policies stems from the ability of the notional aircraft CO<sub>2</sub> standard to improve the efficiency of fleets operating in the U.S. NAS, which lessens the impact to consumer demand reduction impact of potential emission trading schemes. It was shown that this impact to demand in the presence of multiple policies can be quantified and compared against emission trading scheme policies in isolation. Further, it has been shown that through the

concurrent implementation of these policies it is possible to achieve CO<sub>2</sub> mitigation in a more fair and balanced way economically than through either policy in isolation. This is due to the fact that these policies impact different market actors in the U.S. NAS, and the concurrent implementation of them produces more distributed policy induced costs than considering either in isolation.

Given the ability to implement these policies concurrently, and an understanding of the inherent tradeoffs in doing so, the ability to use this analysis for the objective identification of effective policy space was ultimately desired. This third research objective is the primary contribution of this dissertation, and is viewed as a unique contribution to policy analysis and design. In order to address this research objective, systems engineering methods are employed to fully populate the policy alternative space, and the expanded GenPAF policy analysis framework is employed for experimentation. The results of these experiments are then filtered to produce estimates of effective policy space, which is shown to be a novel approach to cost-effectiveness analysis. For a more detailed discussion regarding the implementation and identification of effective policy space, the reader is referred to Chapter 5 of this document. Ultimately, the purpose of conducting this research was meant to address RQ3, which is reproduced below.

*RQ3: How can this knowledge of a policy tradeoff be used to help meet goals, such as those established under the Kyoto Protocol?*

The results of populating the policy alternative space through Monte Carlo Simulation and filtering to identify areas of effective policy space reveals the inherent



tradeoffs that occur due to desires for environmental and economic sustainability. It has been shown that identifying areas of effective policy space in this manner provides policy makers with the ability to dynamically change their desires to see the impacts to effective policy mixes in real time. This provides greater insights into policy tipping points, and the inherent tradeoffs of the policies themselves. Further, the final policy mix selected by policy makers can be visualized in the context of all other effective policies to provide greater insights regarding the applied value systems of the policy makers. This level of traceability for policy analysis and design is entirely unique to this policy support process, and is anticipated to be the greatest contribution of this work.

Finally, due to the fact that we live in an uncertain world, and there are deep uncertainties associated with the policies themselves, it was desired to be able to quantify and potentially reduce the forms of uncertainty present in this problem. As identified in Chapter 2 of this document, the primary forms of uncertainty inherent to this type of problem are the regulatory uncertainties associated with the policies, as well as the aleatory and epistemic uncertainties associated with the physical SoS. It has been argued that the regulatory uncertainty associated with these policy mixes can be reduced through quantification and reduction of the regulatory state uncertainty, which is measured through identification of effective policy space. Further, it has also been shown that quantifying the effects of aleatory uncertainty can be accomplished through the expanded GenPAF policy analysis, and is demonstrated through considerations of fuel price volatility in the context of potential notional aircraft CO<sub>2</sub> standards. A more complete discussion regarding the assessment of these forms of uncertainty is provided in Chapter

5 of this document. Due to the fact that the regulatory uncertainties associated with policy, and aleatory uncertainties inherent in the physical SoS are unique, two separate research questions were posed, and are reproduced below.

*RQ4.1: How can regulatory state uncertainty be reduced in the context of concurrent policy implementation?*

*RQ4.2: How can specific forms of aleatory uncertainty be quantified in the presence of regulatory policy for commercial aviation?*

In conducting this research, it has been shown that the regulatory state uncertainty of these policy mixes can be quantified and bounded through the identification of effective policy space. The area of effective policy space provides a good indication of likely policies to be implemented and, as such, gives a good representation of the possible future regulatory state. Further, it has also been demonstrated that the regulatory state uncertainty can be reduced as effective policy space is reduced. This is typically accomplished through the application of value systems to the problem, and further reductions can occur in the presence of greater desires for CO<sub>2</sub> reduction or reduced economic impacts to aircraft manufacturers and air carriers.

In addition to addressing the regulatory uncertainties of the policies themselves, the GenPAF policy analysis framework has been demonstrated to be capable of quantifying the effects of aleatory uncertainty inherent in the physical SoS. This is accomplished in this research through analysis of fuel price volatility in the presence of notional aircraft CO<sub>2</sub> standards. It has been shown that the impact of changing fuel price

has the potential to alter the relative contribution of fuel cost to overall direct operating costs for air carriers. In the presence of notional aircraft CO<sub>2</sub> standards, this effect can alter the overall direct operating costs due to the relative change in increasing capital costs and reduced fuel costs. As has been shown, at the assumed fuel price of \$3/gallon, all potential stringency options tested result in a reduction of the recurring costs for air carriers as fuel cost savings outpace increases in capital costs. However, this result is dependent on the assumed fuel price, and much lower fuel prices reveal the potential for increased capital costs to outpace reductions in fuel costs. Quantifying this variability is deemed important for a complete understanding of the policy implications, and has been successfully demonstrated in this document.

Ultimately, the integrated policy support process pictured in Figure 6.1 has provided the ability to address each of these research objectives and associated research questions. As such, it is anticipated that this formalized process for policy alternative space generation and effective policy space identification can play a crucial role in the systematic identification of effective baskets of measures for CO<sub>2</sub> mitigation policy in civil aviation throughout the world.

## **6.2 Future Work**

As with any problem of this magnitude, there are a number of avenues upon which this research can be expanded and improved. Discussing all possible areas of improvement and expansion is obviously prohibitive, however, there are a number of improvements and additional studies possible in the framework developed that will likely

lead to greater insights regarding concurrent policy implementation. The most influential areas of future work, as anticipated by the author, will be discussed briefly here.

### **6.2.1 Expansion of the Cost-Effectiveness Environment of the U.S. NAS**

The most obvious, and potentially relevant, area of improvement for this type of policy analysis is in the expansion of the simulation environment developed for the U.S. NAS. As has been stated in Chapter 4, only a subset of the air carriers operating in the U.S. are represented in the developed simulation environment. As such, it is currently not possible to assess the impacts to smaller air carriers that may implement much different organizational strategies than the large carriers considered. Including smaller air carriers can be accomplished through a similar methodology employed for the large air carriers considered.

Further, only aircraft specific to the air carriers included are represented in the current modeling environment. This reduced set of aircraft provided ease of implementation, but is not representative of the entire aircraft fleet that exists. As such, the aircraft included in the simulation environment can be expanded through estimates provided by other aircraft level simulation environments. This expansion of available aircraft would likely provide greater insights into more specific implications of the notional aircraft CO<sub>2</sub> standard. Additionally, a consideration should be given to the impact to the specific aircraft manufacturers so as to not overburden one company versus another.

Finally, it should be noted that the only emissions species included in this study is the CO<sub>2</sub> resulting from aircraft fuel consumption. Due to the fact that the baskets of measures identified through the process are meant to holistically address the environmental concerns of civil aviation, it seems relevant to include considerations of other emissions, such as NO<sub>x</sub>, and also noise. This can be accomplished by establishing surrogate models for other emissions species and noise and then utilizing them directly in the modeling environment to produce estimates of fleet emissions and population exposure to different noise levels. The process by which the vehicle level surrogates can be mapped to fleet and global effects would likely be similar to that employed for fuel burn estimation. Whereas the noise assessment would require a different approach, for which other research has been conducted to reduce computational time for assessments similar to those conducted herein.

### **6.2.2 Improved Technology and Cost Forecasting at the Aircraft Level**

In addition to expanding the considerations of the simulation environment, there are also a number of improvements that can be made to the existing modules discussed throughout Chapter 4. The most influential improvements would likely come from further research regarding technology and cost forecasting. As aforementioned, all aircraft technology forecasting was inherently normative, and no specific technologies have been considered. As such, the application of the value systems are based on gross estimates of technical feasibility and economic viability in the absence of bottom up

technology forecasting. This can be improved through the consideration of specific technologies in the future to bound the technical feasibility of a future aircraft CO<sub>2</sub> standard. There is a great deal of research regarding technologies and their impacts at a vehicle level from organizations, such as IATA, that can be used for this purpose.

Further, both the non-recurring cost incurred by aircraft manufacturers and vehicle price are estimated based on normative forecasting through the notional aircraft CO<sub>2</sub> standard. While research has provided estimates for these costs used in the development of cost estimating relationships, there is a lack of realism inherent in these estimating techniques for a number of reasons. For the non-recurring cost estimates, this is largely due to the fact that no specific technologies are considered. As such, these estimates can likely be improved through greater understanding of future technology packages. Estimates for vehicle price can be improved through additional considerations not included in the developed simulation environment. While price is market driven, factors such as production quantity and schedule should also be considered in determining price, as well as the associated cost to aircraft manufacturers, which is currently not linked.

### **6.2.3 Inclusion of Other Relevant CO<sub>2</sub> Mitigation Policies**

While the policy support process has been demonstrated using the notional aircraft CO<sub>2</sub> standard and emission trading schemes in the U.S. NAS, there are a number of other policies relevant to CO<sub>2</sub> mitigation that could also be included. These have been discussed at a high level in Chapter 2 of this document. Typically, they would fall into

other command and control or market based approaches to CO<sub>2</sub> mitigation. The most relevant policies however, would likely be environmental levies in the form of fuel taxes. While not explored here, these fuel taxes would likely induce behavioral changes similar to emission trading schemes. Further, their implementation would be quite similar to emission trading schemes in terms of consumer demand considerations, and as such, implementation of such modules could occur with less development than other policies. Finally, considering environmental levies may also provide insights regarding the robustness of different policy mechanisms aimed at reducing consumer demand. While no research is provided to support this claim, it is believed that the variability of environmental levies would be less than for ETS due to a more strict control of fees, whereas emission trading scheme impacts have been shown to be highly dependent on the market price of emissions allowances, which can be quite volatile.

#### **6.2.4 Implementation of Policy Phasing**

Finally, due to the fact that the purpose of this dissertation was to demonstrate the ability to identify effective policy space in the presence of multiple policies for a complex SoS, only static policies have been considered. This means that for all of the experiments analyzed a single policy is implemented, and no updates are considered throughout the simulation. While this method of employment was effective at addressing the motivation of this dissertation, it is quite divergent from the reality of policy making. As has been stated, CAEP works on alternating 3 year cycles, and policies in place are continually updated. As such, an interesting consideration that is not accounted for in this dissertation is the implications of policy phasing. Here policy phasing is taken to mean the

implementation and updating of policy throughout time. It's unclear what the effects of effective phasing of policy may look like, but such approaches may produce behaviors that do stabilize emissions, which were not seen in this work. In a sense, the study of effective phasing strategies for policies such as the notional aircraft CO<sub>2</sub> standard and emission trading schemes may serve as the basis for other dissertations in the future.



## **APPENDIX A**

### **CAFE STANDARDS**

The Corporate Average Fuel Economy (CAFE) standards for automobiles and light trucks in the U.S. have provided a real world experiment exuding the benefits and challenges of this type of policy mechanism. Some basic insights from the results of these standards will be briefly discussed here, in order to provide context for discussions on command and control policy for commercial aviation.

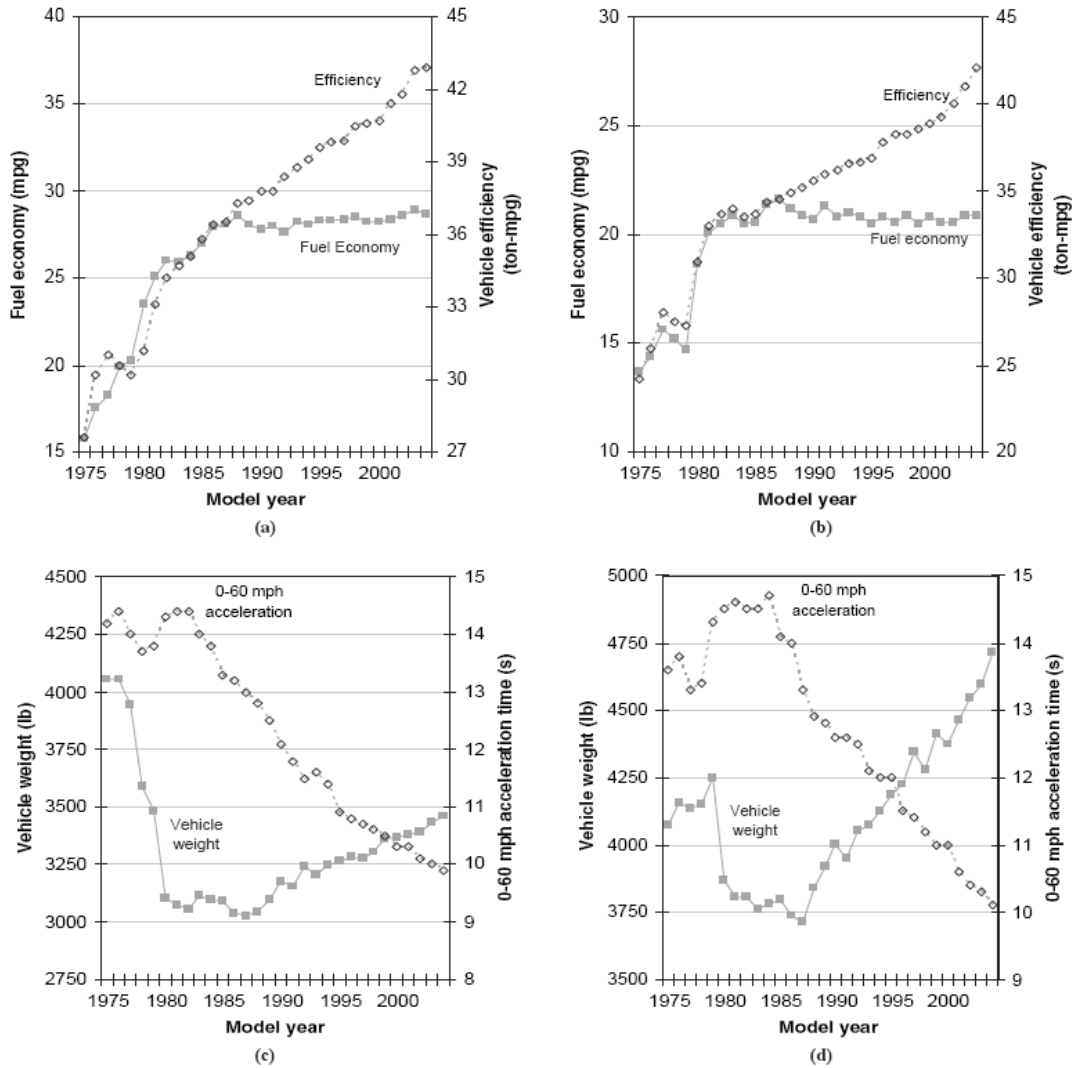
#### **Impacts of Corporate Average Fuel Economy Standards**

Eight years after the CAFE standards went into effect, fuel consumption per vehicle had dropped by 20%; a stunning and rapid energy policy and climate change success [191]. U.S. national gasoline consumption dropped overall, despite an increasing number of total vehicles on the road. Only after 1992, as the average length of a vehicular drive went up, and while more cars were added to the road, did overall fuel efficiency decline [191]. In large part, this is due to an overall trend throughout the life of CAFE standards through which they have become less binding on new vehicle attributes [192]. From 1975 to 1980 the effect of CAFE standards and efficiency technologies was to increase fuel economy by 4.2 mpg (55% of total fuel economy change), with weight reductions contributing another 3.5 mpg (45% of total fuel economy change) to the increase in fuel economy [192]. However, during the period from 1980 to 1987, efficiency technologies for cars were almost entirely responsible for fleet fuel economy increases. This period coincides with the widespread deployment of the automatic

transmission, torque converter lock-up, port fuel injection, and front-wheel drive technologies [192]. These advances that led to an “all-efficiency” approach toward fuel economy signify that either automobile manufacturers and suppliers had the research and lead time to ramp up production of new drive train technologies, or that consumers’ appetite for smaller vehicles had diminished with lower fuel prices and therefore manufacturers had no choice other than to meet CAFE standards via efficiency technologies [192]. Despite this early trend of increasing fuel economy, since 1985 the fuel economy of light-duty vehicles has not increased, and in recent years has actually been on the decline as consumers are overwhelmingly favoring greater performance and increased weight over fuel savings [193]. The more recent period in CAFE standards history represents a period with comparatively little movement in the standards and fuel economy, as can be readily observed in Figure A.1 below [192].

At the time of its passage, the CAFE regulations faced criticism for causing economic harm to domestic automobile manufacturers, but a 2002 National Research Council report found little evidence of such [30]. However, the rising tide of miles traveled per drive ultimately overwhelmed the benefits of an improved standard; as total vehicular miles traveled in the United States “increased by almost 700 million miles, or 25 percent, during the 1990s [194].” Additionally, the standards were never kept updated to match technical advances in vehicle performance – advances that allowed for quicker acceleration, and higher maximum vehicle speeds, and as a result, efficiency gains were used to satisfy customer desires over enhanced fuel economy. It has only been in recent years that the EPA has been challenged by President Barak Obama to update the

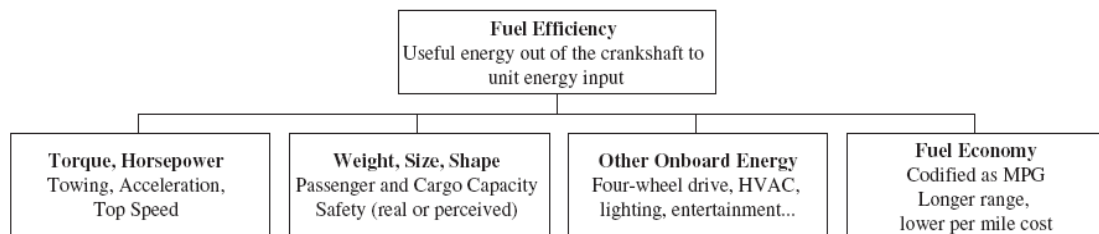
standards and once again enforce more binding regulations on automobile manufacturers [195].



**Figure A.1: Fuel Economy and Other Attributes for Light-Duty Vehicles, 1975-2004: (a and c) passenger cars and (b and d) light trucks [192]**

Despite the relative stagnation of vehicle fuel economy in both passenger cars and light-duty trucks, vehicle fuel efficiency has been continually rising since the implementation of CAFE standards, as is observed in Figure A.1 above. As such, it is

important to keep in mind the distinction between fuel efficiency and fuel economy. To illustrate this distinction Figure A.2 is provided below, where it is shown that fuel efficiency can be applied to a number of vehicle performance attributes including fuel economy. However, as consumers of automobiles exert their desire for increased performance and safety, and as CAFE standards become less binding, manufacturers have become more likely to apply fuel efficiency gains to meet customer demand over improved fuel economy. Subsequently, it has become quite apparent in our most recent history that technological innovation in vehicles is not lagging, but is certainly not being used to improve vehicle fuel economy [192]. These recent trends are the result of a number of policy and market failures that ought to be addressed in the context of future CO<sub>2</sub> policy, especially in light of the upcoming regulation of civil aviation.



**Figure A.2: Fuel Efficiency Areas of Application [196]**

### **Policy Failures of CAFE Standards**

The CAFE regulations themselves set minimum miles-per-gallon requirements for automobiles and light truck manufacturers based on the weighted total vehicle sales. Thus, total output must be at or over the minimum standard, at whatever configuration of automobiles a certain manufacturer may choose [197]. Furthermore, an individual manufacturer can be fined for shortcomings in their corporate average fuel economy, or,

conversely, can present a plan to the Secretary of the Department of Transportation for future mpg-deficit-fulfilling reductions “within the next three model years [197].” Unfortunately, this framework has been undermined by the fact that these standards, divided for two vehicle types, critically allowed light trucks to fall under less stringent fuel economy standards and heavy duty vehicles to avoid any regulation at all. Indeed, the original CAFE standards were written when the personal use of vehicles like the *Hummer* was literally “inconceivable” to the regulators [191]. Thus, as usage patterns shifted towards greater personal use of the light truck class, the overall average fuel economy of the US domestic vehicle fleet declined [198]. This problem has been further expounded by the fact that the distinction between passenger cars and light trucks has become increasingly fuzzy [199], representing one of the most significant policy failures of CAFE standards. It can reasonably be argued that this failure has led to adverse environmental consequences through a shift in fleet mix that may persist for many years after the more stringent CAFE standards for light and heavy duty trucks take effect in the 2012 to 2016 timeframe [195].

A number of additional features of CAFE standards have also contributed to the policy failures and subsequent market disruptions endemic in the automotive industry. One notable example of a failure of CAFE standards comes about through the treatment of vehicle fuel economy calculations for dedicated alternative fuel vehicles and dual-fuel vehicles. The fuel economy of these vehicles is greatly inflated to account for the lower carbon content of alternative fuels that could be used. While these alternative fuel and dual fuel vehicles would lead to lower CO<sub>2</sub> emissions if they were used as intended, in

reality dual fuel vehicles are often run on only gasoline instead of an alternative fuel mix. Thus the fuel economy rating of the vehicle is artificially inflated without leading to lower emissions [199].

Adding to this problem of greater emissions than predicted through the standard is the fact that U.S. EPA methods of measuring and quantifying vehicle fuel economy do not capture patterns of actual usage, and their figures accordingly exaggerate the efficiency ratings of vehicles across the board [191]. The test cycle with which new cars are required to comply is unrealistic of real driving and too predictable, allowing car manufacturers to design cars to pass tests yet produce higher levels of pollution when driven on the road [200]. This is largely due to the slow speeds and low acceleration that the test cycle requires, which is not reflected by typical driving habits. This cycle beating can result in high emissions of carbon monoxide (CO), hydrocarbons (HC), and ammonia (NH<sub>3</sub>) [200].

Finally, through no fault of CAFE standards, there is another serious market failure at work that must be considered in this discussion. This failure is due entirely to consumer behavior, where there is a lack of rational decision making occurring during car purchases. For automobiles, the National Research Council's evaluation of CAFE standards suggests that consumers may only consider the first 3 years of fuel savings when considering the value of higher fuel economy, which understates the true economic value over the life of a vehicle by about 60% [201]. This undervaluing of fuel economy is likely a result of bounded rational behavior [201], in which a decision maker will accept an adequate solution over an optimal solution due to incomplete knowledge or competing

desires. Automobile consumers may not think it is worth the effort to fully investigate the true costs and benefits of higher fuel economy [201], and in addition may be persuaded through manufacturers' marketing that is unrelated to fuel economy concepts. This represents a serious problem that ought to be addressed for the future of CAFE standards, although will likely be less prevalent in the context of civil aviation.

### **Lessons for Civil Aviation**

Many of the lessons CAFE standards offer for civil aviation are quite clear. The certification framework should directly address the objectives of the regulatory policy, especially with a regulation that is structured to be in force for a decade or more in a technologically dynamic industry. The interdependent impact of additional features of a regulation, such as the dual fuel credits under CAFE standards, should be understood in the context of the standard itself. The setting of a CO<sub>2</sub> regulation must have flexibility for revision or amendment built-in; for instance, ICAO should consider a mandatory trigger in any regulation that would require an assessment and re-authorization of the regulation on a frequent basis. Additionally, such revisions should remain squarely in the public eye, as CAFE standards have shown that when regulations are set with little public attention afforded them, regulators are more liable to succumb to political pressure from government and industry alike to create less binding rules.

Moreover, metric parameters must fit not just the technical capacity of an aircraft (or vehicle), but should follow patterns of actual use – an even more important criterion

for civil aviation, given the heavy usage and long life of each individual aircraft which is on the order of 25 to 30 years.

Finally, the market failure occurring due to bounded rationality on the part of consumers' needs to be addressed. Despite the fact that this phenomenon is readily observed in the automotive industry, it's well known that the entire civil aviation industry operates with the intent of generating profit, and subsequently business practices are much more likely to follow the neoclassical economic assumptions of rational decision making. As such, compliance mechanisms for this regulatory policy can be designed with greater certainty than has been seen in CAFE standards, and the market flaws resulting from bounded rationality in the automotive industry will likely be avoided in civil aviation even under stringent CO<sub>2</sub> emissions regulations.



## **APPENDIX B**

### **TRAGEDY OF THE COMMONS**

The idea of the tragedy of the commons was first introduced by the social scientist Garrett Hardin in his 1968 article in *Science* aptly titled “The Tragedy of the Commons” [72]. In this article the problem posed by population growth is introduced. Recognizing that population tends to grow exponentially while the world’s resources are finite, the ultimate end to our population growth will occur as a result of a lack of resources to support the world’s population [72]. In this way we can view the earth’s resources as the commons, and the tragedy occurs as the philosopher Whitehead poses in the “...inevitableness of destiny [that] can only be illustrated in terms of human life by incidents which in fact involve unhappiness. For it is only by them that the futility of escape can be made evident in the drama [202].” While it may be argued that tragedy for the world’s people is not inevitable, and many such as Adam Smith believe that an individual who works towards his own gain is led by an “invisible hand to promote the public interest [203]”, there is a wealth of evidence that disproves this claim.

For Hardin, this evidence came in the form of an 1833 pamphlet produced by the English mathematician William Forster Lloyd, who described the ruin of herdsman acting as rational beings in their own self-interest throughout small villages [204]. In this example, the tragedy of the commons unfolds by considering a pasture open to all, where each herdsman can keep his cattle. In assuming social stability of the community utilizing this common, the inherent logic of the commons becomes each herdsman acting as a rational being seeking to maximize his own gain. In doing so, the herdsman considers the

utility associated with adding another head of cattle to his own flock, which will have an associated positive and negative utility. The positive component of the utility is the increment of adding an animal, and since the herdsman will receive all the profits from that animal it can be said to be nearly +1. The negative component of the utility will be associated with overgrazing created by the addition of that animal; however, since the effects of this overgrazing are shared by all herdsmen utilizing the commons it is only a fraction of -1 [72]. In this way, the rational herdsman will always add another animal, at least until the commons becomes so overgrazed that it cannot support any animals. This specific case of the tragedy of the commons as a “food basket” has been well documented, and is ultimately what led Hardin to originally argue that, “ruin is the destination toward which all men rush, each pursuing his own best interest in a society that believes in the freedom of the commons. Freedom in a commons brings ruin to all [72].”

### **CO<sub>2</sub> Pollution as a Tragedy of the Commons**

While the emission of CO<sub>2</sub> into our atmosphere is different than taking a resource out of the commons as previously discussed, it is viewed in Hardin’s essay as a reverse tragedy of the commons. That is, the tragedy results not from taking something out of the commons, but by putting something in that will ultimately “foul our own nest” [72]. Our atmosphere represents a pristine environment that can be viewed as the commons, which will be brought to ruin as we reach CO<sub>2</sub> concentrations that trigger catastrophic climate change events. This appears to be the recognition among policymakers in civil aviation in recent years, as there has been a strong push to stabilize CO<sub>2</sub> emissions from the aviation

industry. This recognition is a result of evidence within the aviation industry that the individual actors, airlines and manufacturers, acting rationally will lead to growing CO<sub>2</sub> emissions as the industry grows. While progress is measured in economic terms, the potential to bring ruin to our environment is a potential cost of that progress that does not enter the utility maximizing behaviors of the actors involved in the civil aviation industry.

This behavior in civil aviation, and realistically in most sectors of our industrialized world, is a result of similar utility calculations as those described previously for the herdsman. The rational man will find that his share of the cost of the pollutants discharged into the atmosphere is less than the cost of purifying or offsetting those pollutants [72]. Subsequently, as long as each actor behaves as an independent, rational, free enterpriser the result will be continually growing pollution, leading toward ruin for the environment. Due to the global nature of these problems, which will require governance at all levels of society, these types of problems represent some of the most important contemporary environmental challenges that have yet to be solved [29, 205, 206].

### **Addressing Tragedy of the Commons**

Given these tragedy of the commons problems, such as CO<sub>2</sub> mitigation, represent the most important current environmental challenges, a means of addressing these problems must be established. The original literature by Hardin outlines three paths forward, which can be summarized as the “do-nothing”, private ownership, and regulation approaches. Each of these approaches will be outlined briefly here for

completeness; however, it should be recognized that the approach being pursued in commercial aviation is that of regulation.

### **Do-Nothing Approach**

In this case, the system of interest is allowed to continue on a business as usual basis. Adam Smith's "invisible hand" is relied upon to bring controls to the system before ruin is inevitable [203]. While this view may be a popular one among free market capitalists, it has been well established that when costs are allowed to be externalized in a commons the end result will inevitably be ruin. As such, this approach is not advisable for problems such as CO<sub>2</sub> mitigation, as they've already been shown to fail.

### **Private Ownership**

Here, if resources are taken from the commons and put into the hands of private citizens it is reasonable to assume that their worth will be evaluated differently, and ultimately the resource will be better cared for. This is called out directly by Hardin when he states, "the tragedy of the commons as the food basket is averted by private property, or something formally like it [72]." These ideas regarding private ownership extend back to classic philosophers such as Aristotle who wrote in 350 B.C. in Politics that "what is common to many is least taken care of, for all men have greater regard for what is their own than what they possess in common with others [207]." Unfortunately, this answer to the tragedy of the commons is only feasible when the commons can be divided among specific individuals. As has been well established in this document, one of the greatest problems with CO<sub>2</sub> emissions is the global nature of the problem. Due to the fact that

GHG emissions mix throughout the atmosphere and cannot be traced to a single point source, our CO<sub>2</sub> problem cannot be addressed through this private ownership approach. This point is also identified by Hardin in his essay, as he identifies resources such as air and water, which cannot be “fenced”, as commons where private ownership will fail to prevent ruin [72].

### **Regulation (Coercion)**

In some of the earliest literature on tragedy of the commons, Hardin and Crowe, point to “forced coercion” as the only course of action to prevent ruin for global resources such as air and water [72, 143]. For resources that cannot be fenced, sustainability of the commons can only be achieved through coercive laws or environmental levies that make the cost of polluting more expensive than treating the pollutants [72]. This is certainly the case in civil aviation, as highlighted by a 2009 report by ICAO, which showed that emissions from international aviation are global in nature and cannot be associated to any national boundaries, thus assigning responsibility for CO<sub>2</sub> emissions is difficult to implement or enforce [10]. In these instances, the goal of regulation is not to prohibit specific sources of pollution, but to internalize the costs associated with polluting the atmosphere. In this way, there is not a need to forbid entities in civil aviation from conducting their business, there is only a need to make it increasingly expensive to do so, such that the environmental concern is an equitable portion of their utility calculations. Hardin quite playfully states this as, “a Madison Avenue man might call this persuasion; I prefer the greater candor of the word coercion [72].” While it’s quite clear that coercive action must be taken in order to mitigate the

impact of anthropogenic CO<sub>2</sub> emissions from civil aviation, in this document all discussions on regulation will continue to be framed as regulatory policy as opposed to forced coercion.

## **APPENDIX C**

### **OVERVIEW OF EU ETS**

The European Union Emission Trading Scheme was initially implemented in 2005 through Directive 2003/87/EC, and is now touted as a reference point for most GHG emission trading schemes throughout the world [103, 208]. However, this important legislation was not created entirely originally, and it should be noted that it would not exist if it were not for the Kyoto Protocol, which is the “flagship measure” by which all member states of the EU will attempt to meet environmental obligations during the first commitment period from 2008 to 2012 [105, 209]. Despite this fact, the EU ETS is entirely independent of the Kyoto Protocol, and is just one measure aimed at helping meet the GHG reductions established there.

In many ways the EU ETS is a classic cap and trade system, however, there are a few important differences. First, the EU ETS implements an emissions cap that is decentralized in nature, meaning the cap is set for the EU as a whole, but each member state maintains its own trading system. Additionally, the cap that is outlined in the EU directive is actually a cap within a cap from 2008 on, in which each year there is a progressively more stringent cap set [105]. With that said, the EU ETS currently only includes emissions of CO<sub>2</sub>, and covers only a subset of the economy, the power sector for the first phases of trading and recently aviation [105]. Emissions allowances are issued within the EU annually, but are only valid to cover emissions in any year within the trading period. The only other credits allowed to count toward emissions are those created through the provisions of the Kyoto Protocol, specifically relating to the Clean

Development Mechanism (CDM) or Joint Implementation (JI). These credits are known respectively as Certified Emission Reductions (CERs) and Emission Reduction Units (ERUs) [105]. The flexible mechanisms of the EU ETS are outlined in the Linking Directive 2004/101/EC [115, 210]. Ultimately, the function of the EU ETS can be seen as 27 primarily independent trading systems that are in agreement to make their allowances commonly tradable, and they all adhere to agreed upon procedures to make the system functional [105]. In this way, the EU ETS operates very much like an “Acknowledged System-of-Systems” discussed previously.

For the EU ETS, there are two major components that must be understood, which are the cap setting and allocation of allowances, both of which are decentralized negotiation processes that reflect the political structure of the EU. These processes are outlined for each member state within the National Allocation Plans (NAPs), and are meant to address the goals set forth in the Kyoto Protocol [103]. In the cap setting process member states use differentiated criteria to produce caps between “lesser than business as usual” and a “path consistent with the Kyoto Protocol” [103]. For most NAPs, modest caps were initially set with a high dependence on projections into the future; however, it has been noted in literature that most if not all of the projections were largely inflated, which is an observed phenomenon in government forecasting [103, 211]. Subsequently, due to the modest cuts and inflated projections there tended to be a surplus of allowances, reaching levels of approximately 5% of total allowances, in the initial trading period [212]. This issue of over allocation due to modest cap setting will be analyzed more closely later in this section.



Allocation of allowances under a specified cap is typically based on a measure of overall productivity within an industry covered by the EU ETS [103, 105]. The allocation process itself though has been quite divergent throughout the member states in the EU, and since the start of trading has been shown to create allowance prices that can have an impact on investment decisions. Further, literature has noted that significant competition distortions may occur if they remain unchanged [103, 213]. Despite this fact, it has been proposed that these allocation issues may be avoided if member states base allocation on benchmarking, which is a process of determining the best industry practices and how all other practices score relative to this standard [103]. This benchmarking process has been used by some member states in phase 1 NAPs, namely in Germany, Denmark, Finland, Sweden, Netherlands, and Italy, where it was used to benchmark allocation either to new entrants or for fixed energy efficiency rates for energy production entities [103]. Still, the main issue that exists is due to the decentralized nature of the EU, in which benchmarking is occurring through the use of different metrics.

While the initial phases of the EU ETS include CO<sub>2</sub> emissions only from energy intensive industries in the European Union, in December of 2006 the European Commission released an initial proposal to include the airline industry in the EU ETS [102, 214]. Finally, on July 9, 2008 the European Parliament cast a final vote on the inclusion of aviation into the EU ETS, ultimately creating Directive 2008/101/EC where aviation activities within the EU ETS are specifically outlined [95, 102]. One of the main differences with aviation's inclusion in the EU ETS and other industries is the limited tradability of aviation allowances and liquidity of the EU ETS markets as a whole [115].

Despite this fact, under the directive agreed upon in 2008, the costs of inclusion will differ between airlines as a function of how fuel consumption per flight by route changes according to the fuel efficiency of the aircraft used, operational practices, and the overall quantity of passengers and freight carried [102, 111]. As such, it is hoped that this policy will result in more efficient airlines facing lower costs than their less efficient counterparts.

Since aviation activities are the focus of this dissertation, the specific requirements on the aviation activity will be briefly outlined here. Based on Directive 2008/101/EC, CO<sub>2</sub> emissions for air transport are capped at 97% and 95% of the average level from years 2004 through 2006 for the first and second trading years respectively. Thereafter, the cap will diminish to 21% below this level within the trading period from 2014 to 2020 [95, 102]. The other major design elements from this directive are outlined here [95, 102]:

1. Airlines operating within the EU will be included in the EU ETS as trading entities starting in 2012, including stopover airlines landing and departing from EU airports.
2. An emission cap for aviation in the EU will be implemented based on historical CO<sub>2</sub> emissions using the grandfathering approach based on average GHG emissions from 2004 to 2006. In 2012, carbon allowances will be fixed at 97% of those averages, and will increase to 95% in 2013.
3. Allowances will be distributed among airlines in proportion to ton-kilometers flown in the reference year, where the first benchmark period

will be 2010. After the first year, the benchmark period will be the calendar year ending two years before the start of the subsequent trading period.

4. The allocation methodology must be the same across all Member States. Additionally, a certain percentage of allowances will be granted for free, and up to 15% will be auctioned.
5. Certified emissions reductions (CERs) and emission reduction units (ERUs) from the Clean Development Mechanism (CDM) and the Joint Implementation (JI) of the Kyoto Protocol may be used up to 15% of an airline's EU ETS allocation in 2012. However, the use of credits tied to the Kyoto Protocol after this time is unclear.
6. The trading system will be open, allowing the airline sector to trade with all other sectors covered by the EU ETS.
7. A reserve will be established consisting of 3% of allowances in order to account for new entrants and fast growing airlines.

## **Purpose of EU ETS**

Given such a broad overview of the EU ETS and its directives, it's important to state explicitly the purpose of such a standard. Ultimately the purpose of the EU ETS is to set a price for carbon, thus internalizing the cost to output harmful GHG into our environment [103]. Further, it has been shown in both practice and literature that an emissions trading scheme, assuming there are significant allowance prices, can induce behavioral changes in the short and medium term and technological investments in the

long term, all while minimizing the competitiveness for affected companies, countries, and regions [106]. So, while the impact of the EU ETS on airlines and the global economy depends on the design of the scheme, if implemented properly, it is expected to constrain carbon emissions equitably throughout the aviation industry without significant market disruptions.

## **EU ETS Trial Period**

While it's unclear how the EU ETS will impact aviation activities since they are only now being included, the EU ETS has gone through two trial periods in the energy producing sectors of the European Union. Phase 1 of the EU ETS occurred from 2005 to 2007, while phase 2 was implemented from 2008 to 2012. The results of these trial periods have been documented in literature, and will be reviewed here.

### **Phase 1**

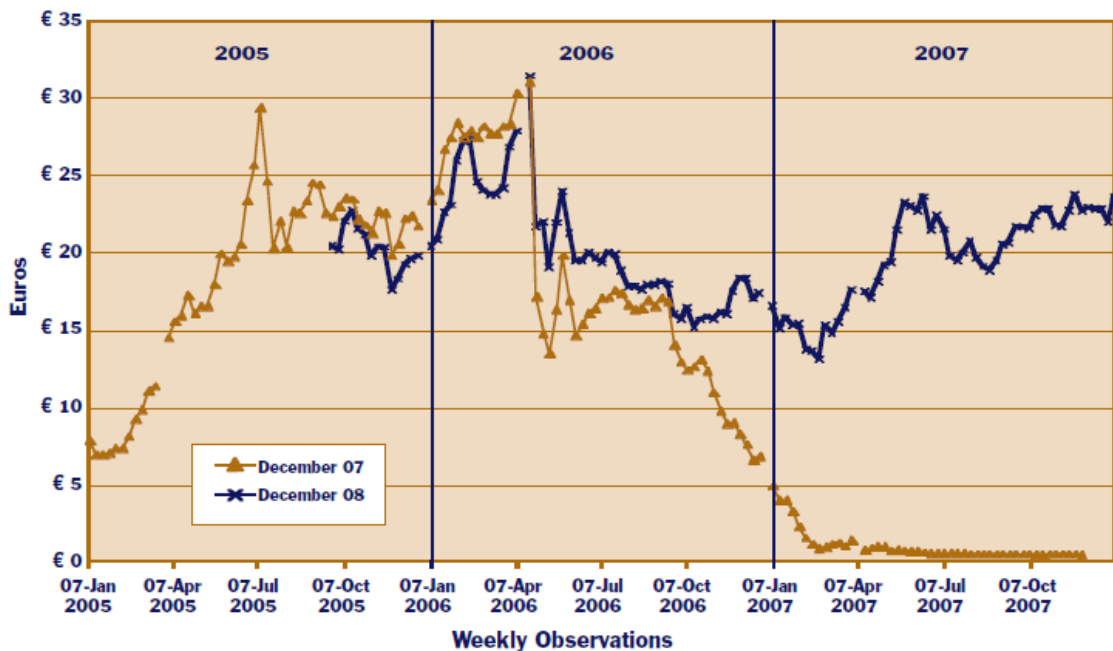
Before delving into the specifics of phase 1 of the EU ETS which occurred from 2005 to 2007, it should be noted that a number of “teething problems” were encountered which may have reduced the effectiveness of this policy during this time period [103]. The first issue was that a number of significant delays occurred regarding member state registries and National Allocation Plans (NAPs), which were late by more than a year in some cases [103]. In large part these delays were spurred by a need to adapt national laws to be consistent with definitions outlined in the Kyoto Protocol and EC directives. These teething problems were further aggravated due to a number of inconsistencies of energy installation definitions, as well as regional issues related to monitoring, reporting, and

verifying emissions [103]. Finally, it has been noted as well that insufficient operation of the CDM and JI programs also created unexpected problems for phase 1 of the EU ETS [103, 215].

With that said, the trial period implemented from 2005 to 2007 was ultimately motivated by the perception of a “performance gap” in the EU’s ability to meet commitments outlined in the Kyoto Protocol, as well as a recognition that experience would be necessary to successfully implement an EU-wide cap [105]. This recognition stems from the fact that while a cap and trade approach could guarantee a limit on EU emissions, the decentralized cap setting and allocation process was very different than any other cap and trade mechanism previously attempted throughout the world [216]. The most obvious counterpart to the EU ETS was the U.S. SO<sub>2</sub> cap and trade system, as aforementioned; however, under this system the cap and allocations were determined centrally through Congressional legislation, the registry was maintained nationally, and impacted entities reported directly to the U.S. Environmental Protection Agency (U.S. EPA) [105]. The NO<sub>x</sub> Budget Program ultimately came closer to replicating the structure of the EU ETS, however even there noted differences occur [217]. In the end, the decentralized nature of the EU ETS has been pointed to throughout literature as its most defining aspect to other cap and trade systems, as well as its most problematic [105, 218].

As noted previously, one potential benefit of a cap and trade system is that placing a single price on GHG emissions leads to the most cost effective attainment of emissions goals. Unfortunately this fact only holds true if the price of emissions allowances is high enough to drive favorable behavioral changes and technological

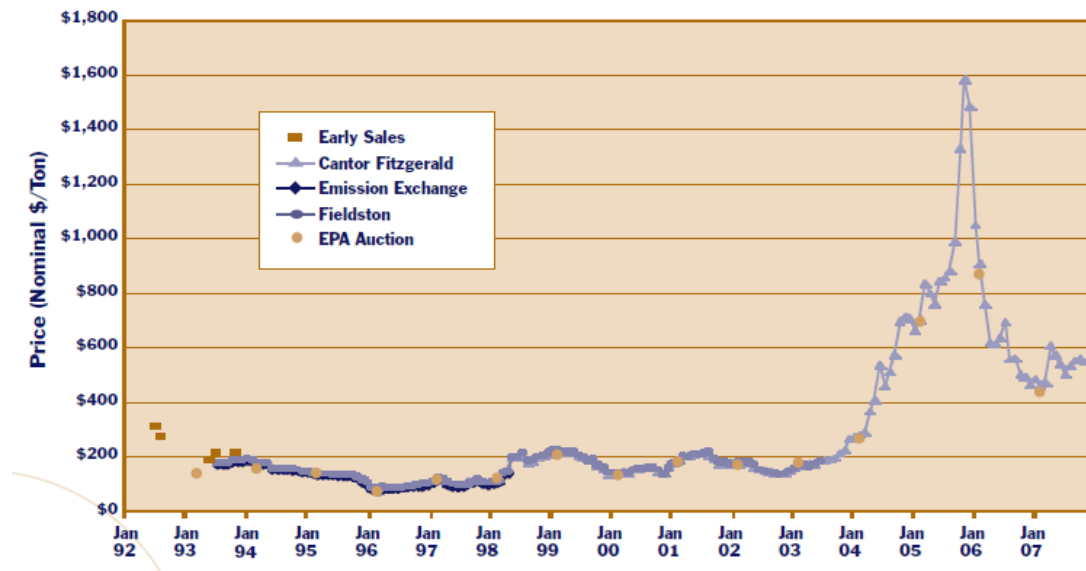
investment. In the EU, the European Union Allowance (EUA) prices showed in the first year of trading that this may not always be possible. One noted feature of the evolution of EUA prices is the drastic decline that occurred in April of 2006, where in less than a week prices fell from €30 to €20 for first period EUAs and then to €15 for second period EUAs [105]. This observation can be seen in Figure C.1. This drastic fluctuation in market price was attributed to the underreporting of 2005 emissions by a number of member states, which was a major contributor to the teething problems due to the decentralized nature of the EU ETS [105].



**Figure C.1: European Union Allowance (EUA) Price Observations (2005-2007) [105]**

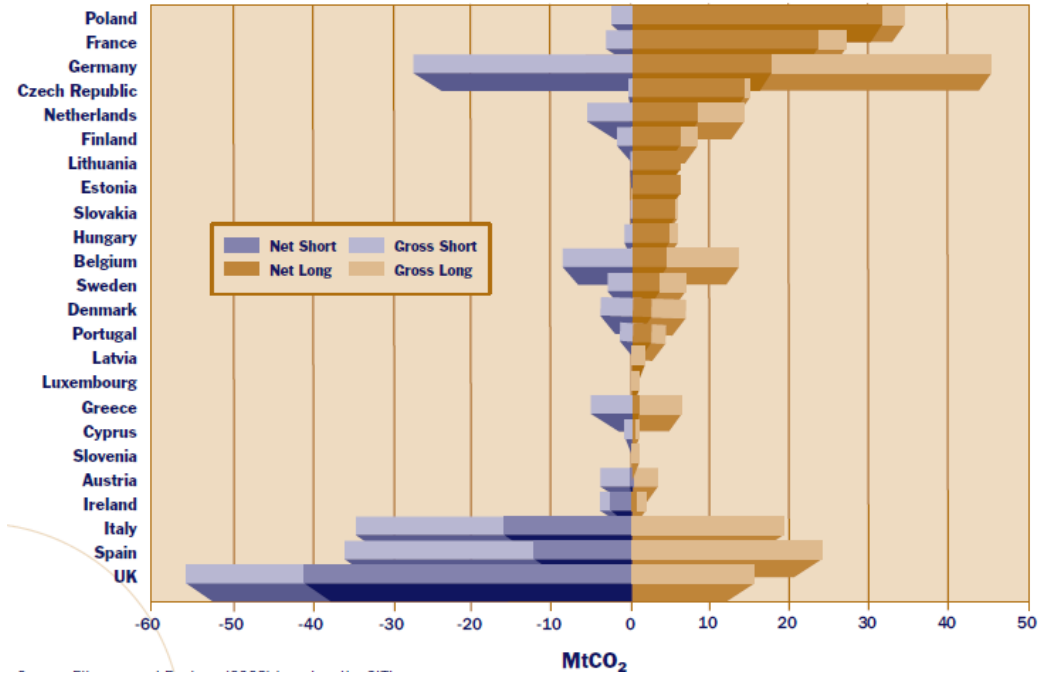
Despite this quite drastic price volatility observed in the initial trading periods of the EU ETS, the price movements were not unusual for cap and trade systems. In fact, similar price movements were observed in the initial trading of SO<sub>2</sub> allowances in the

U.S. Acid Rain Program, where the initial price of approximately \$130 was about half the expected value of \$250. Then after the first few quarters of 1995, the price began to drop again to an all time low of \$70 in early 1996 before rebounding in the 1999 time frame [105, 216]. The market prices of these allowances in the U.S. have continued to fluctuate throughout the early 2000s, as observed in Figure C.2 below.



**Figure C.2: SO<sub>2</sub> Allowance Prices [105]**

One of the other major sources of uncertainty in this first phase of the EU ETS was the demand for allowances. This was expected to be particularly significant at the beginning of this policy implementation because in addition to the usual unpredictable variability of economic activity, weather, and energy prices, there was also a great deal of uncertainty regarding the level of abatement that would occur in response to the EU ETS initially [105]. Further compounding this problem was the uncertainty of where the EUA sellers and buyers would occur both geographically and market-wise.



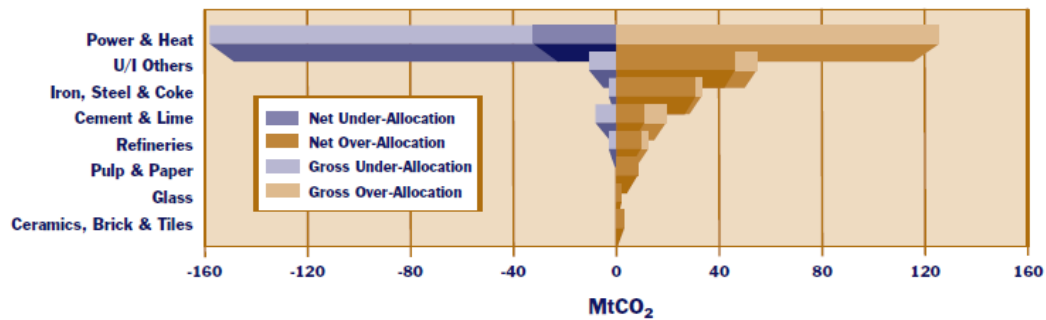
**Figure C.3: Distribution of Long and Short Positions by Member State (2005-2006)**  
[105]

As can be seen in Figure C.3, most member states in the EU were relatively even regarding overall EUA positions in the initial trading year from 2005 to 2006 [105]. As such, much of the trading of EUAs throughout the EU could be confined mostly to national boundaries. However, this figure also makes it quite obvious that a few member states would be net purchasers of EUAs, such as Poland, France, and Germany, while others would be net suppliers, such as Italy, Spain, and United Kingdom. While the EU ETS specifically allows trading to occur throughout the EU, the political ramifications of such national positions could be viewed unfavorably and create energy market distortions in specific regions of the EU.

In addition to the geographic distribution of EUA positions, the positions within specific sectors of the economy also differed greatly. As can be seen in Figure C.4, the



majority of EUAs issued in the 2005 to 2006 period were for the power and heat industries [105]. The ability for many trading entities in this sector to reduce emissions led to surplus allowances that could cover most other sectors' shortcomings. While this still resulted in the abatement of significant CO<sub>2</sub> from the atmosphere, the ability of certain sectors to more readily reduce emissions caused some concern regarding market distortions. In many ways, the ability of the power sector to rapidly abate emissions at a lower cost than other sectors of the economy can be seen as a subsidy to this industry that was not provided equitably across all sectors.



**Figure C.4: Distribution of Long and Short Position by Sector (2005-2006) [105]**

## Phase 2

Despite the growing pains encountered in the initial phase of the EU ETS, a number of improvements were made during phase 2, which occurred from 2008 to 2012. The most widely discussed improvement during this time period was the European Commission's use of explicit "objective" projections based on the results from 2005 verified emissions for all member states [103]. These 2005 ETS emissions were used with gross domestic product (GDP) growth rate projections through 2010 based on validated macroeconomic models, namely PRIMES [103]. The use of these "objective"

models to predict future behavior has allowed more accurate predictions of EUA evolution in the phase 2 trading period of the EU ETS. Further, this new reliance on computational modeling for policy projections demonstrates a willingness within the European Commission to apply objective scientific methodologies across all member states. Such a precedent is quite important for quantitative policy studies, such as the work accomplished in this document.

## **Controversies with the EU ETS**

While many of the unfavorable issues encountered during the trial periods of the EU ETS have already been addressed, much of the criticism of this policy focuses on two main issues that will be discussed here: windfall profits and over-allocation of allowances [105]. The idea of windfall profits refers to the ability of electricity producers to increase prices, and subsequently profit, as a result of freely allocated allowances, and over-allocation refers to the issue of modest emissions caps that did not provide sufficient constraints.

First, to understand the idea of windfall profits, it's important to understand the cost considerations of the electricity generators in the EU ETS. Due to the fact that all EUAs have an associated market value, there is an assumed cost of using those EUAs to cover emissions for electricity generators. Despite this assumed cost, most allowances are allocated freely, thus produce no real cost to the electricity generators. These lost opportunity costs have been observed to be passed through to consumers in their entirety, leading to higher electricity prices, and thus higher profits [105]. Ultimately, the effect on

retail customers also depends on the degree of liberalization in the retail markets, so some of this effect of windfall profits can be abated through regulation of retail markets. For instance, in Spain regulations have stated that companies cannot recover the lost opportunity costs associated with freely allocated allowances, reducing this effect [105]. Additionally, in the UK, regulatory authorities have proposed that the market value of freely allocated allowances be recaptured to help customers in fuel poverty; however, the mechanism by which this would be achieved has yet to be established [105].

One potential solution to the issue of freely allocated allowances leading to windfall profits is the idea of auctioning all allowances instead of allocating them freely [219]. While this idea would not lead to lower electricity prices, it would end the use of lost opportunity costs to pad the wallets of fossil fuel generators. Another advantage of such an approach is that significant revenue could also be raised for the governing authority to improve efficiency by other means and improve equity among citizens [105]. This approach could mitigate some of the political controversy as well regarding geographic EUA positioning, since revenue raised from auctioning would stay within national boundaries of the regulated entity. However, due to the economic power of the electricity suppliers, if they are not compensated in some way they are likely to oppose such market based mechanisms through their lobbying power [105].

The problem of over-allocation is somewhat different than that of windfall profits. Generally, over allocation is understood to mean that the caps created by member states in their respective NAPs were modest to the point of creating a non-binding EU cap [105]. In this way, over-allocation is a signal to regulatory authorities that the cap should

be increased in order to achieve a binding regulatory policy. While abatement potential can be very difficult to estimate because it requires the use of estimates of what emissions would be in the absence of regulation, this problem can be addressed as the program continues. As such, establishing periods or phases within implementation, and assessing new information in real time can improve estimation techniques, allowing regulatory authorities to produce binding caps that don't over constrain markets. This was accomplished to a limited extent in the first phases of the EU ETS, but can certainly be improved as aviation is integrated into the system. It should be noted though, as aforementioned, that aviation is expected to be a net producer of CO<sub>2</sub> emissions. As such, it will likely maintain a long position throughout the foreseeable future, and be a net buyer of EUAs.

What should be evident in this discussion, as Ellerman argues, is that the absence of data did not allow proper modeling of the expected behavior in the EU during the initial phases of the EU ETS [103, 105]. As such, policy makers were lacking the analytical tools necessary to fully understand the consequences of policy implementation, and lacked experience. Despite this fact, it has been shown in literature that “a successful market allows predictability for investment and thereby provides the certainty to make efficient investment decisions [103]”, which can theoretical be captured through objective modeling of the system. At this point in time, many of the models used to study the EU ETS have been shown to be over-simplified, omit important variables, and link a number of models based on inconsistent assumptions [106]. In the end, in order to ensure that future periods of the EU ETS are effective at meeting the goals outlined by the EC

and Kyoto Protocol, effective modeling paradigms and useful models for predicting macroeconomic behavior must be assessed.

## **APPENDIX D**

### **HISTORY OF EXPLORATORY MODELING AND ANALYSIS**

Due to the fact that the idea and terminology surrounding exploratory modeling has only been in existence since 1993, its use has been relatively concentrated by a few groups of researchers from RAND (Banks, Lempert, Schlesinger) and Delft University of Technology (Augustinata, Delaurentis). However, in the last few years the idea has begun to gain traction in a number of fields, and is starting to see more widespread use. Most of the research using exploratory modeling has been focused on issues regarding climate change [18, 220], energy transitions, economic policy [221], and sustainable development [136]. In more recent years, exploratory modeling experienced a resurgence, largely through the work put forth by Augustinata from Delft University of Technology in the Netherlands, and was rebranded as exploratory modeling and analysis (EMA) [78].

#### **Foundations of Exploratory Modeling**

It has been proposed that “exploratory modeling is using computational experiments to assist in reasoning about systems where there is significant uncertainty” [222], such as the regulatory policies currently being addressed in commercial aviation. As such, one of the core tenets of exploratory modeling is the idea that analysts should explore a plethora of hypotheses about the system of interest by broadening the assumptions of a system model to the extent that it is useful and resources will allow [78, 222]. The modeler is able to accomplish this because exploratory modeling treats the

outcome of a plausible system representation as a hypothesis about system behavior in order to ascertain the consequences of the given hypothesis. Ultimately, by exploring a very large set of such hypotheses (in theory an infinite number), the modeler can employ known data mining techniques to explore statements about system behavior that are generally true [78]. In this way, we are able to reason about the system of interest by asking, “if each of the hypotheses were correct what would it mean for the policy in question?”

It should be noted here that this is a fundamental departure from probabilistic thinking in the sense that each model representation and run is treated as a deterministic hypothesis about the system being studied. For this reason, exploratory modeling does not require the assignment of probability or likelihood to uncertain variables, as would be required for sensitivity analysis or even scenario analysis. So, despite the fact that both probabilistic modeling and exploratory modeling aim to quantify and reduce uncertainty, and they both employ similar enablers (design of experiments, data mining techniques, etc.), they do so from fundamentally different perspectives. The reason for approaching the problem from a deterministic viewpoint is to allow for expanded exploration among many of the uncertain parameters which may not have knowable probability distributions.

## **Types of Exploratory Modeling**

Due to the fact that exploratory modeling is inherently so general, since both parametric and non-parametric uncertainty can be searched across, the modeler is immediately confronted with the very real possibility that any given problem can be

infinitely large. While the foundational principles of exploratory modeling readily leads to this conclusion, the philosophy is to remain open to any number of possibilities; however, this philosophy does not exclude the potential to scope and focus a given problem using *a priori* information and even goals of the study. From its inception, this has been well understood, and Steve Banks proposed a classification of exploratory modeling into three distinct types. These types of exploratory modeling are data-driven, question-driven, and model-driven exploratory modeling [222]. Each will be expanded upon further in this section.

### **Data-driven Exploratory Modeling**

In data-driven exploratory modeling, a search is conducted through an ensemble of models for instances that are consistent with a given data set [222]. The goal here is to reveal underlying structure in the data by discovering regularities in the modeling results, although it should be noted that the process may produce many incorrect models. This process actually shares a great deal in common with specification search, in which iterative fitting of regression equations is conducted to obtain an equation that explains a significant portion of observed variability in data [223]. However, in data-driven exploratory modeling the equations or surrogate models created throughout the iterative process are kept along with the heuristics used to evaluate them for further analysis regarding model structure, while in specification search the result is simply the final equation or surrogate model resulting from the search through an ensemble of models. In a sense, there is a wealth of information that is lost by ignoring the process through which a best-estimate model is determined in specification search, and data-driven exploratory



modeling has found an application for the unused byproduct of the specification search process.

### **Question-driven Exploratory Modeling**

Question-driven exploratory modeling begins with a question of interest or policy choice being considered and explores an ensemble of possibilities in the search for answers [222]. As such, question-driven exploratory modeling scopes the problem through *a priori* information regarding the purpose of the study, which is often made necessary where there is deep uncertainty, since an exhaustive search through all models and scenarios may be prohibitive. By posing these questions, we provide structure to the study, narrowing the focus of what should be discovered through the exploratory modeling process. In the context of uncertainty quantification and policy tradeoff analysis, specific questions can be asked and *a priori* information from literature used to scope such a study.

This brings to light the importance of sampling for question-driven exploratory modeling. Borrowing from design of experiments (DoE), the sampling strategy ought to be designed to produce the maximum amount of information for the minimum experimental effort. Thus, for the question-driven approach, the sampling strategy should help answer the question of interest from a limited set of computational experiments. From early literature on exploratory modeling, examples of strategies provided include, uniform sampling across the ensemble (both parametric and nonparametric sources of uncertainty) to determine a range of plausible outcomes, searching for worst case

scenarios to provide risk-averse hedging strategies, listing scenarios where policy failures occur, and discovering bounding cases to support a fortiori arguments as well as those that reveal favorable alternatives [222]. In more recent uses of exploratory modeling, sampling strategies have expanded into the design of experiments literature, and current studies often use full factorial designs, Latin hypercube sampling, and Monte Carlo sampling [78]. That being said, it should also be noted that there is a great deal of ongoing research regarding adaptive sampling techniques that may be well suited to question-driven exploratory modeling that have yet to be employed.

### **Model-driven Exploratory Modeling**

Finally, model-driven exploratory modeling differs from both data-driven and question driven exploration in the sense that an ensemble of models is searched without reference to a data set or policy question for the sole purpose of investigating the properties of the ensemble [222]. It has been noted that this type of investigation is useful for policy analysis whenever a new class of models is proposed to represent the system architecture, and subsequently, it is beneficial to first assess the properties of the models before determining whether the models will be useful [222]. This form of exploration is often useful in cases where multiple models are proposed that represent the same phenomenon at different resolutions or levels of fidelity. It can be beneficial to explore in what instances an aggregate model can be used to represent a higher resolution model, as well as when models of differing resolution may begin to significantly diverge. In the context of the policy studies considered here, this type of exploration may prove

important to a limited extent in validation of the final modeling paradigm chosen to study policy tradeoffs between emission trading schemes and the Aircraft CO<sub>2</sub> Standard.

### **Summary of Exploratory Modeling Types**

In order to provide a quick reference to the reader for the classification scheme of exploratory modeling aforementioned, Table D.1 is provided below. Generally speaking, the public policy problems tackled in this dissertation align most favorably with the question-driven approach to exploratory modeling. The reason for this is threefold: 1) the system-of-systems considered, the global climate and civil aviation activities that produce CO<sub>2</sub>, is so highly complex that exploring all sources of uncertainty is infeasible; 2) CO<sub>2</sub> policy naturally lends itself to questions to be explored, such as, what future scenarios/policy alternatives allow the mitigation of CO<sub>2</sub> production by goals set forth in the Kyoto Protocol?; 3) there are known classes of models and model structures that can be used to predict behavior of the civil aviation industry and resulting emissions (including system dynamics, general equilibrium, agent-based, and statistically regressed models).

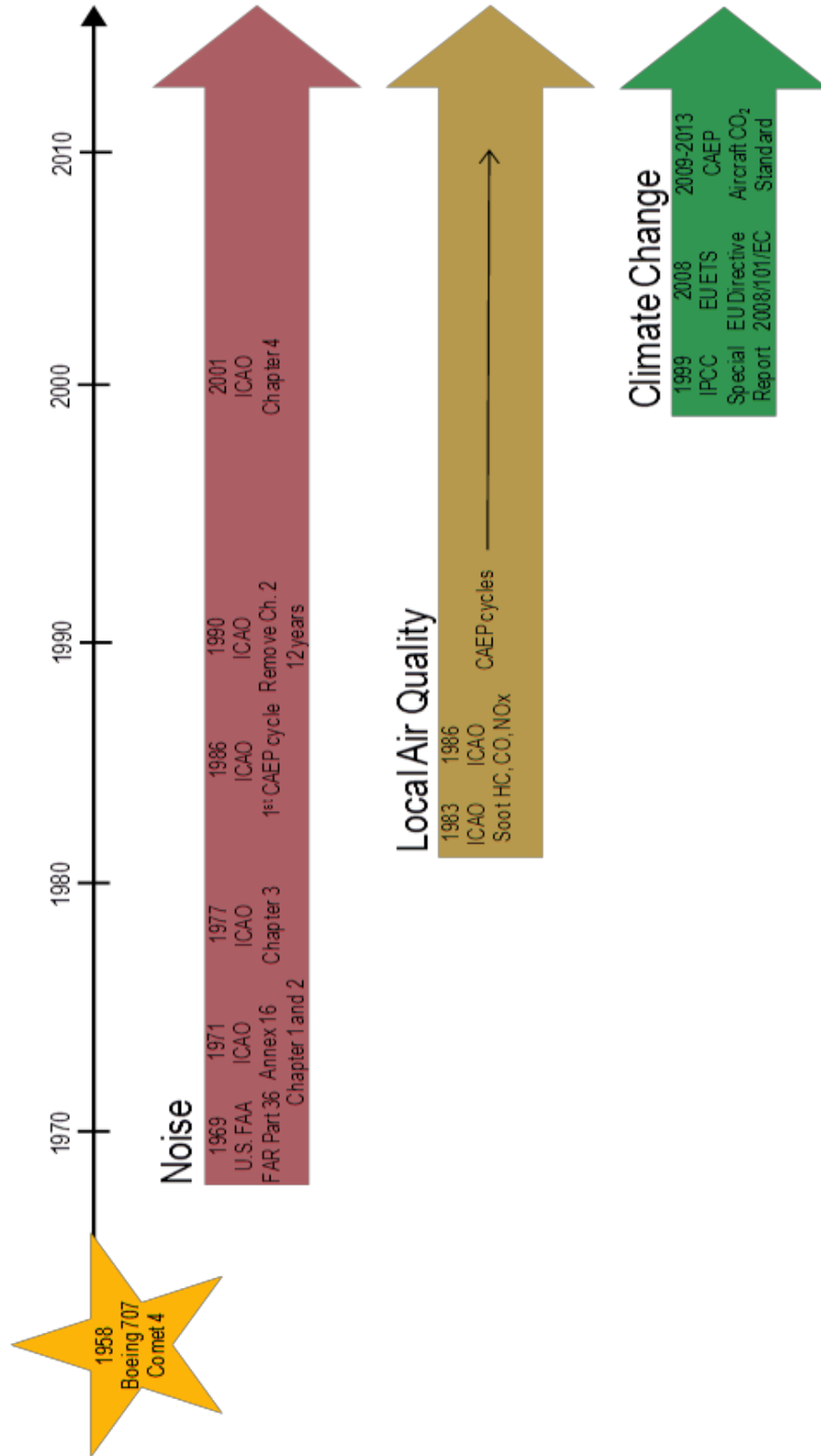
With that said, however, we should not be so quick to dismiss the usefulness of data-driven or model-driven exploratory modeling for the regulatory policy issues explored here. For instance, data-driven exploratory modeling can be used to explore model ensembles based on established best-estimate model structures. Due to the availability of the data that was originally used to validate best-estimate models, other plausible models can be discovered using the same data and established heuristics with

best-estimate models serving as a basis. This could in fact aid question-driven modeling in the sense that a more complete ensemble of models can be discovered and feed into the question driven approach. Additionally, with the cornucopia of different model classes and levels of aggregation used for emissions predictions purposes, model-driven exploratory modeling could provide valuable insights through comparison of previously vetted models.

**Table D.1: Exploratory Modeling Summary**

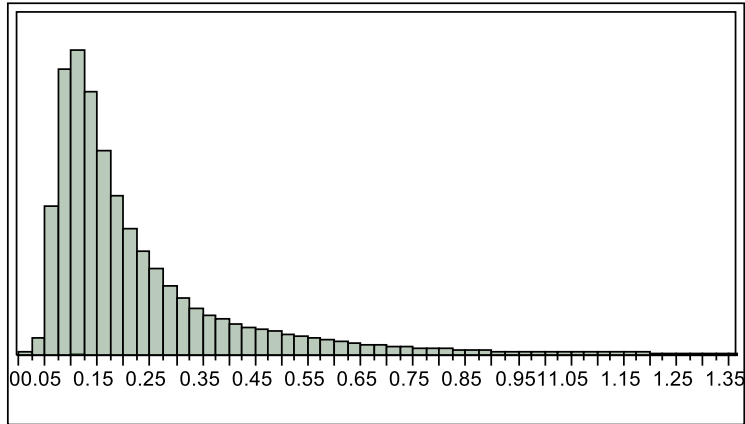
<b>Exploratory Modeling</b>		
<b>Modeling Type</b>	<b>How does it work?</b>	<b>What is the Goal?</b>
<b>Data-driven</b>	Search through an ensemble of models to find instances that are consistent with a given data set.	Determine the structure of models that are consistent with the data.
<b>Question-driven</b>	Ask a question or present a policy choice and search through an ensemble of models in search of the answer.	Scope a policy problem by addressing specific questions.
<b>Model-driven</b>	Search through an ensemble of models without reference to a given data set or policy question.	To investigate the properties of new classes of models or compare models of varying resolution.

# APPENDIX E

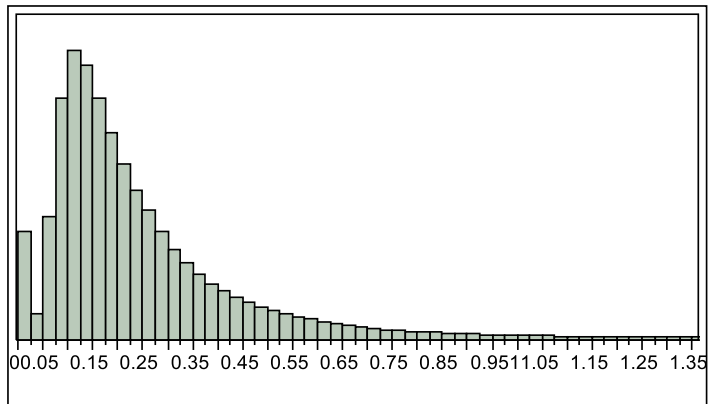


# APPENDIX F

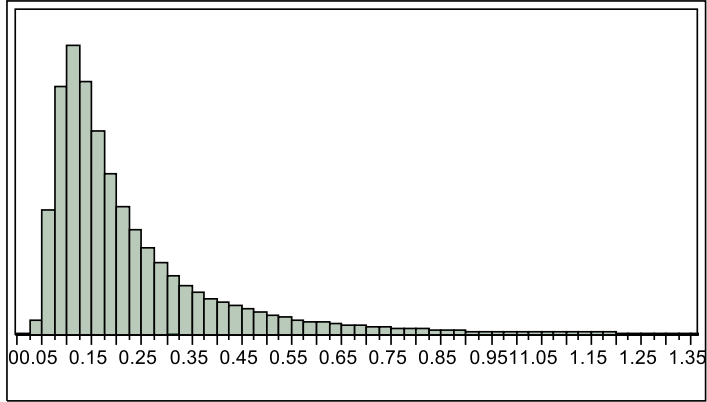
## Air Fare Histograms for All Air Carriers



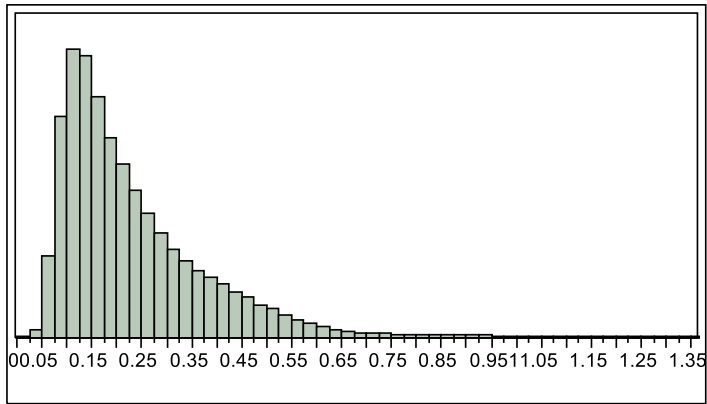
**Legacy Carrier 1 Fare Per RPM Variability**



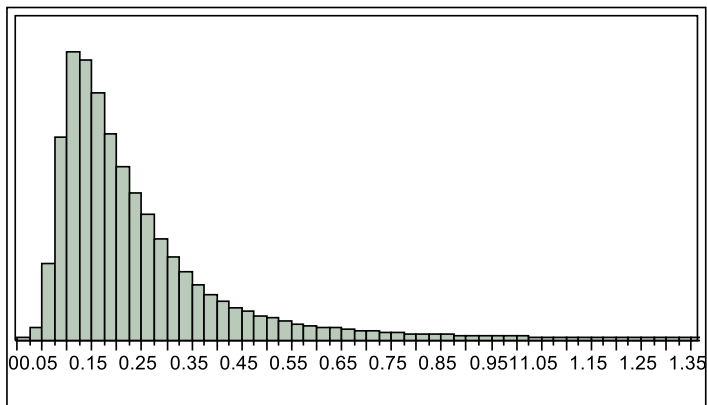
**Legacy Carrier 2 Fare Per RPM Variability**



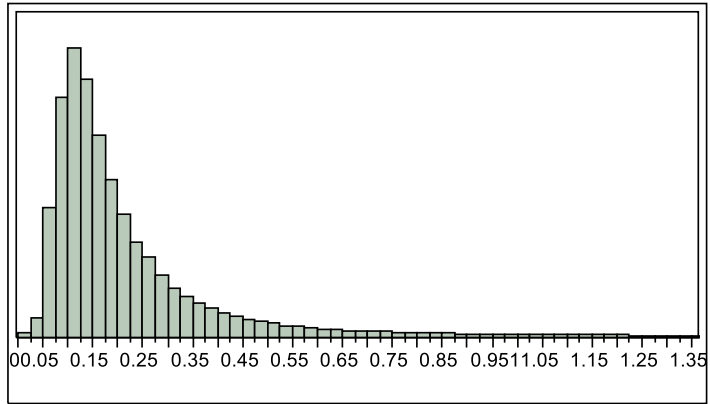
**Legacy Carrier 3 Fare Per RPM Variability**



**LCC 1 Fare Per RPM Variability**



**LCC 2 Fare Per RPM Variability**



**LCC 3 Fare Per RPM Variability**



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